Fuzzy systems for condition assessment of equipment in electric power systems

Anwendung der Fuzzy-Logik zur Zustandsbewertung von Betriebsmitteln der elektrischen Energieversorgung

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genehmigte Dissertation von Dipl.-Ing. Athanasios Krontiris aus Cholargos Attikis, Griechenland
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Genehmigte Dissertation von Dipl.-Ing. Athanasios Krontiris aus Cholargos Attikis, Griechenland

1. Gutachten: Prof. Dr.-Ing. Gerd Balzer
2. Gutachten: Prof. Dr.-Ing. Jürgen Adamy

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Thanos Krontiris

Abstract

In this thesis the use of fuzzy logic techniques for condition assessment and diagnostic analysis of equipment in electric power systems is discussed. Condition assessment may be performed at a strategic level so as to assist in planning long and medium-term maintenance and replacement, or at operational level focusing on day-to-day maintenance. The first part of the thesis addresses the application of fuzzy systems for the purpose of strategic and operational condition assessment using the example of high-voltage circuit breakers. Due to the high dimensionality of operational condition assessment schemes, direct definition of the fuzzy rule base could become quite tedious; for this reason, an alternative approach is proposed here. The second part of the thesis discusses the application of fuzzy logic for diagnostic analysis in power systems, in particular for the purpose of Dissolved Gas Analysis (DGA). The standard DGA interpretation scheme, defined in IEC 60599, is extended by fuzzy reasoning, and the added value is demonstrated by a case study on high-voltage instrument transformers. Furthermore, for diagnostic analysis of power transformers, an adaptive fuzzy DGA interpretation scheme is developed on the basis of the standard scheme. The presented case studies aim at assisting decision makers in power system maintenance departments in developing fuzzy systems for condition assessment and diagnostic analysis.

Keywords: asset health index, condition-based maintenance, condition assessment, condition indicator, diagnostic analysis, dissolved gas analysis, electricity supply system, fuzzy logic

Kurzfassung

Diese Arbeit untersucht das Potential der Fuzzy-Logik für die Zustandsbewertung und Diagnostik von Betriebsmitteln der elektrischen Energieversorgung. Mit Blick auf die Tragweite der Entscheidungsfindung bezüglich der Erneuerung bzw. der Wartung von Betriebsmitteln wird im ersten Teil der Arbeit zwischen strategischer und operativer Zustandsbewertung unterschieden. Am Beispiel von Hochspannungsleistungsschaltern werden Fuzzy-Logik-basierte Bewertungssysteme erläutert, die für die strategische bzw. operative Zustandsbewertung geeignet sind. Bei der operativen Zustandsbewertung steht eine Vielzahl von Informationsquellen zur Verfügung, was den direkten Entwurf eines Fuzzy-Systems erschwert; aus diesem Grund wird hier ein alternatives Verfahren vorgeschlagen. Im zweiten Teil der Arbeit wird das Potential der Fuzzy-Logik für die Diagnostik von Betriebsmitteln am Beispiel der Gas-in-Öl-Analyse untersucht. Das nach der internationalen Norm IEC 60599 standardisierte Interpretationsschema wird durch Anwendung der Fuzzy-Logik erweitert und der erreichte Mehrwert wird am Beispiel der Gas-in-Öl-Analyse von Hochspannungsmesswandlern demonstriert. Weiterhin wird für die Gas-in-Öl-Analyse von Leistungstransformatoren ein adaptives Neuro-Fuzzy-Interpretationssystem entwickelt. Der prinzipielle Aufbau des Systems, insbesondere der implementierten Fuzzy-Regelbasis, richtet sich nach dem standardisierten Interpretationsschema. Die präsentierten Fallbeispiele sollen Entscheidungstreffern bei der Wahl eines geeigneten Fuzzy-Logik-basierten Zustandsbewertungs- oder -Diagnostik-Systems unterstützen.

Schlüsselwörter: Diagnose, Fuzzy-Logik, Gas-in-Öl-Analyse, Instandhaltungsplanung, Zustandsbewertung, Zustandsindex, Zustandsindikator, zustandsorientierte Instandhaltung

Zusammenfassung in deutscher Sprache

Die Frage der Instandhaltung elektrischer Energieversorgungssysteme ist in den letzten zwei Jahrzehnten in den Vordergrund gerückt. Dies hängt mit folgenden Aspekten zusammen: Der Kern der heutigen Energieversorgungsnetze wurde in den sechziger und siebziger Jahren des vergangenen Jahrhunderts erbaut. Damals wie heute wurde für die verschiedenen Betriebsmittel eine erwartete Lebensdauer von dreißig bis vierzig Jahren prognostiziert, was bedeutet, dass viele Betriebsmittel das Ende ihrer geplanten Lebensdauer erreicht oder gar überschritten haben. Zudem ist der Lastzuwachsfaktor in industrialisierten Ländern seit den neunziger Jahren um mehr als zwei Drittel zurückgegangen, so dass der Ersatz von älteren Betriebsmitteln nicht mehr im Rahmen der Netzverstärkung realisiert werden kann. Betreiber von Energieversorgungsnetzen stehen damit zum ersten Mal vor einer massiven Erneuerung ihrer Betriebsmittel aus reinen Altersgründen. Ein weiterer Aspekt, der neues Licht auf die Instandhaltung wirft, ist die Entflechtung von Energieversorgungsunternehmen im Zuge der Marktöffnung in den neunziger Jahren. Somit sind besonders kapitalintensive Geschäftsbereiche der elektrischen Energieversorgung wie etwa Übertragungs- und Verteilnetze noch stärker gefordert, ihre Instandhaltungsstrategie zu optimieren. Nicht zuletzt wird auch die demographische Entwicklung innerhalb der nächsten Jahre die elektrische Energieversorgung vor eine neue Herausforderung stellen. Mit dem altersbedingten Ausscheiden erfahrener Mitarbeiter droht ein weitreichender Wissensverlust.

In Anbetracht dieser Herausforderungen wird der Instandhaltung von Energieversorgungsnetzen eine besondere Wichtigkeit beigemessen. Insbesondere sind heutzutage Methoden der Zustandsbewertung gefragt, die bei der Entscheidungsfindung bezüglich der Wartung bzw. der Erneuerung von Betriebsmitteln behilflich sein können. Die genaue Kenntnis des Betriebsmittelzustands bietet umfangreiche Vorteile: Auf kurze Sicht können fehleranfällige Betriebsmittel identifiziert werden, so dass durch rechtzeitige Wartung oder Außerbetriebnahme das Risiko eines ungeplanten Ausfalls kontrolliert werden kann. Auf mittlere und lange Sicht kann die Instandhaltung insofern optimiert werden, dass die Lebensdauer jedes einzelnen Betriebsmittels möglichst ausgeschöpft wird, ohne dass sich zugleich die Zuverlässigkeit verringert. Aber auch einem drohenden Wissensverlust kann ein systematisiertes, gut dokumentiertes Verfahren zur Zustandsbewertung durch die Integration von Expertenwissen entgegensteuern.

Diese Arbeit untersucht das Potential von Methoden der Fuzzy-Logik für die Zustandsbewertung und Diagnostik von Betriebsmitteln der elektrischen Energieversorgung. Durch ihre innewohnende Eigenschaft, trotz ungewisser Aussagen konsistente Schlussfolgerungen zu liefern, sind Fuzzy-Logik-basierte Systeme dafür gut geeignet. Ungewissheit tritt während der Zustandsbewertung aus mehreren Gründen auf. Zum einen kann die Bewertungsgrundlage, sprich die relevante Informationsbasis, unvollständig oder fehlerbehaftet sein. Unvollständiger Einblick in die Alterungs- und Abnutzungsprozesse des jeweiligen Betriebsmittels, fehlende Auskunft über die in der Praxis aufgetretenen Belastungen, oder Ungenauigkeit von Messungen, die der Informationssammlung dienen, sind Beispiele solcher Ungewissheit. Zum anderen kann aber auch die Bewertungsmethode Quelle von Ungewissheit sein. Die Zusammenfassung verschiedener, teilweise widersprüchlicher Informationsquellen mit dem Ziel, eine Aussage über den aktuellen

Zustand eines Betriebsmittels zu treffen, erfolgt keineswegs nach einem genau definierten Verfahren. Selten kann aus einer einzelnen Beobachtung genau auf den Zustand zurückgeschlossen werden; in der Praxis wird stattdessen oft auf das Expertenwissen erfahrener Mitarbeiter für die Zustandsbewertung zurückgegriffen. Eine Motivation dieser Arbeit ist deshalb das vorhandene Expertenwissen im Bereich der Instandhaltung mit Hilfe der Fuzzy-Logik mathematisch zu modellieren und rechentechnisch nachzubilden.

Im ersten Teil der Arbeit wird die Frage der Zustandsbewertung behandelt. Um eine klare thematische Abgrenzung zu gewährleisten, wird zuallererst der Begriff theoretisch erläutert. Demzufolge wird unter Zustandsbewertung ein Prozess der Informationsanalyse und -synthese zur Bewertung des Zustands eines Betriebsmittels gemäß bestimmter Kriterien verstanden. Mit Blick auf die Tragweite der Entscheidungsfindung bezüglich der Wartung bzw. der Erneuerung von Betriebsmitteln wird zwischen operativer und strategischer Zustandsbewertung unterschieden. Das Ziel der operativen Zustandsbewertung ist die Unterstützung des Instandhaltungs-Tagesgeschäfts durch Empfehlungen zum Zeitplan und Umfang von Inspektionen und Wartungsaktivitäten, während die strategische Zustandsbewertung längerfristig angelegt ist und auch wirtschaftlich-organisatorische Aspekte berücksichtigt.

Bisherige Methoden zur rechentechnischen Zustandsbewertung in der elektrischen Energieversorgung basieren hauptsächlich auf standardisierten Bewertungsbogen. Die theoretische Diskussion in dieser Arbeit verdeutlicht die immanenten Einschränkungen solcher Bewertungsmethoden. Als besonderer Schwachpunkt erweist sich deren Inkonsistenz im Fall einer lückenhaften Informationsbasis. Um diesen Einschränkungen entgegenzuwirken, werden hier Fuzzy-Logik-basierte Zustandsbewertungssysteme entwickelt.

Das erste System, erläutert am Beispiel von Hochspannungsleistungsschaltern, dient der strategischen Zustandsbewertung. Dabei werden folgende Informationsquellen als Bewertungsgrundlage herangezogen: die einschlägige Betriebserfahrung mit der jeweiligen Leistungsschaltertechnik, ausgedrückt z.B. in unternehmensübergreifenden Störungsstatistiken, die unternehmenseigene Erfahrung mit der Instandhaltung des Betrachtungsobjekts, und wirtschaftliche Aspekte wie etwa die dokumentierten mittleren Wartungskosten. Die Bewertung erfolgt auf Basis zuvor definierter Fuzzy-Regeln, mit dem Vorteil, dass diese leicht vom Menschen interpretiert werden können, da sie in natürlicher Sprache ausgedrückt sind. Zudem ist das Bewertungssystem aus Gründen der Übersichtlichkeit modular aufgebaut, so dass zuerst jeder Aspekt getrennt behandelt wird, und dann die Einzelurteile in eine Gesamtbewertung einfließen. Das vorgeschlagene Fuzzy-Logik-basierte System weist ein konsistentes Bewertungsverhalten auf, ist aber trotzdem einfach im Aufbau und kann von einem eventuell vorhandenen Bewertungsbogen abgeleitet werden.

Der Entwurf eines Fuzzy-Logik-basierten Systems für die operative Zustandsbewertung kann sich jedoch als mühsame Aufgabe erweisen, da in diesem Fall wesentlich mehr Informationsquellen zur Verfügung stehen. Eine direkte Eingabe von Regeln oft nicht mehr möglich, denn die Anzahl von Fuzzy-Regeln in einer vollständigen Regelbasis hängt exponentiell von der Anzahl der Dimensionen des Eingangsraums ab.

Aus diesem Grund wird ein alternatives Verfahren für den Entwurf solcher Bewertungssysteme vorgeschlagen. Das Betrachtungsobjekt wird in funktionelle oder strukturelle Einheiten unterteilt und die Aussagekraft verfügbarer Eingangsinformationen über den Zustand jeder dieser Einheiten wird separat ermittelt. Somit können mehrere, potentiell widersprüchliche Informationsquellen in konsistenter Weise vereinigt werden. Die benötigte Informationsgrundlage zur operativen Zustandsbewertung wird aus mehreren Bereichen gewonnen: Zum einen stehen für

Betriebsmittel der elektrischen Energieversorgung heutzutage mehrere hochentwickelte, aussagekräftige Mess- und Diagnostikverfahren zur Verfügung, wie etwa die kontinuierliche Überwachung von Teilentladungsaktivitäten. Üblicherweise wird bei der präventiven Wartung eine Reihe solcher Messungen und Prüfungen durchgeführt, die einen guten Einblick in den Zustand des jeweiligen Gerätes erlauben. Andererseits wird während des Betriebs von Energieversorgungsnetzen auch Information über die Belastung der Betriebsmittel gesammelt. Unter Berücksichtigung der allgemeinen Betriebserfahrung, ausgedrückt in Form statistischer Analysen, kann das somit ermittelte individuelle Belastungsprofil die Zustandsbewertung unterstützen. Diese aus der Betriebserfahrung und dem individuellen Belastungsprofil abgeleitete Information ist umso wichtiger, wenn keine aktuellen Mess- und Diagnostikergebnisse vorliegen. Aus diesem Grund werden in dem implementierten Fuzzy-Bewertungssystem die verschiedenen Informationsquellen entsprechend ihrer Aktualität vereinigt.

Auch hier wird das Beispiel von Hochspannungsleistungsschaltern zur praktischen Erläuterung des Entwurfsverfahrens herangezogen. Die Liste der funktionellen Einheiten umfasst in diesem Fall den Leistungsschalterantrieb, die Strom führenden Teile, die innere und äußere Isolation, die Unterbrechereinheit und die Steuereinheit. Die Informationsgrundlage für die Bewertung stammt aus Betriebsdaten und Ergebnissen von Diagnostikverfahren, die für die Instandhaltung von Leistungsschalter üblicherweise gesammelt bzw. angewandt werden. Für die Ermittlung der Aussagekraft jeder Informationsquelle über den Zustand der definierten funktionellen Einheiten wird auf die einschlägige Literatur zurückgegriffen.

Das hier neu entwickelte Verfahren zum Entwurf Fuzzy-Logik-basierter Systeme für die operative Zustandsbewertung ist übersichtlich, einfach in der Umsetzung und stellt einen effektiven Ansatz dar, um mit einer widersprüchlichen Informationsgrundlage umzugehen. Darüber hinaus ist es auch möglich, das Wissen mehrerer Erfahrungsträger und möglicherweise voneinander abweichende Meinungen zu integrieren.

Im zweiten Teil der Arbeit wird das Potential von Methoden der Fuzzy-Logik für die Diagnostik von Betriebsmitteln untersucht. Prinzipiell läuft jedes Diagnostikverfahren in zwei Schritten ab: Zuerst werden Daten vom Betrachtungsobjekt systematisch gewonnen, üblicherweise durch eine Messung, die eine Reihe von numerischen Zahlen liefert. Durch den Einfluss externer Störfaktoren oder systematischer Fehler während der Messung sind die Messergebnisse immer mit einer gewissen Ungenauigkeit behaftet. Im zweiten Schritt werden die anfangs inhaltslosen Daten interpretiert, um relevante Information zu gewinnen. Die Interpretation erfolgt durch den Vergleich der Daten mit einer entsprechenden Norm, die den Normal- oder Wunschzustand beschreibt. Sowohl die Auswahl der Norm als auch die Gestaltung des Vergleichsschemas setzen eine tiefe Kenntnis der relevanten kausalen Zusammenhänge zwischen Belastung und Alterung bzw. Abnutzung voraus. Unvollständiges Wissen des individuellen Belastungsprofils stellt aber diesen kausalen Zusammenhang infrage. Um diese zwei Quellen von Ungewissheit –Ungenauigkeit der Messergebnisse und Ungewissheit bezüglich der Vergleichsnorm– besser in den Prozess der Interpretation zu integrieren, wird in dieser Arbeit die Anwendung der Fuzzy-Logik vorgeschlagen und untersucht.

Als Beispiel dieser Untersuchung fungiert dabei die Gas-in-Öl-Analyse ölgefüllter Betriebsmittel. Die Entscheidung für dieses Diagnostikverfahren stützt sich auf mehrere Faktoren. Zum einen spielt die Gas-in-Öl-Analyse eine Schlüsselrolle bei der Zustandsermittlung ölgefüllter Betriebsmittel, wie etwa von großen Leistungstransformatoren, die wiederum von besonderer Wichtigkeit für das gesamte elektrische Energieversorgungssystem sind. Zum anderen verfügt das Gebiet der Gas-in-Öl-Analyse sowohl über eine umfangreiche Wissensansammlung als auch über eine hinreichend hohe Komplexität, was die Anwendung eines Fuzzy-Logik-basierten Interpretationssystems rechtfertigt.

Obwohl die ersten Untersuchungen schon anfangs des 20. Jahrhunderts stattfanden, und die erste relevante internationale Norm im Jahr 1978 veröffentlicht wurde, bleibt das Gebiet der Gas-in-Öl-Analyse durch neue Erkenntnisse stets im Wandel. Leider gibt es in der einschlägigen Literatur keine zusammenfassende Beschreibung der über die Jahre entwickelten Interpretationsmethoden. Aus diesem Grund bietet diese Arbeit eine detaillierte Diskussion der wichtigsten Methoden. Die weitere Untersuchung beschränkt sich dann auf die Interpretation nach der zurzeit geltenden internationalen Norm IEC 60599.

In dieser Arbeit wird das standardisierte Interpretationsschema durch Anwendung der Fuzzy-Logik erweitert. Um den dabei erwarteten Mehrwert beziffern zu können, werden gemessene Gas-in-Öl-Konzentrationen aus einem Kollektiv von Hochspannungsmesswandlern sowohl nach dem standardisierten als auch nach dem erweiterten Schema interpretiert. Neben der Eignung Fuzzy-Logik-basierter Interpretationssysteme bietet dieses Fallbeispiel auch Gelegenheit, die prinzipielle Anwendbarkeit der Gas-in-Öl-Analyse bei Messwandlern zu untersuchen. Letzterer Aspekt ist insofern relevant, als in den vergangenen Jahren Kritik an der in der Norm zitierten typischen Gaskonzentrationen geäußert wurde. Hierzu leistet diese Arbeit einen Beitrag mit neuen Erkenntnissen: das Fallbeispiel belegt, dass die in der Praxis gemessenen Gaskonzentrationen erheblich niedriger als die in der Norm angenommenen sind. Angesichts der sehr niedrigen Störungsrate für Hochspannungsmesswandler ist die Verwendung letzterer trotzdem sinnvoll.

Auf der Basis des Fallbeispiels wird auch die erwartete Effizienzsteigerung der Interpretation durch die Anwendung Fuzzy-Logik-basierter Methoden bestätigt. Der erste Vorteil gegenüber dem standardisierten Interpretationsschema besteht in die Ermittlung eines Vertrauensfaktors für jede Diagnose, die ein Maß für deren Aussagekraft darstellt. Somit wird eine Entscheidung über weitere Instandhaltungsaktivitäten besser fundiert. Weiterhin zeigt sich, dass das durch Fuzzy-Logik erweiterte Interpretationsschema fehlerbehaftete Geräte zuverlässiger und genauer identifizieren kann. Von den Messwandlern, bei denen ein interner Fehler durch Demontage und anschließender visueller Inspektion zweifelsfrei verifiziert wurde, werden einige anhand des erweiterten, nicht aber des standardisierten Interpretationsschemas identifiziert. Eine Sensitivitätsanalyse zeigt zudem, dass das Fuzzy-Logik-basierte Interpretationsschema nur unwesentlich von der Parameterwahl abhängt: Obwohl die Erhöhung des Unschärfegrads prinzipiell zur Kennzeichnung mehrerer Geräte führt, ist der Anstieg des dazugehörigen Vertrauensfaktors nur moderat, so dass die zusätzlich gekennzeichneten Geräte nicht als fehlerbehaftet klassifiziert werden. Es wird also die These bekräftigt, dass die Erweiterung der Gas-in-Öl-Analyse durch ein Fuzzy-Logik-basiertes Interpretationsschema deren Anwendbarkeit, Zuverlässigkeit und Genauigkeit steigern lässt.

Die über die Jahre hinaus erarbeiteten Methoden zur Interpretation der Gas-in-Öl-Analyse stellen eine umfassende Sammlung an Fachwissen dar und sind von besonderer Bedeutung für die Zustandsermittlung. Gleichwohl sind sie von mehreren Betriebsmitteltypen geprägt, die ein unterschiedliches Belastungsprofil bzw. Alterungsverhalten aufweisen. Bei der praktischen Umsetzung der Gas-in-Öl-Analyse ist es deswegen sinnvoll, während der Anwendung gewonnene Erkenntnisse in die weitere Interpretation einfließen zu lassen. Besonders nach dem Auftreten eines internen Fehlers an einem Betriebsmittel sollte untersucht werden, ob das Interpretationsschema diesen identifiziert hätte; andernfalls sollte es entsprechend angepasst werden.

Hierin liegt die Motivation zur Entwicklung adaptiver Interpretationssysteme für die Gas-in-Öl-Analyse. Die Literaturrecherche zeigt, dass zu diesem Zweck überwiegend Methoden der künstlichen Intelligenz zum Einsatz kommen, die dem Prinzip der Black-Box-Modellierung folgen. Solche Methoden erlauben zwar eine gute Anpassung an eine vorhandene Datengrundlage, sind aber vom Menschen kaum interpretierbar. Dadurch bleibt das neu erschlossene Wissen im Rechenmodell gebunden und es kann keine allgemeingültige Erkenntnis gewonnen werden. Sollte neben der Adaptionsfähigkeit auch die Interpretierbarkeit gefragt sein, sind adaptive Systeme auf Basis der Fuzzy-Logik besser dafür geeignet, da ihre Regelbasis in natürlicher Sprache ausgedrückt ist.

Im letzten Teil dieser Arbeit wird ein adaptives Fuzzy-Logik-basierte Interpretationssystem für die Gas-in-Öl-Analyse großer Leistungstransformatoren entwickelt. Der prinzipielle Aufbau des Systems, insbesondere der implementierten Fuzzy-Regelbasis, richtet sich nach dem standardisierten Interpretationsschema. Hierfür werden die den Regeln zugrundeliegenden Fuzzy-Mengen so ausgelegt, dass sie eine im Vorfeld definierten Funktionsabhängigkeit aufweisen. Durch die Adaption an die vorhandene Datengrundlage werden lediglich die Parameter dieser Funktionen verändert, nicht aber deren Form. Dieses besondere Merkmal des Systems erlaubt einen direkten Vergleich zwischen dem standardisierten und dem an die Daten angepassten Interpretationsschema.

Für die mathematische Modellierung und rechentechnische Umsetzung wird ein Neuro-Fuzzy-System mit Hilfe des Residual-Backpropagation-Lernverfahrens trainiert. Vor der Anwendung auf die vorhandenen Gas-in-Öl-Daten wird die Zuverlässigkeit des Lernverfahrens anhand einer zu diesem Zweck definierten Datenbasis verifiziert. Somit soll untermauert werden, dass das implementierte Neuro-Fuzzy-System die zugrundeliegende Datenstruktur nachbilden kann. Der Verifizierungstestlauf bestätigt das schnelle und zuverlässige Konvergenzverhalten des Lernverfahrens.

Als Datengrundlage für die Anpassung des Neuro-Fuzzy-Systems dient eine umfangreiche Leistungstransformatoren-Datenbank, die sowohl Information über gemessene Gaskonzentrationen als auch über aufgetretene Störungen beinhaltet. Allerdings wurde die Störungsstatistik nicht aus dem Blickwinkel der Gas-in-Öl-Analyse erfasst, so dass die Daten zuerst entsprechend gefiltert werden müssen. Zu jedem Störungsereignis werden dann die dazugehörigen gemessenen Gaskonzentrationen ermittelt; diese zwei Informationsquellen stellen das Referenz-Ausgangs- und -Eingangssignal für den Lernalgorithmus dar.

Nach Anwendung des Lernverfahrens wird das angepasste Interpretationsschema ermittelt. Es zeigt sich, dass die Effizienz des entwickelten Neuro-Fuzzy-Systems bei der Parameteranpassung durch zwei Faktoren gemindert wird. Die erste Einschränkung stammt von der Datengrundlage selbst: Durch den großen Umfang der Leistungstransformatoren-Datenbank ist ein automatisches Indexierungsverfahren notwendig, um die Gas-in-Öl-Messungen den fehlerbehafteten bzw. fehlerfreien Geräten zuzuordnen. Irrelevante, das Ergebnis verfälschende Einträge können dabei nur bedingt identifiziert werden. Für den Zweck einer Anpassung des Interpretationsschemas ist zudem die in der Datenbank vorhandene Information unvollständig. So fehlt z.B. jegliche Information zum Isolieröltyp, der aber einen wesentlichen Einfluss auf die Freisetzung von Gasen hat. Als weitere Einschränkung während des Lernverfahrens erweist sich die Wahl des Neuro-Fuzzy-Systems, insbesondere die angenommene Struktur der Fuzzy-Regelbasis. Offenbar sind einige der vorgeschriebenen Regeln durch ihre Gestaltung grundsätzlich nicht dafür geeignet, die in der Datengrundlage vorhandene Struktur nachzubilden. Da diese Regeln die Interpretationsgenauigkeit mehr mindern als erhöhen, werden die Parameter der zugrundeliegenden Fuzzy-Mengen vom Lernalgorithmus so bestimmt, dass die Regeln keinen Beitrag zur Interpretation leisten. Dieser Effekt unterminiert jedoch die Forderung nach einem Aufbau entsprechend des standardisierten Interpretationsschemas.

Das Fallbeispiel verdeutlicht die Wichtigkeit der Datenakquisition für die Gas-in-Öl-Analyse: Um eine effektive Adaption des Interpretationsschemas zu erreichen, müssen nicht nur alle relevante Daten der Betriebsmittel vorliegen, sondern auch die genaue Zuordnung der Gas-in-Öl-Messungen nach dem diagnostizierten Zustand der Geräte muss gewährleitet sein. Andererseits wird durch das Fallbeispiel ersichtlich, dass die Gestaltung eines adaptiven Neuro-Fuzzy-Systems unter strengen Auflagen letztendlich dessen Anpassungsfähigkeit eingrenzt.

In dieser Arbeit wird das Potential der Fuzzy-Logik für die Zustandsbewertung und Diagnostik von Betriebsmitteln der elektrischen Energieversorgung untersucht und mögliche Anwendungsgebiete werden aufgezeigt. Durch praktische Fallbeispiele sollen Entscheidungstreffer bei der Wahl eines geeigneten Fuzzy-Logik-basierten Zustandsbewertungs- oder -Diagnostik-Systems unterstützt werden.

Mit Blick in die Zukunft wäre die Entwicklung prognostizierender Zustandsbewertungsmethoden zu empfehlen, die auf Basis der hier präsentierten Fuzzy-Logik-basierten Systeme eine Prognose des zu erwartenden Zustands der Betriebsmittel liefern. Somit könnte die mittel- und langfristige Instandhaltung in elektrischen Energieversorgungsnetzen effektiver geplant werden. Eine weitere potentielle Anwendung der Fuzzy-Logik in diesem Bereich könnte auch die Beschreibung vom ausfallsverbundenen Risiko sein.

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Abbreviations

ACI	Asset Condition Index
AHI	Asset Health Index
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AIS	Air-Insulated Substation
ANN	Artificial Neural Network
ANSI	American National Standards Institute
ASMT	Americal Society on Materials and Testing
BIL	Basic Insulation Level
CB	Circuit Breaker
CBM	Condition-Based Maintenance
CEGB	Central Electric Generating Board
CI	Condition Indicator
CIGRE	Conseil International des Grands Reseaux Électriques
COA	Centre-Of-Area defuzzification method
COG	Centre-Of-Gravity defuzzification method
CR	Consistency Ratio
CT	Current Transformer
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
DGA	Dissolved Gas Analysis
DIN	Deutsche Institut für Normung (German Institute for Standardization)
DP	Degree of molecular Polymerisation
ERP	Enterprise Resource Planning
FIS	Fuzzy Inference System
FMEA	Failure Mode and Effect Analysis
GC	Gas Chromatography
GIS	Gas-insulated Switchgear
HMWH	High Molecular Weight Hydrocarbons
HV	High-Voltage
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineers
IEEE	Institute of Electrical and Electronic Engineers
IIR	Independence of Irrelevant Alternatives

IT Instrument Transformer
KPI Key Performance Indicator
LCC Life-Cycle Costing
LVQ Learning Vector Quantisation
MCDA Multi-Criteria Decision Analysis
MVT Magnetic (inductive) Voltage Transformer
MUP Maximum Usability Period
OECD Organisation for Economic Co-operation and Development
OEM Original Equipment Manufacturer
PCB Polychlorinated Biphenyl
PD Partial Discharge
PDA Personal Digital Assistant
PT Power Transformer
RPROP Resilient backpropagation algorithm
RUI Replacement Urgency Index
SOM Self-Organising Map
TBM Time-Based Maintenance
TCG Total Combustible Gas
TSO Transmission System Operator
UHF Ultra High Frequency

Symbols

Symbols related to fuzzy logic

A	Fuzzy set A
$\mu_A(x)$	Degree of membership of element x to fuzzy set A
$\bar{A}$	Complement of set A
H_A	Entropy of fuzzy set A
$\neg$	Negation operator
$\top$	Triangular norm (fuzzy *AND*)
$\perp$	Triangular conorm (fuzzy *OR*)
$I(x, y)$	Implication operator
w_i	Weighting factor of the ordered weighted average
$\underline{p}$	Parameter vector
ϵ	Approximation error
h	Learning rate
η	Learning rate step

Symbols related to condition assessment

a_{ij}	Ratio of importance of the i^{th} to the j^{th} indicator
$\mathbf{A}$	Matrix of ratios of importance
c_i	Degree of compliance with the i^{th} condition indicator (score)
λ	Eigenvalue of matrix $\mathbf{A}$
λ_{max}	Principal eigenvalue of matrix $\mathbf{A}$
r_i	Intermediate result for the i^{th} condition indicator
w_i	Weighting factor of the i^{th} condition indicator

Symbols related to dissolved gas analysis

p_i	Partial pressure of the i^{th} gas
k_i	Henry's law constant of the i^{th} gas
c_i	Concentration of the i^{th} gas
H_2	Hydrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
C_2H_6	Ethane
C_2H_4	Ethylene
C_2H_2	Acetylene

1 Preface

In the evolving electric power industry
environment, the challenge will be to reduce cost
by improving business processes and increasing
operating efficiency as well as to enhance system
security and quality of power supply.

Prabha Kundur, 2003

Electricity supply systems are a backbone of modern society: all over the world, economic activity and social prosperity depend on the reliable and safe access to low-cost electricity. However, today's public perception of practically unlimited availability of electricity is deceiving. Over the last century, it took a lot of effort by generations of engineers to reach the current level of availability; at least equal effort is continuously required in order to retain it.

In most industrial countries, the core of today's electricity supply system was erected in the 1960s and 1970s. At the time of erection, manufacturers of electric power generation and transmission equipment usually projected an expected technical lifetime of 35 to 40 service years. Consequently, a significant number of components in electricity supply systems are reaching or have even exceeded their design technical lifetime – engineers speak of *ageing electric power systems*.

One could expect an adverse effect of ageing equipment on the overall availability of electricity. However, such an effect cannot be verified in the field: availability still remains high and equipment failure is as seldom as in the past. Nevertheless, equipment ageing is still a major challenge for the electricity supply industry, especially in view of the changing business environment.

When older equipment was decommissioned in the past, this has mainly been driven by load growth rather than because of reaching the equipment's technical lifetime. In the booming years between 1960 and 1980 the rate of increase in electricity demand was typically in the range of $7\,\% - 9\,\%$ per annum. As a result, the power generation and transmission capacity had to be drastically increased. One common solution in order to upgrade the capacity of the supply system has been to replace older devices by newer ones with higher power ratings. In this way equipment was removed from service prior to reaching its technical lifetime. The first major change in the business environment is related to the decrease in load growth. Nowadays, the time of such high rates of load growth is over: especially in industrial countries, progress in energy efficiency and an almost complete electrification of society have pushed the load growth rate down to $1\,\% - 2\,\%$ per annum (table 1.1). Consequently, the need for enhancement of the electricity supply system no longer justifies early decommisioning of equipment.

The second major change in the business environment of electricity supply came with market opening in the 1990s. Up to that time electric power utilities have been vertically integrated companies –mostly state-owned– covering all fields from power generation to power transmission and distribution. Market opening and unbundling reshaped the corporate landscape especially for the transmission and distribution business. Electric power and distribution systems are

Table 1.1.: Increase in electricity demand worldwide and in OECD countries (historical data and prognoses based on the world energy outlook of the International Energy Agency [1.1–1.4]).

	1960–1970	1970–1990	1990–2000	2000–2010	2010–2030
OECD countries	9.96 %	5.31 %	1.61 %	1.95 %	1.26 %
world	9.60 %	6.64 %	2.58 %	3.33 %	3.58 %

highly asset-intensive; as with every asset-intensive business, maintenance is a key issue. In the course of unbundling, the requirement for economic efficiency during maintenance has been therefore tightened.

The historical development of maintenance also fits into this scheme [1.5]. Until the 1960s maintenance has been usually of corrective nature: a piece of equipment was repaired or taken out of service only after an incident has been recorded. Several factors justified the corrective maintenance approach. To that time, technology was still far from technical maturity; failure and defects were rather common events. In addition, many devices (especially in the high-voltage level) were still manufactured by hand, with mass production being the exception. Finally, power plants and transmission substations were usually manned so that technicians could react quickly in case of an incident. For the decades to follow, the maintenance policy for electric power systems switched from corrective to preventive, the equipment being serviced before a failure occurs. In its initial form preventive maintenance has been time-based: a piece of equipment was serviced in regular time intervals, usually as recommended by the manufacturer. In this way, the overall availability of electricity supply could be greatly increased, since equipment outage was planned, thus allowing for appropriate countermeasures. Although time-based preventive maintenance is still the prevailing maintenance policy for electricity supply systems, the requirement for economic efficiency lead to the introduction of condition-based maintenance since the 1980s. Nowadays, decisions on maintenance are based not only on time, but also on the actual technical condition of the equipment. Obviously, this calls for the assessment of the equipment's condition. Detailed knowledge of all factors determining the service behaviour of the equipment is essential for the purpose of effective condition assessment.

Knowledge and ageing are also keywords for the third major change in electricity supply systems. In many countries, the technical personnel of electric power utilities –especially the one in charge of maintenance– is significantly older than in other industrial sectors. In combination with the general demographic change in industrial societies, this problem is expected to intensify in the near future. For the example of Germany, the number of 55^{+} year-old employees in the power sector increased by 29.64 % in the time interval between 2006 and 2009 (compared to an average rate of increase of 13.66 % for all industrial sectors together [1.6, 1.7]). Older, experienced employees carry a great deal of unrecorded knowledge and skills, which younger replacements need years of practice in the field to obtain. As long as procedures are not completely documented and knowledge transfer from the experienced personnel to the younger replacements e.g. by training is not accomplished, workforce ageing can result in significant loss of technical knowledge. According to a survey by the American Public Power Association from 2003 and 2005, two thirds of all participating utilities judged workforce ageing as a serious to moderate challenge, with knowledge loss being the major risk involved [1.8, 1.9].

1.1 Motivation

The aforementioned challenges demonstrate the importance of maintenance for today's electricity supply systems. Effective procedures must be developed especially for condition assessment of the equipment, since this kind of information is essential for decision making on maintenance. In the short term, precise knowledge of the system's technical condition can assist in detecting fault-prone devices; by means of timely servicing or removal from service the risk of unplanned outages can thus be controlled. Condition assessment can further assist in identifying the short and medium-term demand for maintenance and/or replacement. In this way, the economic efficiency of maintenance can be ensured. Finally, a systematic, well-documented procedure for condition assessment can also integrate unrecorded practical experience and thereby counteract knowledge loss.

The focus of this thesis is on techniques for condition assessment and diagnostic analysis of equipment in electric power systems. Since uncertainty is inherent in the process of condition assessment, the use of fuzzy logic is proposed here. In particular, the motivation for introducing fuzzy reasoning is manifold:

Condition assessment resembles a multi-criteria decision problem, where information from several sources has to be combined, cross-weighted and condensed so as to reach a single conclusion e.g. an index describing the technical condition of a piece of equipment. Uncertainty arises both from the implemented preference scheme, used in order to combine the various sources of information, as well as from the input information itself, for example due to variations in ageing mechanisms, incomplete understanding of stresses applied during service or limited measurements available. Common condition assessment schemes usually fail to incorporate uncertainty. The application of fuzzy reasoning can help overcome this limitation; by means of proper modelling uncertainties can be propagated along extended chains of reasoning.

Although advanced diagnostic techniques are nowadays available for all types of equipment in electric power systems, the problem of their interpretation still remains. Every diagnostic analysis is basically a measurement; its output are measuring results. It is the task of a maintenance expert or a computer programme to turn this data into information. Imprecision and uncertainty is inherent in any complex diagnostic problem [1.13] and there is rarely a single observation or measurement which definitely indicates impending failure. Experience with a piece of equipment or diagnostic technique is necessary to overcome this uncertainty and perform effective diagnosis. Contrary to human experts, common computer-aided interpretation schemes could face difficulties when dealing with uncertainty e.g. due to inaccuracy of the measurement. In order to properly treat uncertainty, interpretation schemes on the basis of fuzzy logic can be used instead.

Condition assessment and diagnostic analysis are knowledge-based procedures. In practice, a great deal of relevant know-how is carried by the maintenance personnel involved, although power utilities strive to capture and document this knowledge. Perhaps the most important obstacle to this process is the absence of appropriate mathematical and algorithmic models to capture knowledge. Due to their resemblance to human reasoning fuzzy systems are especially suitable for this purpose.

The major advantage of modelling knowledge and practical experience on a fuzzy system is that uncertainty –inherent in condition assessment– can be incorporated in a precisely defined way, so that similar situations are assessed consistently. Added benefits derived from developing fuzzy assessment systems include: i) keeping maintenance know-how in-house even when the workforce leaves the company e.g. due to retirement, and ii) providing evidence of good decision making on the basis of a well-documented condition assessment process. This aspect becomes more and more important, as regulatory requirements in the power transmission and distribution business are increasingly tightened. For instance, according to the regulatory environment in Germany, electric power utilities must be able to justify their decisions on maintenance [1.14, 1.15].

Despite the wide acceptance of fuzzy logic in the scientific community, its application to maintenance issues in electric power systems has not been seriously considered yet. One of the objective of this thesis is to identify possible fields of application, especially with regard to condition assessment and diagnostic analysis. In the past, fuzzy reasoning has been proposed and partially implemented in the field of electric power systems; however, the focus has been predominantly on control issues – the main application field for fuzzy logic. In [1.16], 46 publications of research work on fuzzy logic applied to power systems have been reviewed: half of them were related to questions of control (power system stabilisation, voltage and load-frequency control), another quarter was dedicated to protection issues (fault localisation, transmission line protection). Applications to maintenance problems were –and still are– rather scarce. So far, research work on the application of fuzzy logic for power system maintenance has been conducted almost exclusively by universities and independent researchers [1.16–1.19]. The main knowledge carriers –electric power utilities and manufacturers– are still rather reserved, with only few exceptions [1.20]. By showing how fuzzy logic can be applied to typical questions of maintenance and condition assessment, this thesis can provide power utilities with a guideline for the introduction of appropriate fuzzy techniques.

1.2 Outline of the thesis

In order to demonstrate the suitability of fuzzy reasoning for the purpose of condition assessment and diagnostic analysis in electric power systems, a number of simple to more sophisticated case studies are presented in this thesis. The examples provided cover both condition assessment (for maintenance planning) as well as detailed diagnostic analysis for different types of equipment.

The thesis is structured in three main parts: The first part (chapter 2) provides the necessary theoretical background on fuzzy sets and fuzzy reasoning. Readers with experience in this field may skip most sections of this chapter, but are encouraged to read through section 2.4, since the fuzzy systems introduced there are used later in the thesis for the case studies. They represent a novel approach for adapting a diagnostic scheme to a given training dataset without changing its principal layout.

The second part of the thesis addresses the application of fuzzy systems for the purpose of condition assessment. The general process of condition assessment, its importance to cost-effective maintenance as well as common assessment techniques are discussed in chapter 3. Generally speaking, condition assessment may be performed at higher level so as to assist in planning long and medium-term maintenance and replacement (strategic condition assessment), or at lower, merely technical level focusing on day-to-day maintenance (operational condition assessment). In sections 3.4 and 3.5 some important limitations of existing condition assessment schemes are discussed both from a theoretical and practical perspective.

In order to overcome these limitations, the use of fuzzy systems for the purpose of condition assessment is proposed in this thesis. The focus of the first case study in chapter 4 is on strategic condition assessment of high-voltage circuit breakers. A simple fuzzy system is introduced, considering the applied technology, the general service and maintenance experience as well as the cost of maintenance.

On the other hand, operational condition assessment is based mainly on findings obtained by a series of diagnostic tests. Due to the large number of input information sources, standard definition of a fuzzy system would become quite tedious in this case. Chapter 5 therefore introduces an alternative way of defining fuzzy systems for this purpose. Again, high-voltage circuit breakers are used as a case study – common diagnostic techniques for circuit breakers are reviewed in section 5.2.1.

In the third part of the thesis the implementation of fuzzy logic for the purpose of detailed diagnostic analysis is illustrated using the example of dissolved gas analysis (DGA). Chapter 6 provides the necessary theoretical background on DGA as applied to oil-impregnated paper insulating systems. To the knowledge of the author, no systematic description of interpretation methods available for DGA is published yet; for this reason, an overview of common methods is given from a historical perspective in section 6.2.3.

The first step towards a fuzzy DGA interpretation scheme is shown in chapter 7. In sections 7.2 to 7.3 a sample of 135 high-voltage instrument transformers is analysed according to the interpretation scheme specified by the International Electrotechnical Commission (IEC). In view of ongoing discussions regarding the applicability of the IEC interpretation scheme for DGA of instrument transformers, some interesting conclusions are drawn on this occasion. The analysis further reveals the principal limitation of all available DGA interpretation schemes: their inability to incorporate uncertainty. In order to overcome this limitation, the extension of DGA interpretation by fuzzy reasoning is proposed. The IEC interpretation scheme is used as a case study.

In a further step, fuzzy logic is applied so as to adjust the original IEC interpretation scheme to a given sample of equipment for which information on fault occurrence is available. Learning fuzzy systems are introduced for this purpose in chapter 8. The case study presented there is based on a large database on power transformers, comprising measurements of dissolved gases as well as registered failure events.

In order to allow for separate treatment of each case study, the respective chapters provide the necessary background information on the type of equipment considered as well as a discussion of improvements reached when applying fuzzy reasoning. Finally, chapter 9 sums up the thesis with some general remarks and a brief outlook of future applications of fuzzy logic to maintenance problems in electric power systems.

2 Fundamentals of fuzzy logic

> As the complexity of a system increases,
> our ability to make precise and yet
> significant statements about its
> behaviour diminishes until a threshold is
> reached beyond which precision and
> significance (or relevance) become
> almost mutually exclusive characteristics
>
> Lofti Zadeh, 1973

The introduction and development of fuzzy logic has been driven by the understanding that real-life decisions are based on subjective perceptions rather than objective facts. Uncertainty is inherent in perceptions: the question of whether an entity matches a particular type is not a matter of affirmation or denial, but rather a matter of degree. The remarkable ability of human beings –and other living beings as well– to integrate uncertainty into logical reasoning allows for effective decision making in a complex world. Fuzzy logic is an approach to formalise this way of reasoning.

This chapter provides an introduction to fuzzy logic and its underlying fuzzy set theory. The theoretical background and a historical perspective of the development of fuzzy logic are presented in the first section, followed by the mathematical definition of fuzzy sets in section 2.2. Section 2.3 is dedicated to the formal description of fuzzy rules used in the reasoning process, and to the construction of fuzzy inference systems.

Readers with experience in the field of fuzzy logic may skip most sections of this chapter, but are encouraged to read through section 2.4, since the fuzzy systems introduced there are used later in the thesis for the case studies. They represent a novel approach for adapting a diagnostic scheme to a given training dataset without changing its principal layout.

2.1 Introduction to fuzzy logic

The distinguishing feature of fuzzy logic is its capacity to properly treat uncertainty during logical reasoning. Generally speaking, uncertainty may arise from three different sources: *ambiguity*, *vagueness* or *ignorance*.

A symbol is *ambiguous* if it has more than one possible distinct meanings. The most obvious example of ambiguous symbols are words. For instance, the word "network" can have several meanings: a group of computers connected together (computer network), a system of interconnected rail tracks (railway network) or a group of people sharing common interests (social network). Ambiguity of symbols imposes severe constraint on the process of logical reasoning. For this reason, formal logic makes use of *words of true logic* – unambiguous terms such as "or" and "not".

On the other hand, a symbol is *vague* if it is not explained precisely or accurately. A famous logical puzzle related to the problem of vagueness is the one of the man who went bald [2.1]: "It is supposed that at first he was not bald, that he lost his hairs one by one, and that in the end he was bald; therefore, it is argued, there must have been one hair the loss of which converted him into a bald man. This, of course, is absurd. Baldness is a vague conception; some men are certainly bald, some are certainly not bald, while between them there are men of whom it is not true to say they must be either bald or not bald".

The notion of vagueness has been discussed vividly during the first decades of the 20th century in an attempt to establish a philosophical foundation of mathematics. The philosophers Bertrand Russell and Max Black have been among the main contributors in this discussion. In [2.1] Russell argues that even words of pure logic are only precise as long as the symbols employed in propositions[1] –words and perceptions– are precise themselves. Consequently, so Russell, every proposition that can be framed in practice has a certain degree of vagueness. He considered a representation to be vague if the underlying relation was not one-to-one, but one-to-many. Black, on the other hand, introduced the theory of *loose concepts* (not precisely defined entities) as opposed to sharply bounded concepts in order to treat vagueness.

Finally, *ignorance* can also be a source of uncertainty. Contrary to vagueness, ignorance accounts for incomplete rather than imprecise knowledge. Typical examples of incomplete knowledge are random experiments: by means of long-term observation one may deduce an expectation for future events; however, complete accuracy of the forecast can not be guaranteed. Partial knowledge of a process has been traditionally treated by the theory of probability with great success. Bayes's theorem further allows for the propagation of this kind of uncertainty along a chain of logical reasoning.

From a historical perspective, the introduction and development of fuzzy logic can be described according to Kuhn's four-phase evolution scheme[2] [2.3, 2.4]. During the first phase (at the beginning of the 20th century) the necessity for an alternative system of logic has been addressed. The discussion was driven by the understanding that many propositions are neither completely true nor completely false, but rather vague. Such proposition can thus not be treated properly by formal logic. Although alternative systems of logic have been proposed since, with Łukasiewicz's three-valued logic [2.5] being the best example, the breakthrough was not reached until the introduction of fuzzy set theory by Zadeh in 1965 [2.6].

The second phase has been characterised by widespread and harsh criticism of the newly proposed theory. For instance, Professor Kalman –inventor of the homonymous filter– stated in 1972: "No doubt Prof. Zadeh's enthusiasm for fuzziness has been reinforced by the prevailing climate in the USA – one of unprecedented permissiveness. Fuzzification is a kind of scientific permissiveness; it tends to result in socially appealing slogans unaccompanied by the discipline of hard scientific work and patient observation" [2.20].

1 In formal logic *propositions* are statements (e.g. "Socrates is a man") that can be either true or false . Russell himself considered propositions as structured entities consisting of objects and properties and questioned their function as truth bearers.

2 Kuhn's four-phase evolution scheme describes the transition between scientific paradigms. A *scientific paradigm* is a set of concepts, theories, principles and methods that are shared and accepted for granted by the scientific community in a particular field.

Table 2.1.: Milestones in the historical development towards fuzzy logic [2.4, 2.7–2.10].

Year	Major developments
4^{th} century B.C.	First documentation of systematic approach to logic (formal logic) Aristotle: Organon
19^{th} century A.D.	Foundation of symbolic formal logic: introduction of appropriate mathematics for the representation of formal logic George Boole: The laws of thought (1854) [2.11] Augustus de Morgan: Formal logic (1847) [2.12]
beginning of the 20^{th} century	Attempts for philosophical foundation of mathematics lead to a discussion of the concept of vagueness Bertrand Russell: Vagueness (1923) [2.1]
1920–1929	Introduction of three-valued logic by Jan Łukasiewicz [2.5]
1965	Introduction of fuzzy sets by Lofti Zadeh [2.6]
early 1970s	Theory of fuzzy sets of higher level [2.13–2.16]
1974	Fuzzy algorithms for the control of a steam plant [2.17]
1978	First technical application of a fuzzy controller (cement kiln) [2.18]
1983	Application of fuzzy control in a water treatment plant, Japan
1987	Fuzzy-controlled Sendai underground railway, Japan [2.19]
1988	Laboratory for International Fuzzy Engineering, Japan
1991	Formation of the Berkeley Initiative in Soft Computing, USA

In the years to follow, successful applications of fuzzy logic in numerous engineering problems altered the situation in favour of the new theory. Table 2.1 gives an overview of early applications of fuzzy logic: In [2.17] Mamdani proposed the first controller on the basis of fuzzy logic. A few years later the first large-scale practical implementation of a fuzzy controller followed [2.18]. One of the most spectacular applications was the control of the Sendai underground railway in Japan [2.19]. In general, Japanese engineers and researchers contributed the most in launching fuzzy controllers for engineering applications.

The success of demonstration projects and the resulting acknowledgement of the significance and relevance of fuzzy logic inspired more researchers to get involved in the field. This lead to the development of new exciting theories and concepts. In the field of fuzzy set theory, several extension of standard fuzzy sets have been proposed, the most important being: *interval-valued* fuzzy sets [2.21–2.24], fuzzy sets of type 2 or higher types [2.13–2.16, 2.25–2.29], *L*-fuzzy sets [2.30], *intuitionistic* fuzzy sets [2.31], and *rough* fuzzy sets [2.32]. Another major advancement was the simplification of the original rule-based fuzzy inference systems by Takagi and Sugeno. The resulting Takagi-Sugeno fuzzy systems can be easily trained to fit a given training dataset and are thus suitable for non-linear system modelling. Last but not least, significant progress has been also recorded in the foundation of formal fuzzy logic.

Since the late 1990s, fuzzy logic has reached the fourth phase of evolution: in the field it is looked upon as a state-of-the-art technology, especially regarding questions of automation and control. Among researchers and scientists, fuzzy logic has found its proper place, with numerous journals published and conferences organised every year. No modern automation engineering curriculum gets by without at least one course on fuzzy logic. The figures provided in appendix A.1 provide evidence of today's importance of fuzzy logic.

Generally speaking, published research work on fuzzy logic can be grouped into two categories [2.33]: In a *narrow sense*, fuzzy logic is a research area devoted to the formal development of the various logical systems of multi-valued logic in a unified way. In this sense, it is also referred to as *mathematical* or *formal* fuzzy logic. On the other hand, fuzzy logic in a *broad sense* covers an extensive field, both theoretical and practical. Its primary aim is to utilise fuzzy set theory for developing concepts and methods for representing and dealing with knowledge. Obviously, for engineering purposes fuzzy logic is seen in a broad sense. The next sections are therefore dedicated to the mathematical description of fuzzy sets.

2.2 Mathematical representation of fuzzy sets

In his seminal paper published in 1965, Lofti Zadeh did not use the term fuzzy logic; he rather preferred the wording *fuzzy sets* [2.6]. In doing so, he pointed out the key role of set theory in logic, both formal as well as fuzzy. Sets are one of the most fundamental and important concepts in mathematics. Georg Cantor (1845–1918), the founder of set theory, defined a set as "a collection of distinct objects of our perception or thought into a whole" [2.34, 2.35]. Accordingly, a set consists of objects (called *elements*), but is itself an object in its own right.

In general, a set may be described in two ways: either by extension, that is by listing all its elements, or by intensional definition, using a rule or semantic description. Defining the set of all odd numbers is an example of intentional set description:

Example 2.1 *Set of all odd numbers*

$$A = \{x \mid x \text{ is an odd number}\} \tag{2.1}$$

The example above illustrates the link between logic and set theory: a candidate element x belongs to the set of odd numbers A if and only if the statement "x is an odd number" is true. In other words, the *membership* of a candidate element in a particular set depends on the truth of its descriptive rule.

2.2.1 Standard fuzzy sets

In example 2.1 above, the statement "x is an odd number" has been used as a semantic description of the set A. In formal, Aristotelian logic, a *statement* or *proposition* is a meaningful declarative sentence which has the property of being either true or false. Accordingly, any candidate element x may or may not belong to the set of odd numbers A; however, both membership and non-membership at the same time are not allowed.

If we adopt the notation of George Boole [2.11] and assign a truth value 1 to true statements and a truth value 0 to false statements, we may rewrite the definition given in example 2.1 as:

$$A = \{x \mid \mu_A(x) = 1\} \tag{2.2}$$

In equation 2.2 function $\mu_A(x)$ returns the truth value of the statement "x is an odd number". Obviously, $\mu_A : x \to \{0, 1\}$ is a mapping of x in the discrete set {0,1}, as the above statement can either be true or false. We may refer to function $\mu_A(x)$ as a *membership function*: if $\mu_A(x) = 1$ then x is an element of the set; if, on the other hand, $\mu_A(x) = 0$ then x does not belong to the set.

Thus, intentional set description in the sense of classical set theory calls for precise descriptive rules of membership. A set is assumed to be *well-defined* if its membership rule has the form of an Aristotelian statement. But how does classical set theory deal with ill-defined concepts?

Example 2.2 *Set of tall students in a college class*

$$A = \{x \mid x \text{ is a tall student}\} \tag{2.3}$$

Obviously, set A above is not well-defined (and as such not a set in the classical sense), as the sentence "x is a tall student" may not be classified as either true or false. The question whether a student x is tall or not is rather a matter of degree. Let us for example consider the students listed in table 2.2.

Table 2.2.: Height of students

Student's name	Height [cm]
Arthur	182
James	166
Prescott	195
Margaret	165
Charlotte	178

It is reasonable to argue that Prescott definitely is a member of the set "tall students". On the other hand, Arthur and Charlotte belong only partly to the considered set, whereas James and Margaret definitely do not belong to the set.

It is exactly this idea of *partial membership* in a set which has motivated Zadeh in introducing fuzzy sets in 1965 [2.6]. In order to account for partial membership he allowed for the membership function $\mu_A : x \to [0,1]$ to receive any value in the unit interval $[0,1]$. In other words, the membership function μ_A now describes the *degree of membership* in a particular set, with $\mu_A(x) = 1$ meaning that the candidate element x completely belongs to the set A and $\mu_A(x) = 0$ meaning that x is not at all a member of the set.

Definition 2.1 *Fuzzy set: A (standard) fuzzy set*[3] *A in a universe of discourse X is a set of ordered pairs:*

$$A = \{(x, \mu_A(x)) \mid x \in X \text{ and } \mu_A(x) \in [0,1]\} \tag{2.4}$$

Obviously, the definition of a fuzzy set is a simple extension of the definition of a classical set in which the membership function is permitted to have *any* values between 0 and 1. In definition 2.1 the unit interval is chosen as the co-domain of the membership function μ_A because of its similarity to boolean algebra, although this is not obligatory.

Membership functions play a key role in fuzzy set theory: every fuzzy set is defined by –one could even say *is*– its membership function μ. Since the beginnings of fuzzy set theory, several membership functions have been proposed in the literature. In table 2.3 examples of common membership functions are shown and their general mathematical definition is provided.

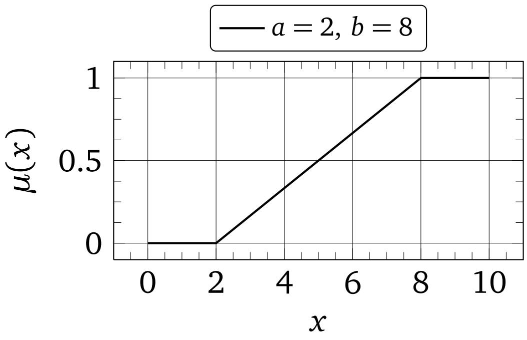
The degree of membership $\mu_A(x)$ of an element x to fuzzy set A is sometimes also referred to as "fuzzy probability". However, there is a distinct difference between fuzzy membership and conventional probability, although experience and data are required in order to quantify any of them [2.36]. For example, consider the fuzzy set $A = \{x \mid x \text{ is a number close to } 7\}$ and the element 6.8 featuring a degree of membership $\mu_A(6.8) = 0.8$. Obviously, the interpretation can by no means be: "the probability of 6.8 being equal to 7 is 80 %". The degree of membership

[3] In his seminal paper [2.6], Zadeh used a discrete notation in order to describe a fuzzy set: $A = \sum_{x \in X} \mu_A(x)/x$. Nowadays this notation is not used any more.

Table 2.3.: Common membership functions: (1) bounded ramp, (2) triangular, (3) trapezoidal, (4) s-shaped, (5) sigmoid, (6) Gaussian, and (7) bell-shaped membership function.

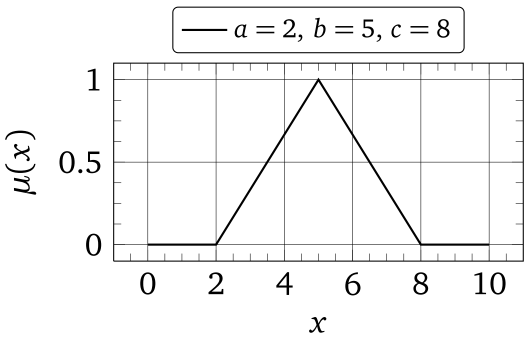
1. Bounded ramp function

$$\mu_{\text{ramp}}(x) = \begin{cases} 0 & , x \leq a \\ \dfrac{x-a}{b-a} & , a \leq x \leq b \\ 1 & , b \leq x \end{cases} \tag{2.5}$$



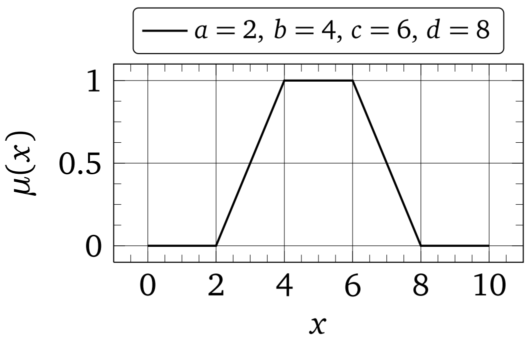
2. Triangular function

$$\mu_{\text{triangular}}(x) = \begin{cases} 0 & , x \leq a \\ \dfrac{x-a}{b-a} & , a \leq x \leq b \\ \dfrac{c-x}{c-b} & , b \leq x \leq c \\ 0 & , c \leq x \end{cases} \tag{2.6}$$



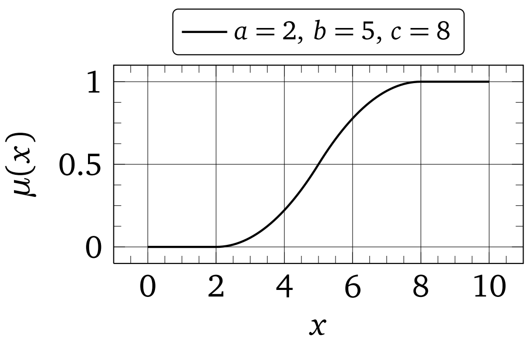
3. Trapezoidal function

$$\mu_{\text{trapezoidal}}(x) = \begin{cases} 0 & , x \leq a \\ \dfrac{x-a}{b-a} & , a \leq x \leq b \\ 1 & , b \leq x \leq c \\ \dfrac{d-x}{d-c} & , c \leq x \leq d \\ 0 & , d \leq x \end{cases} \tag{2.7}$$



4. S-shaped function

$$\mu_{\text{s-shaped}}(x) = \begin{cases} 0 & , x \leq a \\ 2\left(\dfrac{x-a}{b-a}\right)^2 & , a \leq x \leq b \\ 1 - \left(\dfrac{c-x}{c-b}\right)^2 & , b \leq x \leq c \\ 1 & , c \leq x \end{cases} \tag{2.8}$$



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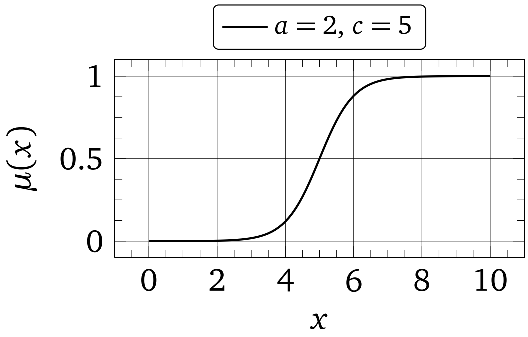
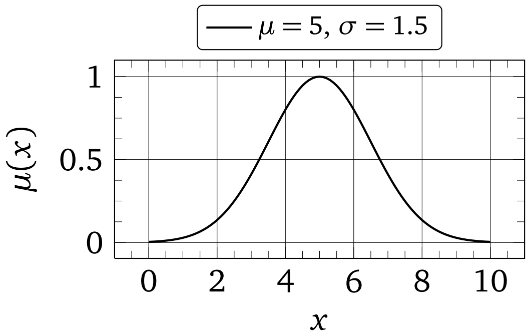
5. *Sigmoid membership function*

$$\mu_{\text{sigmoid}}(x) = \frac{1}{1 + e^{-a(x-c)}} \tag{2.9}$$



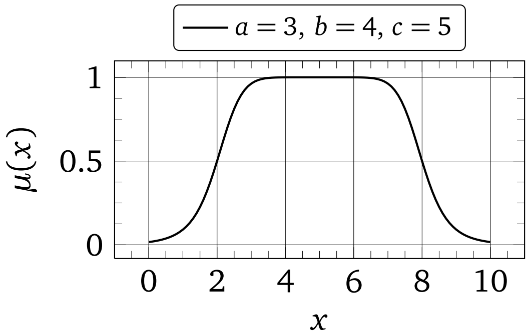
6. *Gaussian membership function*

$$\mu_{\text{Gaussian}}(x) = e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{2.10}$$



7. *Bell-shaped membership function*

$$\mu_{\text{bell-shaped}}(x) = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}} \tag{2.11}$$



merely expresses the similarity between the particular element of the set and the type of the set. A more detailed discussion on the difference between fuzzy membership and traditional, Bayesian probability is given in [2.36–2.38].

For most engineering applications, piecewise-defined, linear membership functions are usually sufficient (compare bounded ramp, triangular and trapezoidal functions in table 2.3). A special case of fuzzy sets with high practical importance is the so-called fuzzy singleton introduced in definition 2.2.

Definition 2.2 *Fuzzy singleton: A fuzzy set A consisting of only one element with degree of membership in A equal to 1:*

$$A = \{(x, \mu_A(x)) \,|\, x \in X\} \quad \text{with } \mu_A(x) = \begin{cases} 1, & \text{if } x = a \\ 0, & \text{else} \end{cases} \tag{2.12}$$

Allowing for the membership function to take any value in the interval $[0, 1]$ has been the key to obtaining a fuzzy set. The other way round, in order to reduce a fuzzy set to a standard set (featuring a two-valued membership function), the concepts of α-cut sets and strong α-cut sets are introduced in following definitions.

Definition 2.3 *α-cut set: The α-cut of a fuzzy set A is a crisp set that contains all elements of its universe of discourse X, whose membership functions in A are greater than or equal to the specified value of α:*

$$A_\alpha = \{x \mid x \in X \text{ and } \mu_A(x) \geq \alpha\} \tag{2.13}$$

Definition 2.4 *Strong α-cut set: The strong α-cut of a fuzzy set A is a crisp set that contains all elements of its universe of discourse X, whose membership functions in A are greater than the specified value of α:*

$$A_{\alpha^+} = \{x \mid x \in X \text{ and } \mu_A(x) > \alpha\} \tag{2.14}$$

The concepts of α-cut sets are important, since they constitute a bridge between fuzzy and traditional set theory. In this way, a fuzzy set can be represented as the union of all its α-cut sets (α-cut decomposition). This representation, together with the extension principle, allows for the transfer of much of the existing mathematical apparatus (theorems, lemmata, corollaries etc.) to fuzzy set theory [2.13].

Definition 2.5 *α-cut decomposition: The α-cut decomposition of the membership function for a fuzzy set A is given by the expression:*

$$\mu_A(x) = \sup_{a \in [0,1]} \min\left\{\alpha, \mu_{A_\alpha}(x)\right\} \quad \forall x \in X \tag{2.15}$$

Definition 2.6 *Extension principle: Let $A = \{(x, \mu_A(x)) \mid x \in X$ and $\mu_A(x) \in [0,1]\}$ be a standard fuzzy set in X and f be a mapping $f : X \to Y$. Then:*

$$B = f(A) = \left\{\left(f(x), \mu_A(x)\right) \mid x \in X, f(x) \in Y\right\} \tag{2.16}$$

In case f is a one-to-many mapping, then there exist:

$$x_1, x_2 \in X, \quad x_1 \neq x_2 : \quad f(x_1) = f(x_2) = y^\star, y^\star \in Y$$

In this case, the degree of membership of $y^\star$ in B is the maximum of the membership grades of x_1 and x_2 in A, or more general [2.39]:

$$\mu_B(y) = \sup_{x:y=f(x)} \mu_A(x)$$

Similar to classical set theory, four fundamental operations are defined on fuzzy sets: fuzzy containment (set inclusion), fuzzy complement, fuzzy set intersection and fuzzy set union. A fifth, commonly used operation is set equality, which can however be derived from the mutual inclusion of two sets. Contrary to classical set theory, where the binary operators $\wedge$, $\vee$ and $\sim$ are used for set operations, there exists a plethora of fuzzy set operators. They will be presented later in section 2.2.2.

Definition 2.7 *Fuzzy containment: Fuzzy set A is contained in fuzzy set B (A is a subset of B) if and only if $\mu_A(x) \leq \mu_B(x)\ \forall x \in X$:*

$$A \subset B \Leftrightarrow \mu_A(x) \leq \mu_B(x) \quad \forall x \in X \tag{2.17}$$

Definition 2.8 *Fuzzy set equality: Two fuzzy sets A and B defined on the same universe of discourse X are equal if and only if:*

$$A = B \Leftrightarrow \mu_A(x) = \mu_B(x) \quad \forall x \in X \tag{2.18}$$

Definition 2.9 *Fuzzy complement: The complement $\bar{A}$ of fuzzy set A is defined as:*

$$\mu_{\bar{A}}(x) = \neg\{\mu_A(x)\} \quad \forall x \in X \tag{2.19}$$

with $\neg$ being the negation operator (usually $\neg\{\mu_A(x)\} = 1 - \mu_A(x)$, section 2.2.2).

Definition 2.10 *Fuzzy set intersection and union: The intersection ($A \cap B$) and union ($A \cup B$) of two fuzzy sets A and B defined on the same universe of discourse X are defined by the membership functions:*

$$\mu_{A \cap B}(x) = \top\{\mu_A(x), \mu_B(x)\} \tag{2.20a}$$

$$\mu_{A \cup B}(x) = \perp\{\mu_A(x), \mu_B(x)\} \tag{2.20b}$$

where $\top$ and $\perp$ are triangular norms and conorms, respectively (refer to section 2.2.2).

Generally speaking, the law of contradiction[4] and the law of excluded middle[5] are broken for fuzzy sets, i.e. $A \cup \bar{A} \neq X$ and $A \cap \bar{A} \neq \emptyset$. Nevertheless, de Morgan's laws are still valid for the union and intersection operation on fuzzy sets (equation 2.21).

$$\overline{A \cap B} = \bar{A} \cup \bar{B} \tag{2.21a}$$

$$\overline{A \cup B} = \bar{A} \cap \bar{B} \tag{2.21b}$$

For the description of a fuzzy set A and its membership function μ_A following concepts are also helpful:

Definition 2.11 *Crossover points: A crossover (or transition) point of a fuzzy set A is a point $x \in X$ at which: $x : x \in X \wedge \mu_A(x) = 0.5$.*

Definition 2.12 *Support: The support of a fuzzy set A is a crisp set that contains all elements of its universe of discourse X which have non-zero degree of membership in A:*

$$A_{\text{support}} = \{x \mid x \in X \text{ and } \mu_A(x) > 0\} \tag{2.22}$$

Definition 2.13 *Core: The core of a fuzzy set A is a crisp set that contains all elements of its universe of discourse X with a degree of membership equal to 1:*

$$A_{\text{core}} = \{x \mid x \in X \text{ and } \mu_A(x) = 1\} \tag{2.23}$$

4 The *law of contradiction* states that contradictory statements cannot be true at the same time, e.g. the two propositions "A is B" and "A is not B" are mutually exclusive.

5 The *law of excluded middle* states that for any proposition, either that proposition or its negation must be true, the other one being false.

The concepts of set support and set core are actually special cases of the more general concepts of α-cuts and strong α-cuts [2.13]. Using definitions 2.3 and 2.4, we may re-write the definitions of fuzzy set support and fuzzy set core as $A_{\text{support}} = A_{0^+}$ and $A_{\text{core}} = A_1$, respectively. For the example of the trapezoidal membership function $\mu_{\text{trapezoidal}}$ in table 2.3-3, we can thus identify the set support in the interval $[a, d]$ and the set core in the interval $[b, c]$. Obviously, for a classical set as in example 2.1, the core and the support of the set are identical, as degrees of membership in classical set theory may only take values in $\{0, 1\}$. Thus, a comparison between the core and the support of a fuzzy set can provide a first, intuitive measure of the uncertainty expressed by a fuzzy set.

The aspect of uncertainty expressed by a fuzzy set deserves closer attention: *How fuzzy is a fuzzy set*? Can we define a quantity which will measure, in some sense, how much uncertainty is associated with a particular fuzzy set? The concepts introduced below are helpful in order to answer this question.

Definition 2.14 *Fuzzy entropy: Fuzzy entropy is a measure of the uncertainty associated with a fuzzy set. Any expression must feature following properties in order to qualify as fuzzy entropy [2.40]:*

P–1: $H_A = 0$ *if and only if* A *is a crisp set, i.e.* $\mu_A(x_i) = 0 \quad \forall\, x_i \in A$

P–2: H_A *is maximum if and only if* $\mu_A(x_i) = \frac{1}{2} \quad \forall\, x_i \in A$

P–3: $H_A \geq H_{A_\alpha}$ *where* H_{A_α} *is the fuzzy entropy of the* α*-cut set of* A

P–4: $H_A = H_{\bar{A}}$ *where* $H_{\bar{A}}$ *is the fuzzy entropy of the complement set* $\bar{A}$

In the literature several expressions have been proposed to quantify fuzzy entropy [2.40]. The most famous has been developed by de Luca and Termini –based on Shannon's definition of information entropy[6]– in [2.42]. They expressed the entropy of a fuzzy set A as:

$$H_A = -\frac{1}{n}\sum_{i=1}^{n}\{\mu_i \log(\mu_i) - (1-\mu_i)\log(1-\mu_i)\} \tag{2.24}$$

with $\mu_i = \mu_A(x_i)$ being the degree of membership of the i^{th} element in fuzzy set A, $i = 1, \ldots, n$. Although the expression in equation 2.24 is very similar to Shannon's definition of information entropy, it expresses the uncertainty associated to fuzzy set A due to vagueness, rather than due to randomness (refer to the discussion at the beginning of this chapter).

Another definition of fuzzy entropy has been proposed by Shang and Yang in [2.43] based on the membership function of the intersection and the union of a fuzzy set A and its complement $\bar{A}$:

$$H_A = \frac{1}{n}\sum_{i=1}^{n}\frac{\mu_{A\cap\bar{A}}(x)}{\mu_{A\cup\bar{A}}(x)} = \frac{1}{n}\sum_{i=1}^{n}\frac{\top\{\mu_A(x),\, \mu_{\bar{A}}(x)\}}{\perp\{\mu_A(x),\, \mu_{\bar{A}}(x)\}} \tag{2.25}$$

Obviously, the definition in equation 2.25 depends on the choice of the intersection and union operators. In case fuzzy set A contains infinite number of elements the sum operator in equations 2.24 and 2.25 has to be substituted by an integral.

[6] The concept of entropy is fundamental in information theory. The main contribution is this field has been made by Shannon in [2.41], where he defined *entropy* as a measure of the information contained in a signal.

2.2.2 Fuzzy set operations

For the purpose of axiomatic characterisation of fuzzy intersections and unions, triangular norms and their counterparts (triangular conorms) are used. Triangular norms have been introduced in the past to measure distances in probabilistic metric spaces [2.7]. Following definitions are taken from [2.44].

Definition 2.15 *Triangular norm: An operator* $\top : [0,1] \times [0,1] \rightarrow [0,1]$ *is a triangular norm (T-norm) if and only if it features following properties* $\forall x, y, z \in [0,1]:$

P–1: $\top(x,y) = \top(y,x)$ *(commutativity)*

P–2: $\top(x,y) \leq \top(x,z)$ *if* $y \leq z$ *(monotonicity)*

P–3: $\top\big(x, \top(y,z)\big) = \top\big(\top(x,y), z\big)$ *(associativity)*

P–4: $\top(x,1) = x$ *(boundary condition)*

Definition 2.16 *Triangular conorm: An operator* $\perp : [0,1] \times [0,1] \rightarrow [0,1]$ *is a triangular conorm (T-conorm) if and only if it features following properties* $\forall x, y, z \in [0,1]:$

P–1: $\perp(x,y) = \perp(y,x)$ *(commutativity)*

P–2: $\perp(x,y) \leq \perp(x,z)$ *if* $y \leq z$ *(monotonicity)*

P–3: $\perp\big(x, \perp(y,z)\big) = \perp\big(\perp(x,y), z\big)$ *(associativity)*

P–4: $\perp(x,0) = x$ *(boundary condition)*

In [2.45] Yager provides proof that no T-norm can return a value higher than the one obtained by standard minimum operator, and no T-conorm can return a value lower than the one obtained by the maximum operator:

$$\top(x,y) \leq \min\{x,y\} \quad \forall x, y \in [0,1] \tag{2.26a}$$

$$\perp(x,y) \geq \max\{x,y\} \quad \forall x, y \in [0,1] \tag{2.26b}$$

The symbols $\star$ and $\oplus$ are also frequently used in the literature for T-norms and T-conorms, respectively. In addition to triangular norms and conorms, the negation operator is important for obtaining the complement of a fuzzy set.

Definition 2.17 *Fuzzy negation: An operator* $\neg : [0,1] \rightarrow [0,1]$ *is a fuzzy negation function if and only if it features following properties:*

P–1: $\neg(x) < \neg(y)$ *if* $x > y \quad \forall x, y \in [0,1]$ *(strict monotonicity)*

P–2: $\neg(\neg(x)) = x$ *(involution)*

P–3: $\neg(0) = 1$ *and* $\neg(1) = 0$

Usually, the operator $\neg(x) = 1 - x$ is used for fuzzy negation. On the other hand, a plethora of triangular norms and conorms have been proposed in the literature; the most important are summarised in table 2.4. One should note that T-norms and conorms should be only used pair-wise, so that $\neg(\top(x,y)) = \perp(\neg(x), \neg(y))$. The choice of the right operator is always a matter

Table 2.4.: Overview of some pairs of triangular norms and conorms used for evaluating the intersection and union of fuzzy sets (abstract from [2.44]).

Code	T-norm $\top(x,y)$	T-conorm $\perp(x,y)$	Comment
1	$\min\{x,y\}$	$\max\{x,y\}$	standard operators introduced by Zadeh [2.6]
2	xy	$x+y-xy$	algebraic product/sum
3	$\max\{0,x+y-1\}$	$\min\{x+y,1\}$	bounded product/sum
4	$\begin{cases} x & \text{if } y=1 \\ y & \text{if } x=1 \\ 0 & \text{otherwise} \end{cases}$	$\begin{cases} x & \text{if } y=0 \\ y & \text{if } x=0 \\ 1 & \text{otherwise} \end{cases}$	drastic product/sum (Weber's operators)
5	$\dfrac{\lambda xy}{1-(1-\lambda)(x+y-xy)}$	$\dfrac{\lambda(x+y)+xy(1-2\lambda)}{\lambda+xy(1-\lambda)}$	Hamacher's operators for $\lambda\to 0$: case 5 for $\lambda=1$: case 2 for $\lambda\to\inf$: case 4

of context, and it mostly depends on the modellings requirements. In this thesis, the standard minimum/maximum operators as well as the algebraic product/algebraic sum operator will be used.

Furthermore, in fuzzy set theory sets can be aggregated not only by taking their intersections or unions, but also by *averaging their membership functions*. This approach has no counterpart in classical set theory. Averaging operators are monotonic and idempotent[7], but not associative [2.4]; for this reason they must be defined as mappings $f : [0, 1]^n \to [0, 1]$ rather than $f : [0, 1] \times [0, 1] \to [0, 1]$. The most common averaging operator is Yager's *ordered weight averaging* (OWA) operator, introduced in [2.45]. Ordered weight operators play an important role in multi-criteria decision making by means of fuzzy reasoning.

Definition 2.18 *Ordered weight averaging: A mapping $f_w : [0, 1]^n \to [0, 1]$ with the associated vector $\underline{w}$ is an OWA operator if:*

$$w_i \in (0,1) \quad \text{and} \quad \sum_i w_i = 1 \qquad i = 1,\ldots,n \tag{2.27a}$$

$$f_w(x_1,\ldots,x_n) = w_1 b_1 + \ldots + w_n b_n \qquad x_1,\ldots,x_n \in [0, 1] \tag{2.27b}$$

where $\underline{b}$ is the ordered (in ascending order) vector of $\underline{x}$, such that $b_i \geq b_j$ if $i < j$.

A fuzzy set operation of particular importance to fuzzy reasoning is *fuzzy implication*, which will be introduced in section 2.3.1 along with appropriate operators. In brief, implication is based on a relation between the premise and the consequence[8] of a fuzzy rule. Following definition describes in general the concept of fuzzy relations [2.9, 2.48]:

[7] An operator f is *idempotent* if it can be applied multiple times without changing the result i.e. $f(f(x)) = f(x)$.

[8] In a rule having an "if ... then ..." form, the *premise* or *antecedent* of the rule is the if-part, while the rule's *consequence* or *conclusion* is the then-part (refer to section 2.3.1).

Definition 2.19 *Fuzzy relation: A fuzzy relation R represents a degree of of association, interaction, of interconnectedness between elements of two fuzzy sets A and B, defined in the universe of discourse X and Y respectively. It is defined as:*

$$R = \left\{ \left((x,y),\, \mu_R(x,y)\right) \middle|\, (x,y) \in X \times Y \text{ and } \mu_r(x,y) \in [0,\,1] \right\} \tag{2.28}$$

A fuzzy relation $R : X \times Y \to [0,\,1]$ is itself a fuzzy set in the product space $X \times Y$. It is therefore possible to define set operations between two fuzzy relations R_1 and R_2. As long as both relations are based on the same universe of discourse, the fuzzy set operations described in section 2.2.1 –fuzzy intersection and fuzzy union– are still valid. In the opposite case, fuzzy relations have to be composed.

Definition 2.20 *Fuzzy composition: Let R_1 and R_2 be two fuzzy relations defined on $X \times Y$ and $Y \times Z$, respectively. The general fuzzy composition of R_1 and R_2 is a fuzzy set defined as:*

$$R_1 \circ R_2 = \left\{ \left((x,z),\, \underset{y \in Y}{\perp} \left[\top \left\{ \mu_{R_1}(x,y),\, \mu_{R_2}(y,z) \right\} \right] \right) \middle|\, x \in X,\, y \in Y,\, z \in Z \right\} \tag{2.29}$$

Calculation of the composition $R_1 \circ R_2$ is almost the same as matrix multiplication, except that the $\times$ and $+$ operators are replaced by the $\top$ and $\perp$ operators, respectively. Generally speaking, any T-norm and T-conorm can be used in equation 2.29. By applying the minimum and maximum operator, one obtains the *standard composition* (also called *max-min composition*) initially introduced by Zadeh in [2.6]. The significance of the standard fuzzy composition is that it is the only cutworthy[9] one.

The last fuzzy set operation of importance is *defuzzification*, which reduces a fuzzy set A into a single number x_A (definition 2.21). In rule-based fuzzy inference systems e.g. for control applications, defuzzification is thus necessary in order to provide a useful output signal; it takes place after the reasoning process has been completed, just before returning the system's answer (compare section 2.3.2). Although several defuzzification methods have been proposed in the literature, none of them has any theoretical justification. Defuzzification is rather driven by the requirement for computational simplicity.

Definition 2.21 *Defuzzification: A defuzzifier (or defuzzification operator) f is a mapping of a fuzzy set A to a (representative) element x_A of its own universe of discourse X:*

$$f : A = \left\{ (x, \mu(x)) \middle|\, x \in X \text{ and } \mu(x) \in [0,1] \right\} \to x_A \in X \tag{2.30}$$

Common defuzzification methods are shown in page 20, along with their mathematical definition [2.48]. The maximum and mean-of-maxima methods are easy to determine, but do not always represent the underlying fuzzy set in a proper way. Centroid defuzzification –also called centre-of-gravity (COG) or centre-of-area (COA) method– provides a good representation of the fuzzy set, but requires calculation of the membership function's integral. A good trade-off between computational simplicity and representation significance is reached when the fuzzy set A can be decomposed in several subsets A_k. This case is typical for a rule-based inference system. In this case the centre of gravity of the subsets x_k can be determined in advance. Every subset A_k can thus be reduced in a respective singleton, and centroid fuzzification method can be

9 An operation $f(A)$ on fuzzy set A is said to be *cutworthy* if $\left(f(A)\right)_\alpha = f\left(A_\alpha\right)$.

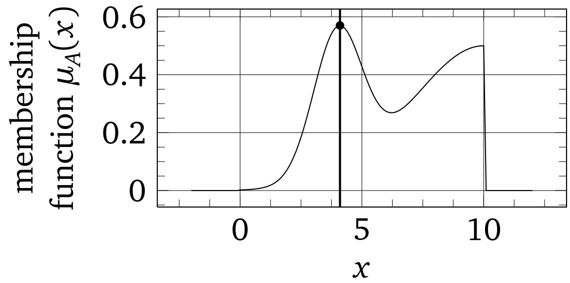
Table 2.5.: Common defuzzification methods: (1) maximum method, (2) mean-of-maxima method, (3) centroid defuzzification (also called centre-of-area or centre-of-gravity), (4) height (or singleton) method, and (5) modified height method.

For the examples shown following membership function has been considered: $\mu_A(x) = \frac{1}{2}\exp\left\{-\frac{1}{2}\left(\frac{x-4}{1}\right)^2\right\} + \frac{1}{2}\exp\left\{-\frac{1}{2}\left(\frac{x-10}{3}\right)^2\right\}$ with $x \in [0, 10]$

1. Maximum defuzzification method

$$x_A = x : \mu_A(x) = \max(\mu_A(y)) \quad \forall y \in A$$

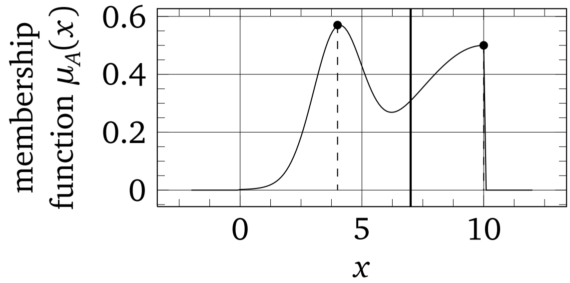
Example: $x_A \approx 4.1$



2. Mean-of-maxima defuzzification method

$$x_A = \frac{1}{n}\sum_{k=1}^{n} x_k : \mu_A(x_k) = \max(\mu_A(y)) \quad \forall y \in A$$

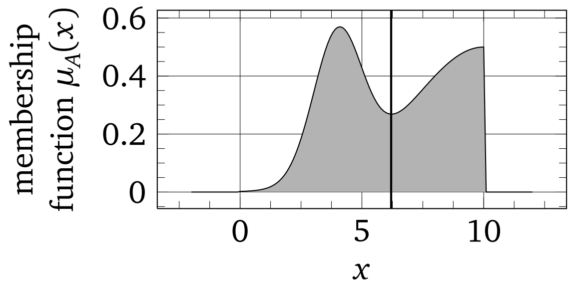
Example: $x_A = 7$



3. Centroid defuzzification method

$$x_A = \frac{\int x\mu_A(x)dx}{\int \mu_A(x)dx}$$

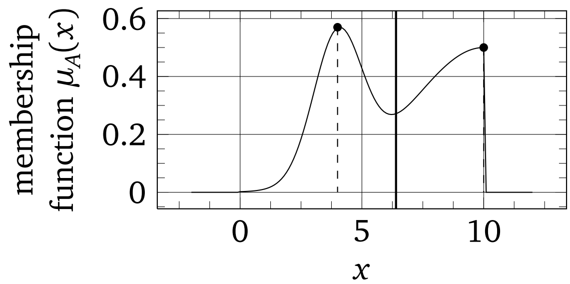
Example: $x_A \approx 6.2$



4. Height defuzzification method

$$x_A = \frac{\sum_{k=1}^{n} x_k \mu_{A_k}(x_k)}{\sum_{k=1}^{n} \mu_{A_k}(x_k)}$$

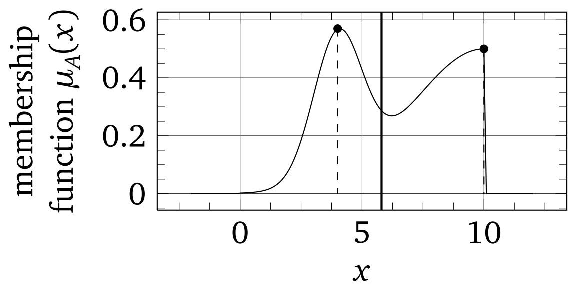
Example: $x_A = 6.4$



5. Modified height method

$$x_A = \frac{\sum_{k=1}^{n} x_k \mu_{A_k}(x_k)/\delta_k^2}{\sum_{k=1}^{n} \mu_{A_k}(x_k)/\delta_k^2}$$

Example: $x_A \approx 5.8$



simplified to the so-called height defuzzification method (method 4 in table 2.5). In order to partially account for the shape of each subset, a measure of its entropy (δ_k) can be introduced, leading to the modified height defuzzification method. For this purpose, simple measures such as the spread of the membership function of each subset A_k (for example the standard deviation of a Gaussian membership function) are usually adequate [2.48].

2.3 Fuzzy reasoning

When we refer to logic in everyday language, we usually think of propositional logic, a form of deductive reasoning based on arguments. According to traditional logic, *propositions* are declarative sentences or statements e.g. “Socrates is a man” that can be either true or false; they are therefore used as truth bearers. The combination of a set of propositions in such a way that all but one of them (the premises) provide support for the remaining one (the conclusion) is called an *argument*.

Traditionally, propositional logic makes use of categorical syllogisms – arguments consisting of exactly three categorical[10] propositions (two premises and a conclusion). In categorical syllogisms three terms appear: the minor term (subject of the syllogism’s conclusion), the major term (predicate of its conclusion), and a middle term (term employed as subject or predicate in each of its premises). The premises are called major or minor if they involve the major or minor term of the syllogism, respectively. A commonly used example of a categorical syllogism is given below:

major premise:	All men are mortal
minor premise:	Socrates is a man
conclusion:	Socrates is mortal

The introduction of formal logic in the 19th century brought about two significant changes: the introduction of logic variables and the formalisation of inference rules. Logic variables are used instead of linguistic propositions in order to express the corresponding truth value. Different logic variables may be combined according to five fundamental operations: negation, conjunction, disjunction, equivalence, and implication. For reasons of abstraction, each of these operations is defined by a symbol listed in table 2.7. Table 2.6 shows the result of logic operations on two variables p and q in tabular form (such a representation is usually called *truth table*).

Table 2.6.: Truth table for logic operations on two propositions p and q: $\sim$ negation, $\wedge$ conjunction, $\vee$ disjunction, $\rightarrow$ implication, and $\leftrightarrow$ equivalence. T and F stand for true and false propositions, respectively.

p	q	$\sim p$	$p \wedge q$	$p \vee q$	$p \rightarrow q$	$p \leftrightarrow q$
T	T	F	T	T	T	T
T	F	F	F	T	F	F
F	T	T	F	T	T	F
F	F	T	F	F	T	T

By far the most important logic operation is implication, which is used to deduce one logic variable from another one (definition 2.22).

10 A *categorical proposition* involves two terms: a subject (e.g. Socrates) and a predicate (e.g. man) which may be affirmed or denied.

Definition 2.22 *Implication: An logic implication $p \to q$ is a relation between two logic variables p and q which can be expressed in form of an "if p then q" rule.*

Similar to the categorical syllogism introduced above, the logic variable corresponding to the existing proposition is called *antecedent* or *premise*, while the deduced one is called *consequence* or *conclusion*. Deductive reasoning suggests that –should the implication be valid– the conclusion cannot be false while the antecedent is true at the same time (compare table 2.6). In terms of formal logic, the operation of implication $p \to q$ can be rewritten as: $\sim (p\wedge \sim q)$. The reader is encouraged to prove this equivalence by means of a truth table. This alternative representation is important for the mathematical description of logic rules, as will be shown in section 2.3.1.

The equivalent of categorical syllogisms in formal logic is denoted as *modus ponens*[11]. In general, it involves an implication (major premise) and a positive antecedent (minor premise) in order to evaluate the truth value of the conclusion, as shown below:

$$\begin{array}{rl} \text{implication:} & p \to q \\ \text{antecedent:} & p \\ \hline \text{conclusion:} & q \end{array}$$

In terms of formal logic, modus ponens is thus expressed as $(p \wedge (p \to q)) \to q$.

At this point we shall stress one more time the strong relation between logic and set theory. Indeed, if we substitute logic variables p and q by expressions such as $x \in X$ and $y \in Y$, we can redefine modus ponens in a set theoretic approach. For this purpose, the five fundamental logic operations (negation, conjunction, disjunction, equivalence, and implication) must also be substituted by the corresponding set theoretic operation, as shown in table 2.7.

Table 2.7.: Principal relation between logic and set theoretic operations.

Logic operations		Set theoretic operations	
$\sim$	negation	$\neg$	negation
$\wedge$	conjunction	$\cap$	intersection
$\vee$	disjunction	$\cup$	union
$\to$	implication	R	set relation
$\leftrightarrow$	equivalence	$=$	set equality

2.3.1 Fuzzy rules

Traditional logic requires for every proposition to be either true or false, but not both at the same time. Contrary to this assumption, most propositions that can be framed in practice have a certain degree of uncertainty or vagueness. Consider for example the sentence "James is a tall student"; it cannot be affirmed or denied with certainty, but is rather a question of degree: *how* tall is James? If, however, propositions violate the fundamental requirement of being either true or false, how can we treat them in a logical way, in order to be able to deduce relevant conclusions? Obviously, the concepts of categorical syllogism and modus ponens introduced above are not applicable any more.

[11] *Modus ponendo ponens* or –short– *modus ponens* is a deductive approach to reasoning where the conclusion is reached by affirmation, that is on the basis of a positive antecedent.

Fuzzy logic[12] is an approach to provide a formal way of reasoning in order to account for uncertainty in propositions. Fuzzy logic acknowledges the fact that although reasoning is based on precise logic rules, the propositions involved arise from perception, which by default is of uncertain nature. The aforementioned modus ponens must be therefore extended in a way to capture uncertainty, the result being the *generalised modus ponens*:

$$\begin{array}{rl} \text{implication:} & p \rightarrow q \\ \text{antecedent:} & p' \text{ (similar to } p) \\ \hline \text{conclusion:} & q' \text{ (similar to } q) \end{array}$$

In terms of formal logic, generalised modus ponens is thus expressed as $(p' \wedge (p \rightarrow q)) \rightarrow q'$. We may rewrite this expression by adopting a set theoretic approach. In particular if we substitute logic variables p and p' by fuzzy sets A and A', defined on the universe of discourse X, and logic variables q and q' by fuzzy sets B and B', defined on the universe of discourse Y, we obtain:

$$(p' \wedge (p \rightarrow q)) \rightarrow q' \quad \Rightarrow \quad B' = A' \circ R_{A \rightarrow B} \tag{2.31}$$

Note that the logic conjunction operation must be modelled as relational composition rather than as fuzzy set union (table 2.7) because fuzzy set A' is defined on X, while relation $R_{A \rightarrow B}$ (representing implication) is defined on the product space $X \times Y$. The degree of membership of the conclusion $\mu_{B'}(y)$, $y \in Y$ is equivalent to the truth value of logic variable q' given variable p'. It can be determined from equation 2.31 by applying fuzzy composition (definition 2.20):

$$\mu_{B'}(y) = \underset{x \in X}{\perp} \left[\top \left\{ \mu_{A'}(x), \mu_{A \rightarrow B}(x, y) \right\} \right] \quad x \in X, y \in Y \tag{2.32}$$

Generally speaking, the membership function $\mu_{A \rightarrow B}(x, y)$ represents the operation of implication. It is described mathematically by an implication operator I which will be defined shortly. Therefore, by substituting $\mu_{A \rightarrow B}(x, y)$ by $I(\mu_A(x), \mu_B(y))$ and making use of the associative property of T-norms and T-conorms we obtain:

$$\begin{aligned} \mu_{B'}(y) = \underset{x \in X}{\perp} \left[\top \left\{ \mu_{A'}(x), I\left(\mu_A(x), \mu_b(y)\right) \right\} \right] = \\ = I\left(\underset{x \in X}{\perp} \left[\top \left\{ \mu_{A'}(x), \mu_A(x) \right\} \right], \mu_b(y) \right) = I\left(\alpha, \mu_b(y)\right) \end{aligned} \tag{2.33}$$

with $\alpha = \underset{x \in X}{\perp} \left[\top \left\{ \mu_{A'}(x), \mu_A(x) \right\} \right]$.

Variable α is thus a measure of the similarity between fuzzy sets A and A', standing for logic variables p and p' respectively. Obviously, in order to evaluate the degree of membership of the conclusion $\mu_{B'}(y)$ a mathematical expression of the implication operator is necessary. In section 2.3 we already postulated the tautology $p \rightarrow q \longleftrightarrow \sim (p \wedge \sim q)$. Rewritten in set theoretic terms, it provides a possible implementation of fuzzy implication:

$$I\left(\mu_A(x), \mu_b(y)\right) = \neg \top \left\{ \mu_A(x), \neg \mu_B(y) \right\} \quad x \in X, y \in Y \tag{2.34}$$

[12] Synonyms for fuzzy logic are: fuzzy reasoning, approximate reasoning, and generalised modus ponens.

If we implement the standard operators (compare section 2.2.2) in the above we obtain:

$$I\left(\mu_A(x), \mu_b(y)\right) = 1 - \min\left(\mu_A(x), 1 - \mu_B(y)\right) \quad x \in X,\ y \in Y \tag{2.35}$$

In fact, the expression in equation 2.35 is only one of many possible fuzzy implication operators. A general definition of implication operators is given below:

Definition 2.23 *Fuzzy implication: An operator* $I : [0, 1] \times [0, 1] \rightarrow [0, 1]$ *is a fuzzy implication if and only if it features following properties* $\forall x, y, z \in [0, 1]$:

P–1: if $x \leq z$ *then* $I(x, y) \geq I(z, y)$ *(left antitonicity)*

P–2: if $y \leq z$ *then* $I(x, y) \leq I(x, z)$ *(right isotonicity)*

P–3: $I(0, 0) = 1$

P–4: $I(1, 1) = 1$

P–5: $I(1, 0) = 0$

Obviously, the first two properties imply that a fuzzy implication operator is not associative. In other words, the truth value of both the antecedent and the conclusion independently affect the overall truth value of the statement itself. The left antitonicity of the function I captures the idea that a decrease in the truth value of the antecedent increases its efficacy to state more about the truth value of its consequent.

A list of common fuzzy implication operators as well as a discussion of their properties can be found in [2.49]. With regard to the application of fuzzy reasoning to engineering problems, definition 2.23 poses two striking difficulties [2.48]:

- Large support of the membership function of the conclusion: applying an implication operator according to definition 2.23 in equation 2.33 results in values of the membership function $\mu_{B'}(x) > 0$ unless both $\mu_A(x') = 1$ and $\mu_B(y) = 0$ at the same time. Since in most cases $\mu_A(x') < 1$, the support of the membership function of the conclusion extends over the whole universe of discourse Y. This in turn increases the entropy of the fuzzy set B' –representing the conclusion– so that its relevance diminishes.

- Lack of *causality*: The second property postulated in definition 2.23 (left antitonicity) implies that the validity of the implication is higher for lower truth values of the antecedent. From an engineering point of view this is most disturbing, as cause (system input i.e. antecedent of a rule) should lead to effect (system output i.e. conclusion), and non-cause should not lead to anything.

For these reasons, fuzzy inference systems designed to facilitate causality do not make use of implication operators according to definition 2.23. Instead, they apply T-norms to fuzzy implication, with the standard minimum operator and the algebraic product operator being the most popular:

$$I(x, y) = \min(x, y) \qquad x, y \in [0, 1] \tag{2.36a}$$

$$I(x, y) = x \cdot y \qquad x, y \in [0, 1] \tag{2.36b}$$

Obviously, neither minimum nor product inference agree with the propositional logic definition of implication (table 2.6). They should rather be regarded as *engineering implications* [2.48], as they preserve cause and effect (rule is valid only when both antecedent and conclusion are true).

The following graphical example illustrates the process of fuzzy reasoning in case standard (maximum and minimum) operators are used.

Example 2.3 *Consider following fuzzy rule, where A and A' are similar fuzzy sets defined in X, and B and B' are similar fuzzy sets defined in Y. Fuzzy sets A, A' and B are described by triangular membership functions $\mu_A(x)$, $\mu_{A'}(x)$ and $\mu_B(y)$ as shown in figure 2.1.*

$$\begin{array}{rl} \text{implication:} & \text{if } (x, \mu_A(x)) \in A \text{ then } (y, \mu_B(y)) \in B \\ \text{antecedent:} & (x, \mu_{A'}(x)) \in A' \text{ (similar to } A) \\ \hline \text{conclusion:} & (y, \mu_{B'}(y)) \in B' \text{ (similar to } B) \end{array}$$

The membership function of the conclusion $\mu_{B'}(y)$ is evaluated according to equations 2.33 and 2.36a:

$$\mu_{B'}(y) = I\left(\alpha, \mu_B(y)\right) = \min\left\{\alpha, \mu_B(y)\right\} = \min\left\{\underset{x \in X}{\perp}\left[\top\left\{\mu_{A'}(x), \mu_A(x)\right\}\right], \mu_B(y)\right\}$$

If we apply the standard operators to the fuzzy composition we obtain following expression:

$$\mu_{B'}(y) = \min\left\{\max_{x \in X}\left[\min\left\{\mu_{A'}(x), \mu_A(x)\right\}\right], \mu_B(y)\right\}$$

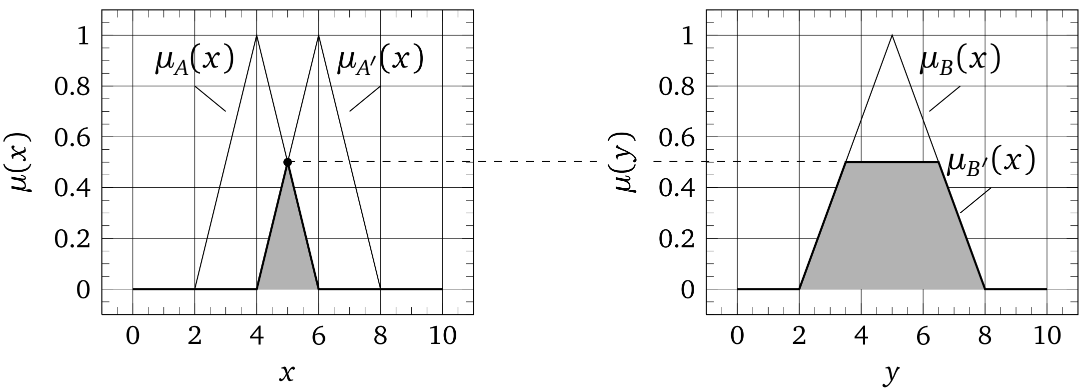


Figure 2.1.: Minimum-type fuzzy implication for example 2.3.

Figure 2.1 graphically illustrates the above expression. The shaded surface on the left plot is the result of the $\min\{\mu_A(x), \mu_{A'}(x)\}$ operation; its maximum $\alpha = 0.5$ appears at $x = 5$. The membership function $\mu_B(y)$ on the consequence part of the rule is therefore limited to this value, according to the minimum implication method (shaded space on the right plot). ■

So far we have regarded implications involving only one proposition in the antecedent and one proposition in the conclusion. It is however possible to combine several propositions by means of logic conjunction or disjunction (in terms of set theory, this combination is based on set intersection and union, respectively). This aspect will be stressed in the next section.

2.3.2 Fuzzy inference systems

A *fuzzy inference system* (FIS) is a computing framework based on the concepts of fuzzy set theory and fuzzy reasoning. In general, it provides a non-linear mapping from some input variables into some output variables. The main advantage of incorporating fuzzy reasoning is that inference rules can be defined in a precise and consistent way, while uncertainty originating from the input information is considered by defining one or more fuzzy sets for each input. The basic structure of a FIS consists of three conceptual components: a set of inference rules called *rule base*, a *dictionary* which defines the fuzzy sets used to model propositions in the antecedents and conclusions of the rules, and a *reasoning mechanism* which performs the inference procedure upon the rules and given input information to derive a reasonable output [2.39].

The process of inference within a FIS can be divided into five distinct steps:

Fuzzification: Every input of a FIS is modelled as a *linguistic variable*[13]. In brief, a linguistic variable u_i takes its values from an own set of *linguistic values* $U_i = \{U_{i,1}, U_{i,2}, \ldots, U_{i,n_i}\}$, each of them being described by a fuzzy set $U_{i,j} = \{(x_i, \mu_{U_{i,j}}(x_i)) | x_i \in X_i\}$ defined on the domain of the crisp input x_i[14]. The first step in the inference process is therefore to evaluate the degree of membership of each crisp input variable x_i to all corresponding fuzzy sets $U_{i,j}$. The result is an indication of the similarity of every linguistic variable to the respective linguistic values.

Aggregation: Usually, FISs will feature several inputs. In this case, a fuzzy inference rule will involve more than one linguistic variables in its antecedent. In order to evaluate the similarity of given data to the antecedent, the degrees of membership to the fuzzy sets involved have to be aggregated. For this purpose the operations of fuzzy intersection, fuzzy union, and fuzzy negation are employed – in analogy to formal logic, where the conjunction, disjunction and negation operator are used for combining propositions. The result of the aggregation can thus be regarded as *firing strength* of the particular rule, since it describes the degree to which the antecedent is satisfied.

Implication: The process of implication has been described in detail in section 2.3.1. For FISs designed for engineering applications, T-norms are used for implication, with the minimum operator being the most popular. At the end of this step, one (or more, in case the rule has multiple conclusions) fuzzy set is determined for the consequence of each rule.

Accumulation: In the previous two steps each rule has been treated separately. As a result, more than one fuzzy sets may have been generated for each output y_k of the FIS. This feature is denoted as *parallel processing* and is characteristic for FISs. The process of accumulation aims at combining all generated fuzzy sets for each output variable. Since rules in the rule base are treated equally, accumulation must be mathematically modelled as a fuzzy set union i.e. by using a T-conorm.

Defuzzification: At the end of the fourth step, every output variable of the FIS is described by an accumulated fuzzy set. However, the final output of a FIS must be numerical values. For this reason, the accumulated fuzzy sets must be transformed by applying appropriate defuzzification operators (compare table 2.5).

[13] The concept of linguistic variables has been introduced by Zadeh in a trilogy of papers in 1975 [2.13–2.15].

[14] In the description provided here we assume a FIS with $i = 1, \ldots, n$ inputs, $r = 1, \ldots, \ell$ rules, and $k = 1, \ldots, m$ outputs. Each input i is associated with $j = 1, \ldots, n_i$ linguistic values i.e. fuzzy sets.

In order to better understand the process of inference within a FIS, a simple example shall be given at this point. It comprises only two input variables, one output variable and a small rule base consisting of three rules.

Example 2.4 *The coach of the college basketball team is searching for a talented power forward. He is judging the potential of students according to following rules:*

1. *If* student x is tall *and* student x is fast *then* his potential is high
2. *If* student x is tall *and* student x is slow *then* his potential is moderate
3. *If* student x is short *then* his potential is low

The degree of membership of a particular student to fuzzy sets *tall* ($U_{1,1}$) and *short* ($A_{1,2}$) is determined by his height (x_1). On the other hand, his membership to fuzzy sets *fast* ($U_{2,1}$) and *slow* ($U_{2,2}$) is judged on the basis of his performance in a 60 m run (x_2). The corresponding membership functions as well as the inference process are shown in figure 2.2 for the example of a particular student ($x_1 = 195\,\text{cm}$, $x_2 = 7.3\,\text{s}$). The shaded plots on the right are the results of each rule's implication, which are then accumulated to yield the combined fuzzy set of the output (bottom right plot). Finally, the crisp output of the FIS is obtained by applying COA defuzzification. ■

As can be seen from example 2.4, the general layout of the rules can be quite different: some of the rules may involve all linguistic variables while others involve only a subset of possible combinations (rule 3 of the example). Furthermore, the way in which different linguistic variables are aggregated in the antecedent of a rule may vary: some rules may use *and*-connectives (represented by fuzzy set union i.e. T-norms), while other can be defined on the basis of *or*-connectives (T-conorms).

Nevertheless, most FISs have rule bases consisting of complete[15] rules, and use T-norms for the aggregation of the antecedent (*and*-connectives). In this case, the accumulated fuzzy set for output variable y_k is:

$$\mu_{res}(y_k) = \perp_{ac} \left\{ \top_i \left[\mu_r(y_k), \top_{ag} \left\{ \mu_{U_{1,j}}(x_1), \mu_{U_{2,j}}(x_2), \ldots, \mu_{U_{n,j}}(x_n) \right\} \right] \right\} \tag{2.37}$$

where $\perp_{ac}$ is the T-conorm for accumulating all $r = 1, \ldots, \ell$ rules, $\top_i$ is the T-norm used for determining the implication result, and $\top_{ag}$ is the T-norm for aggregating the fuzzy sets involved in the antecedent of each rule.

An important feature of FISs is their *interpretability*: the concept of linguistic variables, along with the description of the fuzzy rule base in natural language allows for easy interpretation of the FIS. Nevertheless, special care has to be taken when defining the dictionary of a FIS, should it remain transparent. *Transparency* of a system is a property which enables us to understand the influence of each parameter of the system on its output [2.51, 2.52]. In order for a FIS to be transparent, following requirement must be fulfilled for all linguistic variables x_i, $i = 1, \ldots, n$:

$$\sum_{j=1}^{n_i} \mu_{U_{i,j}}(x_i) \quad \forall x_i \in X_i \tag{2.38}$$

[15] If a rule is incomplete (involving only some of all possible linguistic variables) it can be completed by defining appropriate fuzzy sets for the missing linguistic variables: the membership function of such a default fuzzy set equals one over its complete universe of discourse in case the rule uses *and*-connectives, and zero if *or*-connectives are used.

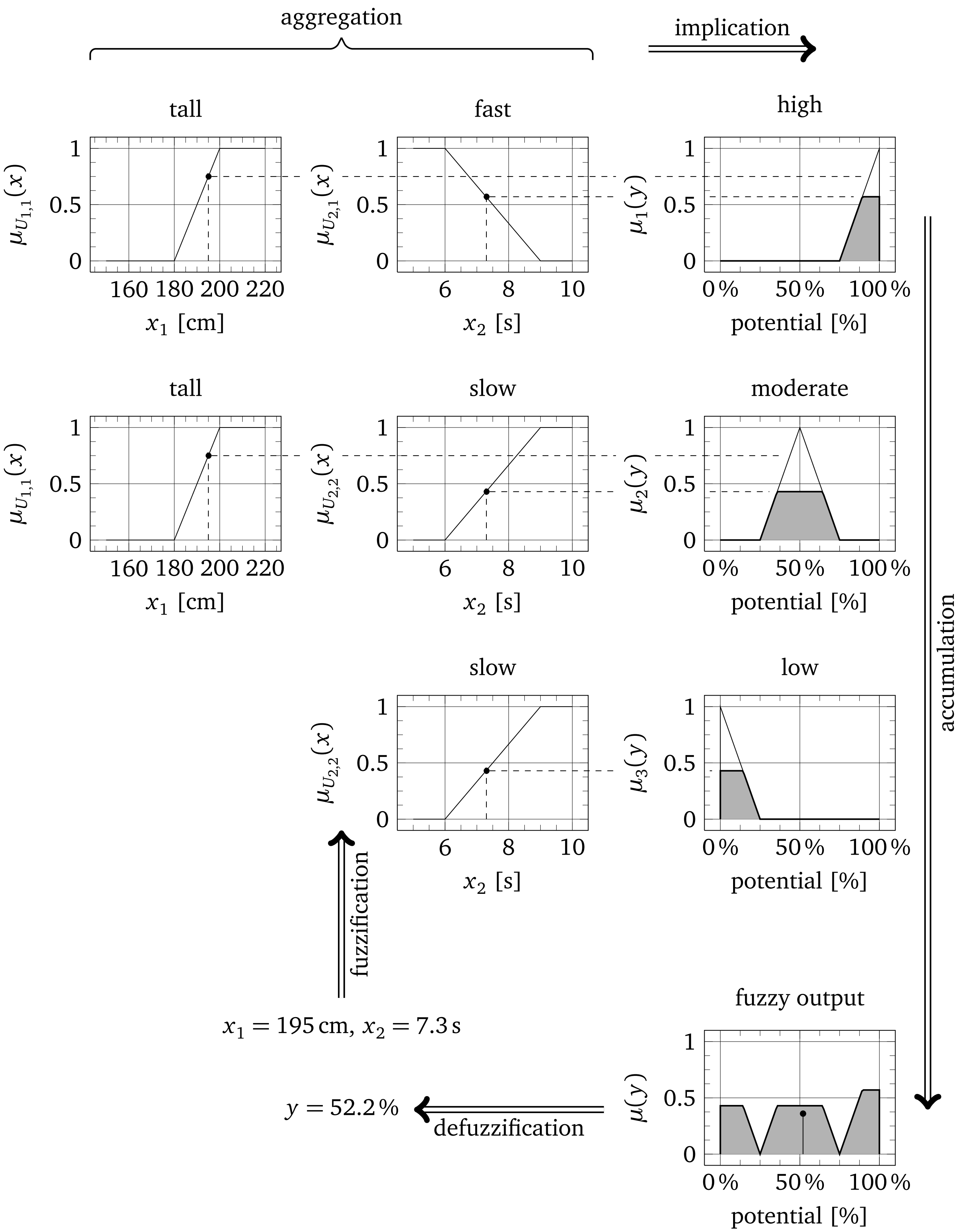


Figure 2.2.: Overview of the inference process for example 2.4.

2.4 Adaptive fuzzy systems

In the previous section we have already introduced the three main components of a FIS: the dictionary, the inference mechanism and the rule base. Designing a FIS for modelling a process calls for the definition of all these components. Generally speaking, two approaches are possible: In case sufficient a priori information is available –in other words the user's experience and knowledge of the process is complete– the FIS can be defined directly in a heuristic way, as in example 2.4. If, however, a priori knowledge is incomplete, the process can be observed in order to gain insight. The FIS is described parametrically, and the parameters are adapted in such a way that the input-output mapping behaviour of the FIS fits the observed samples as much as possible.

Adaptation of a FIS can be achieved by altering any of its components: the membership functions describing the fuzzy sets of its linguistic variables (dictionary), the fuzzy inference method, or the number of fuzzy rules. The result of adaptation is a change in the modelled input-output mapping function $f : X \rightarrow Y$. The process of adapting the parameters of a FIS to a set of available observation samples is called *learning*. Depending on the scope of observation, learning can be categorised as follows [2.53]:

- *Supervised* learning: In supervised learning, both input and output of the process is being observed. In other words, for every observed input vector $\underline{\hat{x}}_i$, the corresponding output vector $\underline{\hat{y}}_i$ is also known[16]. The objective of learning is thus to adapt the FIS in such a way that its answer $\underline{y}_i = f(\underline{\hat{x}}_i)$ for every sample approximates the desired output $\underline{\hat{y}}_i$. The deviation between $\underline{y}_i$ and $\underline{\hat{y}}_i$ is used as teaching signal, according to a reward-or-punishment approach. For this reason, supervised learning is also called "learning with a teacher".

- *Reinforcement* learning: Contrary to supervised learning, in reinforcement learning the feedback provided by the environment is not instructive, but only evaluative. In other words, the assessment of the system's performance is neither expressed as a teaching signal, nor is it coupled to one observation. Due to this fact, reinforcement learning is referred to as "learning with a critic".

- *Unsupervised* learning: Finally, in unsupervised learning no information about the desired output of the system exists. The main purpose of systems featuring unsupervised learning is to find some inherent structure or pattern within the training data.

Most adaptive FISs are trained by means of supervised learning algorithms. This is quite reasonable, since the main motivation in using a FIS is to describe the input-output mapping as rules expressed in natural language, so as to allow for easy interpretation of the underlying process. With unsupervised learning, however, the mapping from input to output is of no relevance. This section gives a short overview of common adaptive FISs.

The most straightforward approach (described for example in [2.55]) uses training datasets to automatically generate the fuzzy rule base. Although this approach is quite effective, it cannot be regarded as learning: neither does an optimisation function exist, nor are any iterations involved. In particular, the design process is structured in five steps: first the input and output space is divided into fuzzy regions by the user, i.e. the membership functions for the fuzzy sets

[16] The ordered pair $(\underline{\hat{x}}_i, \underline{\hat{y}}_i)$ is called *training dataset*.

corresponding to each linguistic variable are defined arbitrarily. In the next step, one rule is generated for each training dataset. During the third and fourth step, the firing strength of each rule is evaluated and multiple or contradictory rules are eliminated on this basis. Finally, the resulting rule base is integrated into the FIS.

Another approach is to use evolutionary programming or genetic algorithms so as to train some parameters of the FIS [2.56]. In this way both the dictionary as well as the rule base can be adapted. Furthermore, this approach can support not only supervised, but also reinforcement learning, as the formulae for updating the parameters of the FIS are not derived directly from the objective function.

By far the most common approach is to combine FISs with Artificial Neural Networks (ANN) into so-called *neuro-fuzzy systems*[17]. Generally speaking, neuro-fuzzy systems can be grouped in three categories [2.57, 2.58]: i) *cooperative* systems, where the ANN is used in the pre-processing phase in order to determine some sub-blocks (for instance the fuzzy sets and/or fuzzy rules) of the fuzzy system, and is removed thereafter, ii) *concurrent* systems, where both ANN and FIS work continuously in parallel, with the ANN pre-processing the input or post-processing the output of the FIS, and iii) *hybrid* systems, where the ANN is used to learn some parameters of the fuzzy system (parameters of the fuzzy sets, fuzzy rules or weights of the fuzzy rules) in an iterative way, but –contrary to cooperative neuro-fuzzy systems– is not removed after learning. Nowadays, hybrid neuro-fuzzy systems are the standard choice if an adaptive FIS is needed.

The most popular hybrid neuro-fuzzy system is the *adaptive network-based fuzzy inference system* (ANFIS) proposed and discussed by Jang, a student of Zadeh, in [2.59]. ANFIS implements a Takagi-Sugeno-Kang FIS[18] and has a five-layered architecture: In the first layer, input variables are fuzzified and T-norm operators are deployed in the second layer to compute the firing strength of the rules. The third layer normalizes the rule strengths followed by the fourth layer, where the consequent parameters of the rule are determined. Finally, the overall output is calculated in the last layer by summing up the conclusion of all rules.

The motivation for employing ANNs in order to adapt the parameters of a FIS lies in the the well-developed ANN learning algorithms. In particular, the backpropagation algorithm and its extensions [2.60] allow for fast and reliable learning, even for problems of high dimensionality i.e. when many parameters have to be estimated. Furthermore, the solid theoretical background on approximation by means of ANNs[19] has also played a role when first introducing neuro-fuzzy systems.

The following section introduces an adaptive FIS which has been developed in this thesis for the purpose of fault classification. The main requirement was to parametrically define the membership functions of the fuzzy sets in the input space, and then use training datasets in order to adjust the parameter to given observation samples.

[17] Neuro-fuzzy systems are also referred to as “neural-fuzzy systems” or “fuzzy neural networks”.

[18] Unlike the fuzzy implication process discussed in section 2.3.1, Takagi-Sugeno-Kang implication does not return a fuzzy set, but rather a crisp numerical value, which is expressed as a linear function of the degrees of membership in the antecedent of the rule. Takagi-Sugeno-Kang (TSK) fuzzy inference systems can be trained with high efficiency, but are not as interpretable as traditional (Mamdani-type) FISs.

[19] In particular, ANNs have been proven to be universal estimators already in 1962, when Rosenblatt published the *perceptron convergence theorem*. This theorem postulates that, if there is a set of weights that correctly classify a particular (linearly separable) training pattern, a perceptron (the simplest kind of feed-forward neural network, consisting of only one neuron) can be taught in a finite number of iterations to find this set of weights.

2.4.1 Rule learning for parametrically defined membership functions

The learning procedure presented in this section applies for rules where the general form of the membership functions involved in the premise is known, however their specific parameters (scale and shape parameters) are still unknown and shall be adapted to a given sample.

In general, a fuzzy rule consisting of n inputs and one output has the form:

$$\textit{if } x_1 \textit{ is } K_{x_1} \textit{ and } x_2 \textit{ is } K_{x_2} \textit{ and} \ldots \textit{and } x_n \textit{ is } K_{x_n} \textit{ then } y \textit{ is } K_y$$

The degree of similarity in the relation "x_i *is* K_{x_i}" is given by the membership function $\mu_{x_i}\left(x_i\right)$, for $i = 1, \ldots, n$. For the learning procedure described here, membership functions in the premise of the rule are provided as *sets* (or *families*) of curves:

$$\mu_{x_i}\left(x_i\right) = f\left(\underline{p}_i, x_i\right) \quad i = 1, \ldots, n \tag{2.39}$$

where $\underline{p}_i$ is the parameter vector of the i-th membership function.

For a given input vector $\left(x_1, x_2, \ldots, x_n\right)$, the fuzzy output of the above rule is calculated as:

$$\mu_{res}\left(\underline{x}, y\right) = \top_i \left\{\mu_y(y), \top_{ag}\left[\mu_{x_1}\left(\underline{p}_1, x_1\right), \mu_{x_2}\left(\underline{p}_2, x_2\right), \ldots, \mu_{x_n}\left(\underline{p}_n, x_n\right)\right]\right\} \tag{2.40}$$

with $\top_i$ being the implication T-norm and $\top_{ag}$ being the aggregation T-norm for the premise. Figure 2.3 graphically illustrates equation 2.40. We may furthermore calculate the crisp result for the output by applying centre-of-area defuzzification (compare section 2.2.2):

$$y_{res} = \frac{\int y\, \mu_{res}(y)\, dy}{\int \mu_{res}(y)\, dy} \tag{2.41}$$

Given a sample of s reference input-output pairs $\left(\underline{\tilde{x}}^\nu, \tilde{y}^\nu\right)$, the objective of learning is to find appropriate parameter estimates $\underline{\hat{p}}_i$ so as to best fit this sample, that is:

$$y_{res}\left(\underline{\hat{p}}_1, \underline{\hat{p}}_2, \ldots, \underline{\hat{p}}_n, \underline{\tilde{x}}^\nu\right) \overset{!}{\approx} \tilde{y}^\nu \quad \forall \nu = 1, \ldots, s \tag{2.42}$$

Typically, the *method of least mean squares* is used for such problems. Accordingly, the mean square error ϵ provides a measure of the model's approximation (in)accuracy:

$$\begin{aligned} \epsilon &= \frac{1}{2s}\sum_{\nu=1}^{s}\left(y_{res}\left(\underline{p}_1, \underline{p}_2, \ldots, \underline{p}_n, \underline{\tilde{x}}^\nu\right) - \tilde{y}^\nu\right)^2 \\ &= \frac{1}{2s}\sum_{\nu=1}^{s}\left(\frac{\int y\, \mu_{res}\left(\underline{p}_1, \underline{p}_2, \ldots, \underline{p}_n, \underline{\tilde{x}}^\nu\right)\, dy}{\int \mu_{res}\left(\underline{p}_1, \underline{p}_2, \ldots, \underline{p}_n, \underline{\tilde{x}}^\nu\right)\, dy} - \tilde{y}^\nu\right)^2 \end{aligned} \tag{2.43}$$

The objective of learning is then to find parameter estimates $\underline{\hat{p}}_i$ so that:

$$\underline{\hat{p}}_1, \underline{\hat{p}}_2, \ldots \underline{\hat{p}}_n : \quad \min_{\underline{p}_1, \underline{p}_2, \ldots, \underline{p}_n} \epsilon \tag{2.44}$$

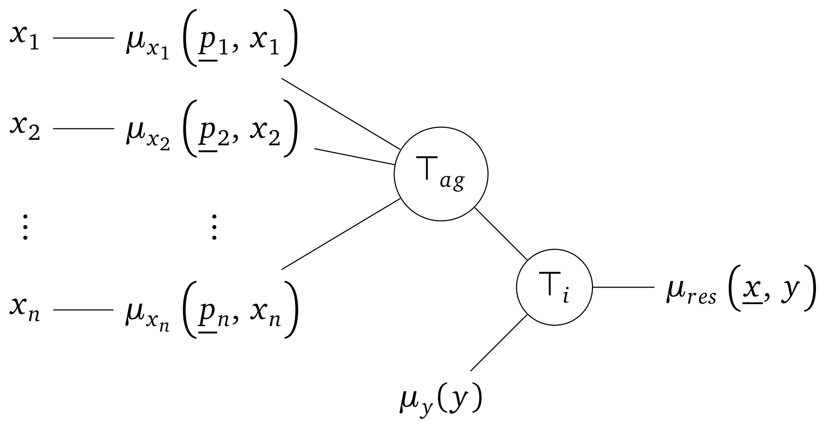


Figure 2.3.: Graphical representation of the fuzzy rule "*if x_1 is K_{x_1} and x_2 is K_{x_2} and ... and x_n is K_{x_n} then y is K_y*". The far left layer consists of the (crisp) input vector $\underline{x}$, which is then fuzzified.

In this work, the *resilient backpropagation algorithm* (RPROP) is chosen for solving the optimisation problem in equation 2.44. RPROP, introduced by Riedmiller and Braun in 1992 [2.61], is traditionally applied in supervised learning of feed-forward neural networks (also called *multilayer perceptrons*). It is a first-order optimisation algorithm, i.e. learning is based on the first-order derivative of the objective function. Contrary to traditional backpropagation, only the sign of the derivative (rather than its magnitude) is taken into account [2.60–2.62].

Figure 2.4 shows the general flowchart of the resilient propagation algorithm. At first, initial values for all parameters are assumed and the membership functions in the premise are parametrised accordingly. By solving equations 2.40 and 2.41, the output of the initially parametrised model is calculated for all s input-output data pairs of the reference sample. Following, the first order partial derivative of the mean square error ϵ with respect to each parameter is computed. Finally, equations 2.45 in figure 2.4 are applied to update the estimate of each parameter. Obviously, RPROP acts independently on each parameter by means of an individual update value (also called *learning rate*). Each parameter is changed by its own update value, in the opposite direction of its partial derivative, so as to minimise the total error function. Steps two to five are repeated until the approximation performance of the model satisfies a convergence criterion ($\epsilon < \epsilon_{max}$).

In particular, the learning procedure comprises following rules (compare equations 2.45 in figure 2.4): in case of a sign change in the partial derivative compared to the last iteration, the update value for the respective parameter is multiplied by a factor η^- where $\eta^- < 1$. On the other hand, if the last iteration produced the same sign, the update value is multiplied by a factor of η^+, where $\eta^+ > 1$. In other words, the learning rate for a parameter increases when the sign of the respective partial derivative of the total error remains constant and decreases otherwise.

Obviously, the main task involves computing the partial derivatives of the approximation error with respect to all parameters. In turn, this calls for the differentiation of equation 2.43. In the following, we shall try to stepwise simplify the problem.

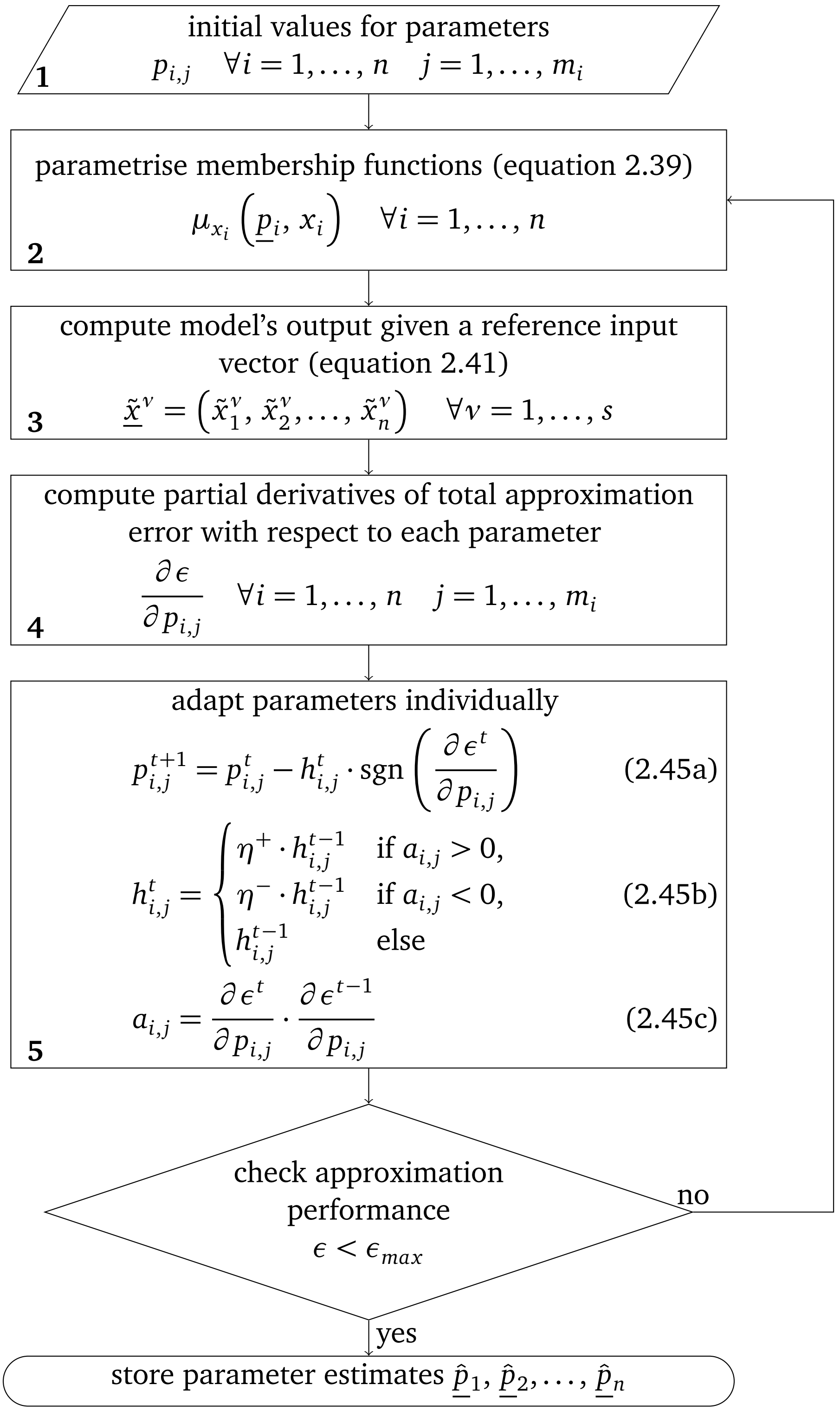


Figure 2.4.: Flowchart of the resilient propagation algorithm (RPROP). Learning is performed for each parameter individually, with $p_{i,j}$ being the j-th parameter of the i-th membership function. The algorithm uses first-order partial derivatives of the total approximation error ϵ with respect to each parameter (step 4). Parameters are adapted in an iterative procedure (t is the iteration counter), using equation 2.45a. Only the sign of the derivative (rather than its magnitude) is taken into account when computing the learning rate $h_{i,j}$.

Without loss of generality[20] we will assume that the codomain of the output variable y is the unity interval, i.e. $y \in [0, 1]$. The next step is to simplify the defuzzification process given in equation 2.41. For this purpose, we could consider implementing a singleton membership function for the output variable, as in equation 2.46.

$$\mu_{y_1} = \begin{cases} 1 & \text{if } y = 1, \\ 0 & \text{else} \end{cases} \tag{2.46}$$

However, this approach is not satisfactory: applying the singleton membership function above into equation 2.41 would result into $y_{res} = 1$ for all $\mu_{res} > 0$. With only one rule acting, the combination of centre-of-area defuzzification with a singleton membership function for the output variable fails to perform correctly.

For this reason, an alternative approach is adopted here. The main idea is to use the negation of the rule stated at the beginning of this chapter and assign a further membership function for the implication result of the new rule. Under consideration of De Morgan's laws, the negated rule reads:

if x_1 is not K_{x_1} or x_2 is not K_{x_2} or ... or x_n is not K_{x_n} then y is not K_y

Instead of using the formal complement of the function in equation 2.46, we will rather introduce an alternative membership function μ_{y_2} for the new rule's implication part (equation 2.47). As will be shown shortly, defining μ_{y_2} as a singleton ensures correct performance of the resulting fuzzy model while significantly simplifying further calculations.

$$\mu_{y_2} = \begin{cases} 1 & \text{if } y = 0, \\ 0 & \text{else} \end{cases} \tag{2.47}$$

With both rules (the initial one and its negated) acting in parallel, we can ammend equation 2.40 so as to obtain the fuzzy output:

$$\begin{aligned} \mu_{res}\left(\underline{x}, y\right) = \bot_{ac} \Big\{ &\top_i \left\{ \mu_{y_1}(y), \top_{ag}\left[\mu_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \mu_{x_n}\left(\underline{p}_n, x_n\right) \right] \right\}, \\ &\top_i \left\{ \mu_{y_2}(y), \bot_{ag}\left[\bar{\mu}_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \bar{\mu}_{x_n}\left(\underline{p}_n, x_n\right) \right] \right\} \Big\} \end{aligned} \tag{2.48}$$

where $\bot_{ac}$ is the T-norm applied for the accumulation of the two parallel rules and $\bot_{ag}$ is the T-conorm applied for the aggregation of the negated rule's premise. Note that $\top_{ag}$ and $\bot_{ag}$ must be dual, in other words they must belong to the same family (compare section 2.2.2). Finally, $\bar{\mu}_{x_i}$ is the complement of the original membership function μ_{x_i}.

Applying the aforementioned singleton membership functions for μ_{y_1} and μ_{y_2} and keeping in mind that $\top(x, 1) = x$ for any T-norm and $\bot(x, 0) = x$ for any T-conorm (section 2.2.2), we obtain:

$$\mu_{res}\left(\underline{x}, y\right) = \begin{cases} \top_{ag}\left\{ \mu_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \mu_{x_n}\left(\underline{p}_n, x_n\right) \right\} & \text{if } y = 1 \\ \bot_{ag}\left\{ \bar{\mu}_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \bar{\mu}_{x_n}\left(\underline{p}_n, x_n\right) \right\} & \text{if } y = 0 \\ \text{else} & \end{cases} \tag{2.49}$$

[20] It is indeed possible to scale any domain down to the unity interval, e.g. by means of a linear transformation.

If we now apply the above expression into the centre-of-area defuzzification formula in equation 2.41, we obtain the crisp result of the fuzzy rule:

$$y_{res} = \frac{1 \cdot \top_{ag}\left\{\mu_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \mu_{x_n}\left(\underline{p}_n, x_n\right)\right\} + 0 \cdot \perp_{ag}\left\{\bar{\mu}_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \bar{\mu}_{x_n}\left(\underline{p}_n, x_n\right)\right\}}{\top_{ag}\left\{\mu_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \mu_{x_n}\left(\underline{p}_n, x_n\right)\right\} + \perp_{ag}\left\{\bar{\mu}_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \bar{\mu}_{x_n}\left(\underline{p}_n, x_n\right)\right\}} \tag{2.50}$$

The fuzzy model corresponding to equation 2.50 above is illustrated graphically in figure 2.5.

Let us now consider equation 2.50 in more detail: obviously, the denominator always equals one, since the two terms are dual[21], that is the second term is the negation of the first one and vice versa. Thus, we finally obtain:

$$y_{res} = \top_{ag}\left\{\mu_{x_1}\left(\underline{p}_1, x_1\right), \ldots, \mu_{x_n}\left(\underline{p}_n, x_n\right)\right\} \tag{2.51}$$

which complies with equations 2.40 and 2.41 if the membership function $\mu_y(y)$ as in equation 2.46 is applied.

Returning to the parameter estimation problem by means of resilient backpropagation, we need to individually compute the partial derivatives of the approximation mean square error ϵ with respect to all parameters (step 4 in figure 2.4). For this purpose, equation 2.43 is differentiated with respect to parameter $p_{i,j}$, and the term y^v is replaced by equation 2.51:

$$\begin{aligned}
\frac{\partial \epsilon}{\partial p_{i,j}} &= \frac{\partial \frac{1}{2s} \sum_{v=1}^{s} \left\{y_{res}\left(\underline{p}_1, \ldots, \underline{p}_n, \underline{\tilde{x}}^v\right) - \tilde{y}^v\right\}^2}{\partial p_{i,j}} \\
&= \frac{1}{s} \sum_{v=1}^{s} \left\{y_{res}\left(\underline{p}_1, \ldots, \underline{p}_n, \underline{\tilde{x}}^v\right) - \tilde{y}^v\right\} \cdot \frac{\partial y_{res}\left(\underline{p}_1, \ldots, \underline{p}_n, \underline{\tilde{x}}^v\right)}{\partial p_{i,j}} \\
&= \frac{1}{s} \sum_{v=1}^{s} \left\{y_{res}\left(\underline{p}_1, \ldots, \underline{p}_n, \underline{\tilde{x}}^v\right) - \tilde{y}^v\right\} \cdot \frac{\partial \top_{ag}\left[\mu_{x_1}\left(\underline{p}_1, \tilde{x}_1^v\right), \ldots, \mu_{x_n}\left(\underline{p}_n, \tilde{x}_n^v\right)\right]}{\partial p_{i,j}}
\end{aligned} \tag{2.52}$$

Obviously, the partial derivative invokes differentiation of the T-norm for premise aggregation $\top_{ag}$ as well as differentiation of the individual membership function in the premise of the rule μ_{x_i}. However, many common T-norms (for example the standard minimum operator, compare section 2.2.2) are piecewise defined and, thus, not continuously differentiable, so that their derivative is not defined over the whole domain. For this reason, the aggregation operator in the premise $\top_{ag}$ must implement a continuously differentiable T-norm (for example the product operator). Similar requirements apply also for all membership functions in the rule's premise. They too have to be continuously differentiable over their respective domains. Examples of such membership functions are given in section 2.2.1.

In order to demonstrate the learning procedure for rules with parametrically defined membership functions, a simple example shall be given at this place.

[21] The standard fuzzy complement of a fuzzy variable x is defined as $\bar{x} = 1 - x$, consequently $x + \bar{x} = 1$.

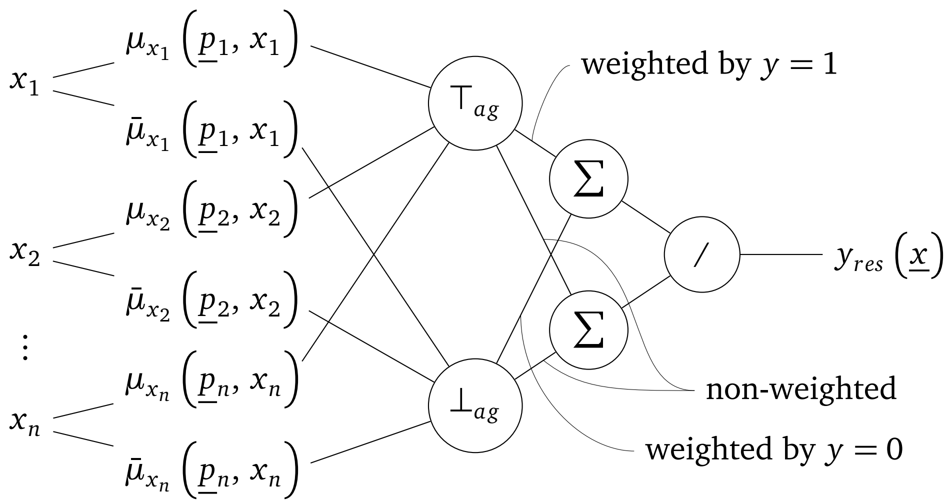


Figure 2.5.: Graphical representation of the fuzzy model with both the original rule as well as its negation (equation 2.50). The weights on the branches between the third and fourth layer account for the implication results of the two rules. The network yields the crisp output variable y_{res}.

Example 2.5 *The willingness to have a Sunday picnic is assumed to be governed by the following simple rule: "if the temperature forecast is higher than T_f and the chance of rain is lower than* Pr_r *then the willingness is high." Table 2.8 shows the results of a virtual survey on this rule. Given the membership functions in equation 2.53 for the expressions "higher than ..." and "lower than ...", what are the best parameter estimates so as to fit the reference values in table 2.8?*

As shown above, the membership functions in the premise of the rule have to be continuously differentiable in order to apply the RPROP algorithm. In this case, sigmoid functions –as in equation 2.53– are implemented. An increasing sigmoid function (2.53a) accounts for the expression "higher than ...", a decreasing one (2.53b) for the expression "lower than ..." (compare section 2.2.1):

$$\mu_{x_1}(x_1) = \frac{1}{1 + e^{-p_{1,1}(x_1 - p_{1,2})}} \quad \text{with } p_{1,1} > 0 \tag{2.53a}$$

$$\mu_{x_2}(x_2) = \frac{e^{-p_{2,1}(x_2 - p_{2,2})}}{1 + e^{-p_{2,1}(x_2 - p_{2,2})}} \quad \text{with } p_{2,1} > 0 \tag{2.53b}$$

where x_1 is the temperature forecast T_f and x_2 is the chance of rain Pr_r. The parameters in equation 2.53 may be divided into shape factors[22] ($p_{1,1}$, $p_{2,1}$) and scale factors ($p_{1,2}$, $p_{2,2}$).

[22] The scale parameter (usually denoted as c) of a sigmoid function determines the inflexion point, i.e. $\mu_{sigmoid}(c) = 0.5$. On the other hand, the shape parameter (a) influences the slope of the function: the higher the value of a, the steeper will the membership function be.

Table 2.8.: Virtual survey regarding the willingness to have a Sunday picnic with temperature forecast T_f and chance of rain Pr_r as influencing factors.

Respondent	T_f [°C]	Pr_r [%]	willingness
1	22	20	high
2	20	30	low
3	30	15	high
4	25	25	low
5	27	12	high

For the aggregation T-norm T_{ag} in equation 2.52, the product operator is applied. Thus, we obtain following expressions for the partial derivative of the mean square error ϵ:

$$\frac{\partial \epsilon}{\partial p_{1,1}} = \frac{1}{5}\sum_{\nu=1}^{5}\left(y_{res}^{\nu} - \tilde{y}^{\nu}\right) \cdot \mu_{x_2}(\tilde{x}_2^{\nu}) \cdot \frac{(\tilde{x}_1^{\nu} - p_{1,2}) \cdot e^{-p_{1,1}(\tilde{x}_1^{\nu} - p_{1,2})}}{\left(1 + e^{-p_{1,1}(\tilde{x}_1^{\nu} - p_{1,2})}\right)^2} \tag{2.54a}$$

$$\frac{\partial \epsilon}{\partial p_{1,2}} = \frac{1}{5}\sum_{\nu=1}^{5}\left(y_{res}^{\nu} - \tilde{y}^{\nu}\right) \cdot \mu_{x_2}(\tilde{x}_2^{\nu}) \cdot \frac{-p_{1,1} \cdot e^{-p_{1,1}(\tilde{x}_1^{\nu} - p_{1,2})}}{\left(1 + e^{-p_{1,1}(\tilde{x}_1^{\nu} - p_{1,2})}\right)^2} \tag{2.54b}$$

$$\frac{\partial \epsilon}{\partial p_{2,1}} = \frac{1}{5}\sum_{\nu=1}^{5}\left(y_{res}^{\nu} - \tilde{y}^{\nu}\right) \cdot \mu_{x_1}(\tilde{x}_1^{\nu}) \cdot \frac{-(\tilde{x}_2^{\nu} - p_{2,2}) \cdot e^{-p_{2,1}(\tilde{x}_2^{\nu} - p_{2,2})}}{\left(1 + e^{-p_{2,1}(\tilde{x}_2^{\nu} - p_{2,2})}\right)^2} \tag{2.54c}$$

$$\frac{\partial \epsilon}{\partial p_{2,2}} = \frac{1}{5}\sum_{\nu=1}^{5}\left(y_{res}^{\nu} - \tilde{y}^{\nu}\right) \cdot \mu_{x_1}(\tilde{x}_1^{\nu}) \cdot \frac{p_{2,1} \cdot e^{-p_{2,1}(\tilde{x}_2^{\nu} - p_{2,2})}}{\left(1 + e^{-p_{2,1}(\tilde{x}_2^{\nu} - p_{2,2})}\right)^2} \tag{2.54d}$$

$$\text{with } y_{res}^{\nu} = \mu\left(p_{1,1}, p_{1,2}, \tilde{x}_1^{\nu}\right) \cdot \mu\left(p_{2,1}, p_{2,2}, \tilde{x}_2^{\nu}\right)$$

The first three iterations of the RPROP algorithm will be demonstrated here according to the flowchart in figure 2.4. The tables in appendix A.2 show all relevant intermediate results. The reader is encouraged to verify the results by computing equations 2.54 and 2.45 iteratively. Following initial conditions were assumed:

- scale factors: $p_{1,2} = 24.8$ and $p_{2,2} = 19.4$ (mean values of the data in table 2.8),
- shape factors: $p_{1,1} = p_{2,1} = 1$,
- initial learning rate: $h_{i,j} = 0.1 \quad \forall i, j$,
- required output: $\tilde{y}_i^{\nu} = 1$ for high willingness and $\tilde{y}_i^{\nu} = 0$ for low willingness.

Applying a total of 40 iterations yields following results for the parameter estimates:

$$\hat{p}_{1,1} = 1.005 \quad \hat{p}_{1,2} = 13.39 \quad \hat{p}_{2,1} = 4.07 \quad \hat{p}_{2,2} = 22.74$$

In appendix A.2, the learning performance as a function of the number of iterations is also given (figure A.2). Summing up, we may re-formulate the rule at the beginning of this example for the given sample in table 2.8 as:

"if the temperature forecast is higher than 13.4 °C *and the chance of rain is lower than* 22.7 % *then the willingness is high."*

■

3 General notes on condition assessment for maintenance purposes

Information is a source of learning. But unless it is organized, processed, and available to the right people in a format for decision making, it is a burden, not a benefit.

William G. Pollard (1911 – 1989)

Maintenance cannot be cost-effective unless equipment is serviced according to its special needs. In this way unnecessary wasting of maintenance resources, both material and human, can be avoided. The objective of condition assessment is to estimate the equipment's special needs from the associated service and maintenance experience as well as from any equipment-specific information available. The result of condition assessment are thus maintenance recommendations on the base of which appropriate decisions can be made.

Maintenance in electric power systems is a field of interaction: technical requirements and specifications meet financial targets and operational constraints. The complexity of the problem is also evident from the partial confusion with regard to correct terminology. Depending on the perspective, several keywords such as condition monitoring, diagnostic analysis, lifetime estimation etc. are employed to describe the process of condition assessment. For this reason, section 3.1 provides a set of definitions which will be used throughout the thesis.

Further sections of this chapter describe the current practice of condition assessment as applied by electric power utilities. Generally speaking, the assessment process takes place in two distinct steps: In the first step, any information available about the equipment's condition is analysed and assessed separately. For this purpose, factors influencing the performance of the equipment have to be identified; in this thesis, such factors are labelled *condition indicators* (CIs). Depending on the type of the equipment as well as on the scope of condition assessment different CIs are used. Section 3.2 gives an overview of common CIs as proposed in the literature.

The second step in condition assessment is one of synthesis: the results of previous assessment according to individual CIs are combined and condensed into an appropriate index. Practical evaluation of such indices is made by means of condition assessment matrices, featuring a set of weights for the various CIs. The weights define how each indicator is reflected in the index at a higher level. Determining the weights associated with each CI is not an easy task, especially when many CIs have to be included. In section 3.3 common methods for weight determination are described. In general, they all use simple preference structures and pairwise comparison of the importance of CIs in order to determine weights.

The application of condition assessment matrices during the synthesis process involves some limitations which are also discussed in this chapter. The discussion is raised on the basis of multi-criteria decision analysis introduced in section 3.4. Due to its structure, condition assessment resembles decision making with multiple objectives: The objectives or criteria result from the compliance of a particular piece of equipment with chosen CIs while the decision lies in determining the value of the high-level index. An aspect of particular interest is the impossibility theorem by Arrow. On its basis the limitations of common condition assessment methods (presented by means of practical examples in section 3.5) are discussed from a theoretical perspective.

The limitations of existing schemes are at the same time the motivation of this thesis for introducing fuzzy systems for the purpose of condition assessment. Examples of such systems will be described later in chapters 4 and 5.

3.1 Condition-based maintenance in power systems

The main difference between corrective and preventive maintenance is that, in the latter case, maintenance and servicing is performed according to a schedule rather than in the course of unplanned equipment outage. When scheduling preventive maintenance activities, two general approaches exist: either the schedule is defined way in advance without taking into account any information about the equipment's state (timed or *time-based maintenance*), or maintenance is initiated in a case-specific manner according to the condition of the equipment (*condition-based maintenance*).

Time-based maintenance (TBM) has traditionally been the standard approach for electric power systems since the mid-20$^{\text{th}}$ century. Its main advantages are of operational nature. The time schedule for preventive maintenance is known already at the time of installation; this allows for better planning and efficient resource allocation. In addition, TBM accounts for the fact that several pieces of equipment often form a functional section – especially in power transmission and distribution systems[1]. By coordinating preventive maintenance activities within a functional section, its overall unavailability due to maintenance can be minimised.

On the other hand, TBM bears the risk of being potentially cost-ineffective. Since no information about the equipment's condition is considered, the approach to maintenance is reserved, allowing for high safety margins so as to keep the probability of unplanned equipment outage low. This results in performing rather more maintenance than actually justified by the equipment's condition: wasting of maintenance resources is the consequence. The second major limitation of TBM lies in the fact that it cannot be applied unless sufficient experience is available. In particular the mechanisms in which equipment gradually deteriorates and eventually fails must be known in detail. At the time a new type of equipment is introduced, however, no maintenance experience is available. The only source of knowledge about failure modes is experience with similar devices as well as accelerated ageing tests conducted by the manufacturer during the design phase. On the basis of this knowledge manufacturers recommend appropriate time schedules for preventive maintenance activities. Their recommendation must consider the equipment's design specifications, which however is significantly more severe than the stress the equipment is subjected to in the field. This effect also results in performing more maintenance than necessary when employing a time-based scheme.

In order to increase the cost effectiveness of preventive maintenance, the condition-based maintenance (CBM) approach utilises information about the equipment's actual condition when

1 For example, consider a typical substation bay consisting of: busbar disconnector(s), circuit breaker, instrument transformers, earthing switch and line disconnector. Taking any of these units out of service for maintenance results in (planned) outage of the complete bay. For this reason, when de-energising the bay, several units are serviced in parallel.

Table 3.1.: Common practice for preventive maintenance of power transmission systems (data extracted from surveys by Cigré in the late 1990s [3.1–3.4]).

	TBM	CBM	Other
all equipment [3.2]	47 %	39 %	14 %
gas-insulated switchgear [3.1]	73 %	21 %	6 %
substations[a] [3.3]	67 %	58 %	3 %
circuit breakers[b] [3.4]	40 % (24 %)	38 % (47 %)	22 % (29 %)

[a] Responses of this survey add up to more than 100 % because approximately 28 % of the participating utilities apply a combination of time-based and condition-based maintenance.

[b] Values in parentheses correspond to future maintenance plans of participating utilities.

deciding on whether, when, and to which extent to perform maintenance. In this selective way cost saving can be achieved without letting the risk of unplanned outage increase. Obviously, the main prerequisite for CBM is *knowledge of the equipment's condition*. Turning relevant information e.g. results from diagnostic tests into knowledge is the task of condition assessment, as will be shown later.

Several surveys [3.1–3.4] published by Cigré[2] and summarised in table 3.1 provide good insight into common practice regarding maintenance, especially for high-voltage transmission systems. Generally speaking, TBM is still the most prevalent approach, although CBM has significantly gained in importance in the last two decades [3.5]. The choice between time-based or condition-based maintenance is always case-specific. For example, gas-insulated switchgear and disconnectors are maintained predominantly on a time basis, while power transformers and overhead power lines are maintained more and more on a condition basis [3.2]. The trend in maintenance of electric power systems is towards a combination of the time-based and condition-based approach. Already, many utilities use a predefined time schedule in order to assess the condition of their equipment (time-based approach), while their decisions whether and when to perform maintenance are based on the assessment results (condition-based approach).

This brings us back to the question of condition assessment. Obviously, knowledge of the equipment's condition is essential for making decisions on maintenance. The question is which sources of information to consider and how to process this information in order to extract useful knowledge out of it. The paradigm shift of electric power utilities from time-based to condition-based maintenance since the late 1990s initiated a vivid discussion in this field. In 1997, a business unit manager of a large German transmission company wrote [3.6]:

> *"Besides the pragmatic approach to develop commercial software [for the purpose of asset management], research work is also necessary for the description of missing modules. To these belong: i) establishing classification schemes for practical assessment of the equipment's condition [. . .] iii) developing diagnostic techniques for fully-automated condition monitoring of the equipment [. . .]"*

[2] *Cigré* stands for "Conseil International des Grands Reseaux Électriques" (English: International Council on Large Electric Systems). It was founded in 1921 with headquarters in Paris and has over 5,000 members.

In response to such appeals from the electricity supply business, many universities intensified research in the topic of condition assessment. For instance, the German Research Foundation (DFG – Deutsche Forschungsgemeinschaft) initiated a research programme "condition assessment in electric power systems" in the year 2000, and provided funding for forty research initiatives [3.7]. However, only a glimpse at the titles of the programmes reveals the conceptual confusion in the field. Material scientists focus on chemical degradation processes, high voltage engineers investigate diagnostic techniques and power system engineers address all issues ranging from diagnostic analysis to maintenance decision making. In order to reach clarification, definition 3.1 describes condition assessment in the meaning of this thesis.

Definition 3.1 *Condition assessment is a process of analysis and synthesis for estimating the condition of a piece of equipment according to a set of criteria.*

Following features of condition assessment are stressed in this definition:

Process: Condition assessment involves a series of logical steps, beginning at the collection of relevant available information and ending at the determination of an estimate of the condition. It is a well-defined, systematic, consistent and objective procedure which can be described and modelled in an algorithmic way for the purpose of automation.

Analysis: The principal mode of reasoning is analytic. Relevant knowledge and available information is analysed, that is, the various aspects of interest are subjected to separate investigation governed by consistent logical rules.

Synthesis: Condition assessment involves more than one aspects of interest. The intermediate conclusions obtained from analytic investigation of input information are condensed to yield a single estimate of the condition.

Estimation: The result of the process is an estimate. The process itself is heuristic, that is, it incorporates knowledge and returns an educated guess for the condition. Uncertainty arises both from the input information considered as well as from the assessment process.

Condition: Condition is an open, theoretical concept which cannot be observed or measured in real life. It can be expressed by means of a linguistic term e.g. "in good condition" or as a numerical index (compare section 3.3). No matter how condition is expressed, it is used as a basis for further decisions on maintenance and/or replacement of equipment.

Equipment: Condition assessment is always equipment-specific. Detailed knowledge of relevant failure modes as well as profound service and maintenance experience are essential for effective condition assessment.

Criteria: The scope of condition assessment is governed by the implemented assessment criteria. They establish the framework according to which the condition of the equipment is measured. In practice, assessment criteria are defined as *condition indicators*[3].

[3] The term *condition indicator* is introduced in this thesis in analogy to the popular concept of *key performance indicators* used in the world of finance to measure the performance of a process or organisation.

On the basis of definition 3.1 it is now possible to draw a clear line between condition assessment and adjacent research fields. In particular, *condition assessment is no . . . :*

. . . *reliability assessment*. Contrary to many publications, it is the opinion of this author that the risk of unplanned outage is not directly reflected into the condition of the equipment. The reliability behaviour of electromechanical devices is traditionally described by the so-called *bathtub curve*. According to this description, the failure rate[4] of the equipment during the first service years is rather high due to wear-in failures occurring as a result of insufficient manufacturing and/or installation. The development of such failures is rapid, but their consequences are usually limited, so that affected devices can be operated without any further problems once the fault has been removed. In a way, wear-in failures act similar to quality tests, where minor flaws are detected and corrected. It is thus reasonable to argue that, during the wear-in period, the risk of unplanned outage is high, whereas the condition of the equipment is at the same time good.

. . . *lifetime estimation*. Some researchers e.g. [3.8–3.12] define condition on the basis of lifetime estimation. They use probabilistic models and statistical information for this purpose. However, this approach is not in the sense of definition 3.1 because of following reasons: First, depending on the chosen set of criteria condition assessment may be of broader scope than the mere estimation of the equipment's technical condition (for example, it may also consider financial, operational or other aspects as well). Second, condition assessment, although related to the question of remaining lifetime, yields a "snapshot"; future rate of wear is largely influenced by the stress applied during service, which is not included in the assessment process. Finally, the focus of condition assessment is on a particular piece of equipment for which information is available – at least to a certain extent. Randomness is thus the wrong way to model uncertainty within the assessment process.

. . . *diagnostic analysis*. An important feature of condition assessment according to definition 3.1 is the process of synthesis, which implies that information from different sources –potentially contradictory– has to be aggregated and condensed into one estimate. On the other hand, diagnostic analysis is confined to the interpretation of information obtained from applying a single diagnostic technique e.g. measurement of partial discharges.

The introduction of condition assessment schemes takes place in two distinct phases: In the *design phase* the scope of assessment is defined and appropriate assessment criteria are identified. Logical rules for the process of analysis and synthesis are then established and the assessment scheme is finalised. In the following *application phase* required information about the equipment's condition is collected and processed according to the previously defined assessment scheme. Obviously, modelling knowledge and service/maintenance experience is confined to the design phase; this is also where the focus of the thesis is on.

[4] The *failure* (or *hazard*) *rate* describes the marginal probability of a unit failing within the next time interval under the assumption that it has not failed before. In the case of very low failure probabilities, the failure rate is approximately equal to the (discrete) failure probability density function.

3.2 Defining condition indicators

Analysis is the first integral process in condition assessment. It involves the definition of the scope of assessment and the subsequent identification of appropriate assessment criteria, according to which available information about the equipment's condition has to be analysed. Criteria used in condition assessment aim at providing insight into the actual condition of the equipment; they are thus labelled *condition indicators*. A general description of an indicator is given in definition 3.2.

Definition 3.2 *Indicators are abstract metrics.*

Two features of indicators are highlighted in the above definition. Indicators describe a process or an entity in an *abstract* manner, so that the observer needs not to delve into the process/entity itself. This is especially important in case only some aspects of the underlying process/entity are relevant to further analysis or decision making. Moreover, indicators are *metrics*, which in turn implies two further features: i) information is represented in an objective, quantitative way (e.g. by a numerical value) according to a predefined scheme, and ii) a comparison to an expected or required value is performed.

Summing up, condition indicators are defined and introduced during the phase of analysis so as to quantify and represent information relevant to condition assessment in an objective and abstracted manner. For example, relevant information for the assessment of the technical condition of a piece of equipment can be acquired by applying a diagnostic test e.g. measurement of partial discharges. However, only when the results of the test are compared to some predefined specification and the output of this comparison is expressed quantitatively (e.g. as a numerical degree of compliance with the specification) does the applied diagnostic test constitute a condition indicator.

Condition indicators should not be confused with the popular concept of key performance indicators (KPIs). While CIs provide insight into the equipment's condition, KPIs measure the performance of a process and monitor its efficiency. With regard to maintenance in electric power systems, two large groups of KPIs exist: The first group consists of indicators describing the technical performance of the equipment, basically by listing its key required functions. For example, KPIs for a power transformer include –among others– its integrity to carry current and its mechanical withstand strength to short-circuit currents. A detailed overview of technical KPIs for equipment in high-voltage transmission systems is provided in [3.14]. On the other hand, the second group of indicators monitor the efficiency of the maintenance process as a whole. Such indicators are usually defined as ratios of two quantities e.g. total cost of preventive maintenance activities divided by the expected cost of equipment replacement. The European standard EN 15341 provides a long list of such maintenance KPIs, grouped in three categories: financial performance indicators, technical performance indicators, and organisational performance indicators [3.15].

The major difference between condition and performance indicators is that the first are mainly related to "being" while the latter correspond to "doing". In other words, performance can be influenced/changed, whereas condition cannot – at least not before appropriate decisions on maintenance or replacement are taken, which however occurs only after the condition assessment process has been completed. For this reason, the use of CIs is the right choice for the purpose of condition assessment.

Returning back to the question of how to define appropriate CIs, the analytical approach can be structured in following three steps:

1. Defining the scope of maintenance decisions. The ultimate objective of condition assessment is to assist in making decisions on maintenance and replacement issues by providing appropriate recommendations. Obviously, these recommendations should be in line with the scope of decisions. For example, if for some reasons replacements are beyond the scope of possible actions, recommending the replacement of a piece of equipment would be of little use. Following questions can help identify the scope of maintenance decisions:
   - Which maintenance activities are possible i.e. to what extent can maintenance be performed?
   - What is the time horizon for planning maintenance activities?
   - Are there any other limitations to decision making e.g. issues of insurance, guarantee or legal requirements?

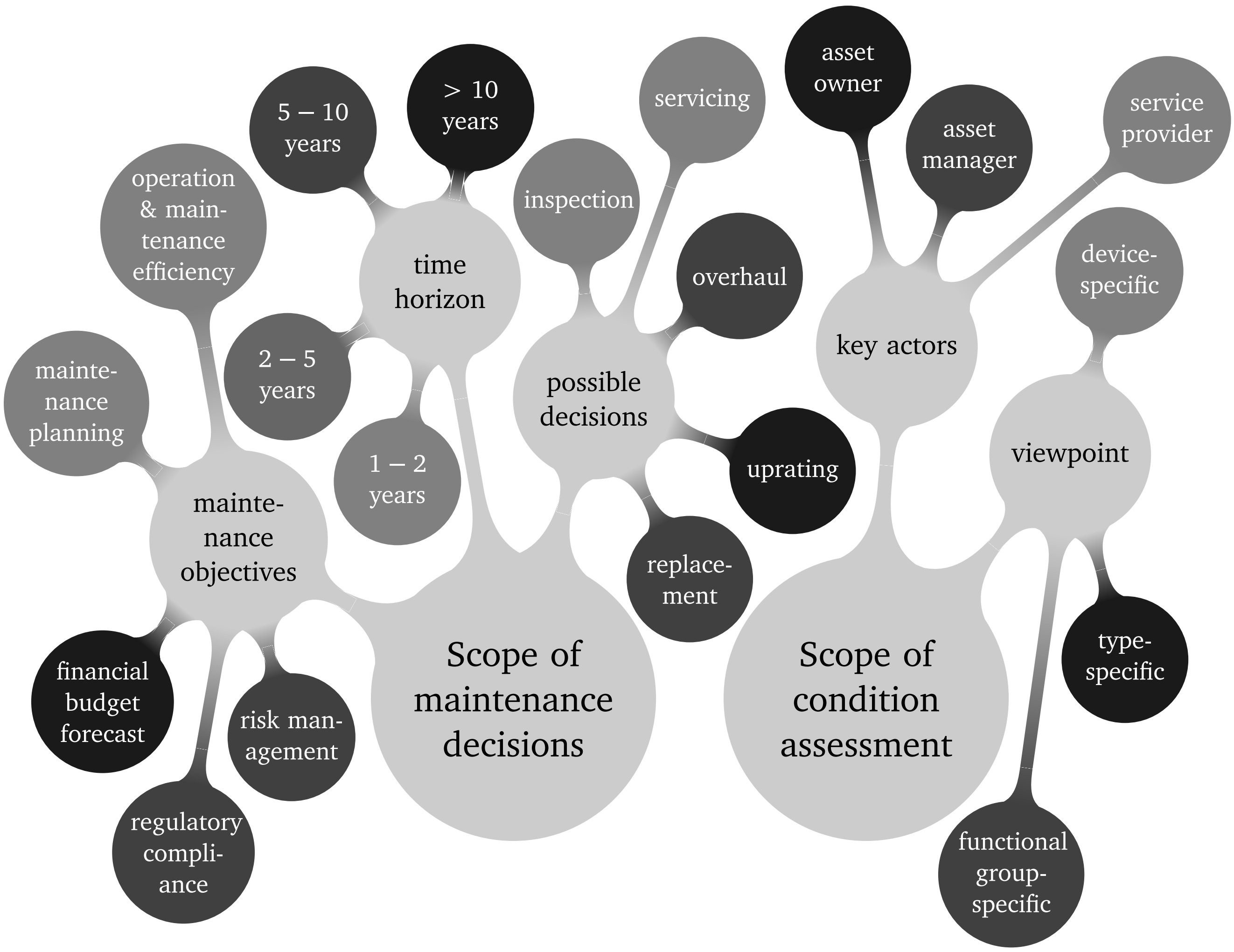


Figure 3.1.: Scope of condition assessment. The specification for condition assessment are derived from the general scope of decision making on maintenance. The darker (lighter) the colour of the end nodes in the figure, the more strategic (operational) is the scope of condition assessment.

In addition, the scope of maintenance decisions should be also examined with respect to its objectives. Only by knowing the far-reaching objectives can we distinguish between good and bad decisions[5]. For this reason, the maintenance objectives must be clearly defined prior to condition assessment. Examples of common maintenance objectives include: risk management, compliance with regulatory requirements, operational or maintenance efficiency, maintenance planning, and financial budget forecast.

2. Defining the scope of condition assessment. In the second step, requirements for the condition assessment process are derived from the maintenance objectives. In particular, the responsibilities of organisations and persons involved must be clearly defined in order to ensure reliable information exchange channels. This matter deserves special attention in view of increasing outsourcing of maintenance activities. When outsourcing, the acquisition of information takes place in the field by the subcontractor while decisions on preventive maintenance are usually made by the asset manager – in special cases e.g. replacement of expensive equipment even by the asset owner[6]. Good communication and exchange of information is essential in this case. At the same time the viewpoint for condition assessment has to be defined. Depending on the scope for decision making it is possible to distinguish between device-specific assessment, when only one piece of equipment is considered, functional group-specific assessment, when a functional group of apparatus e.g. a substation bay is considered, and type-specific assessment, when all units of a particular type are considered. Figure 3.1 shows a mind map for defining the scope of condition assessment. The concepts of strategic and operational assessment, as denoted in the figure's caption, will be presented shortly.

3. Defining appropriate condition indicators. Once the scope of condition assessment has been defined, sources of exploitable, relevant information must be identified. With the emphasis being at *relevant*, it is essential to involve experts and knowledge-carriers who understand both the objective of the assessment i.e. the scope of decisions, but also the nature of the underlying process e.g. the ageing or failure mechanism of a particular asset when defining CIs. On the other hand, and with the emphasis being now on *exploitable*, it is equally important to involve the parties supposed to collect the necessary information in order to identify any difficulties in acquiring the information at an early stage.

   A comprehensive check list for identifying CIs is given in table 3.2. The most important aspects include:

   - Applicability: The information captured within a CI should represent reality in an unambiguous and accurate way. The definition of a CI must therefore account for easy interpretation so that the resulting assessment scheme is well-understood by the intended users.

[5] A decision is said to be *good* if it is derived from the information available at the time of decision making in a consistent, logical way. On the other hand, a decision is *right* if it is justified by its outcome.

[6] Today's paradigm for the electricity supply business distinguishes between the concepts of asset owners, asset managers, and service providers [3.14, 3.16, 3.17]. The *asset owner* is in charge of the business strategy and the overall financing of the investments, the *asset manager* makes investment decisions to balance asset/service performance, financial performance and risk, while the *service provider's* task is to make maintenance decisions related to delivering work on time, within budget and in a safe manner in accordance with agreed specifications.

- Availability: The temporal, spacial and modal availability of information must be examined. With regard to time, a distinction is made between data collected on-line or off-line, with off-line data being possibly even so old as the equipment itself. In order to make sure that condition assessment is not based on data which are out-of-date, a time stamp should always be provided when data is collected and stored. Spacial and modal availability address the question of where and how information can be retrieved. This question is crucial for integrating a CI into a computer-based condition assessment scheme; if for instance, some information necessary for evaluation of a particular CI is collected in the field by a subcontractor for own use, it might be difficult for the asset manager to gain access to it. Even within the same organisation, some information might not be visible to all departments, in case e.g. it is stored on paper or in a local data base. The integrability of a particular CI into enterprise resource planning (ERP) systems is therefore an important aspect.
- Cost analysis: Cost analysis should address not only material expenses for introducing a CI, but also the resulting demand for human resources. Furthermore, it must include all associated expenses, covering training, future cost of operation, cost of data storage and handling as well as other possible hidden cost aspects.

Table 3.2.: Check list for the identification of condition indicators. Answering most of the above question with "yes" suggests that the considered CI is useful for condition assessment.

	Applicability
✓	Is the information captured within the CI relevant to condition assessment?
✓	Is the definition of the CI unambiguous?
✓	Is the representation of reality accurate / does the CI assess similar situation consistently?
✓	In case of composite CIs: are they well-structured?
	Availability
✓	Can the information be incorporated into an ERP system?
✓	Is relevant data already implemented in an ERP system?
✓	Is the update frequency appropriate (on-line/off-line)?
✓	Can new information be collected without service interruption?
✓	Is the information collected mainly by the same party performing condition assessment?
✓	Is the access to necessary data unlimited?
✓	Is relevant data already being collected?
✓	Are older data available for comparison?
✓	Are reference values available in-house or in the literature?
	Cost analysis
✓	Is acceptance within the organisation secured?
✓	Is expertise available?
✓	Are the necessary human resources available?
✓	Is training of the maintenance personnel realisable?
✓	Are the additional costs (e.g. for measuring equipment) justifiable?
✓	Does cost analysis account for any hidden costs?

Another common approach to identifying relevant indicators is the so-called *SMART* scheme [3.18]. According to this scheme, indicators should be: *specific*, in that they are clearly defined to avoid misinterpretation, *measurable*, in that relevant information can be quantified and compared to other data, *attainable*, in that their objective is achievable, reasonable, and credible under conditions expected, *realistic*, in that the CI fit into the organisation's constraints and is cost-effective, and *timely*, in that they are feasible to evaluate within the time frame given.

Once sources of relevant information have been identified, a scorecard must be set up for every condition indicator. By means of such scorecards the compliance of the equipment with the chosen criteria for condition assessment can be evaluated. Practical examples of scorecards will be given in section 3.2.2.

Depending on the scope of decision making on maintenance, condition assessment may be performed on a strategic or an operational level. *Strategic condition assessment* intends to assist in planning long and medium-term maintenance and replacement activities and in evaluating the necessary financial budget. On the other hand, the focus of *operational condition assessment* is more on day-to-day maintenance, with the objective to assist in decision about whether, when and how to perform preventive maintenance. Figure 3.1 shows a first classification of strategic and operational condition assessment; a more detailed description of objectives and applicable CIs will be given in the next sections.

3.2.1 Indicators for strategic condition assessment

Strategic condition assessment is a high-level approach which should help decide primarily on major maintenance activities such as refurbishment or replacement of specific pieces of equipment or even whole groups of devices. It is related to the concept of end-of-life decision making[7], although no decisions are actually taken during the assessment process. The necessary skills for strategic condition assessment are located primarily on the asset manager's side; it is also the asset manager who usually implements the assessment results for maintenance planning or when claiming the necessary financial budget from the asset owner. The time horizon for strategic condition assessment lies in the medium and long term, typically in the range of five to ten years or more. In many cases strategic decisions in electricity supply systems dictate guidelines e.g. for the preferred type of technology or some favoured equipment manufacturer; in these cases the perspective for condition assessment is rather type-specific than device-specific.

This section presents applicable CIs for the purpose of strategic condition assessment. Many concepts have been adapted from a Cigré technical brochure on lifetime management of circuit breakers [3.4], although the viewpoint here is not limited to any specific type of apparatus. Figure 3.2 shows some important CIs for strategic condition assessment of equipment in electric power systems which will be briefly explained in the following. The darker the colour of the nodes in figure 3.2, the more device-specific the respective CI is; the lighter the colour, the more type-specific it is.

[7] Contrary to the concept of end-of-life *estimation*, which usually regards statistical information on equipment failure to determine the end of its useful technical lifetime, the concept of end-of-life *decision making* is used to denote the question of intentionally removing a piece of equipment from service prior to the end of its useful technical lifetime (refer also to the discussion on definition 3.1, section 3.1).

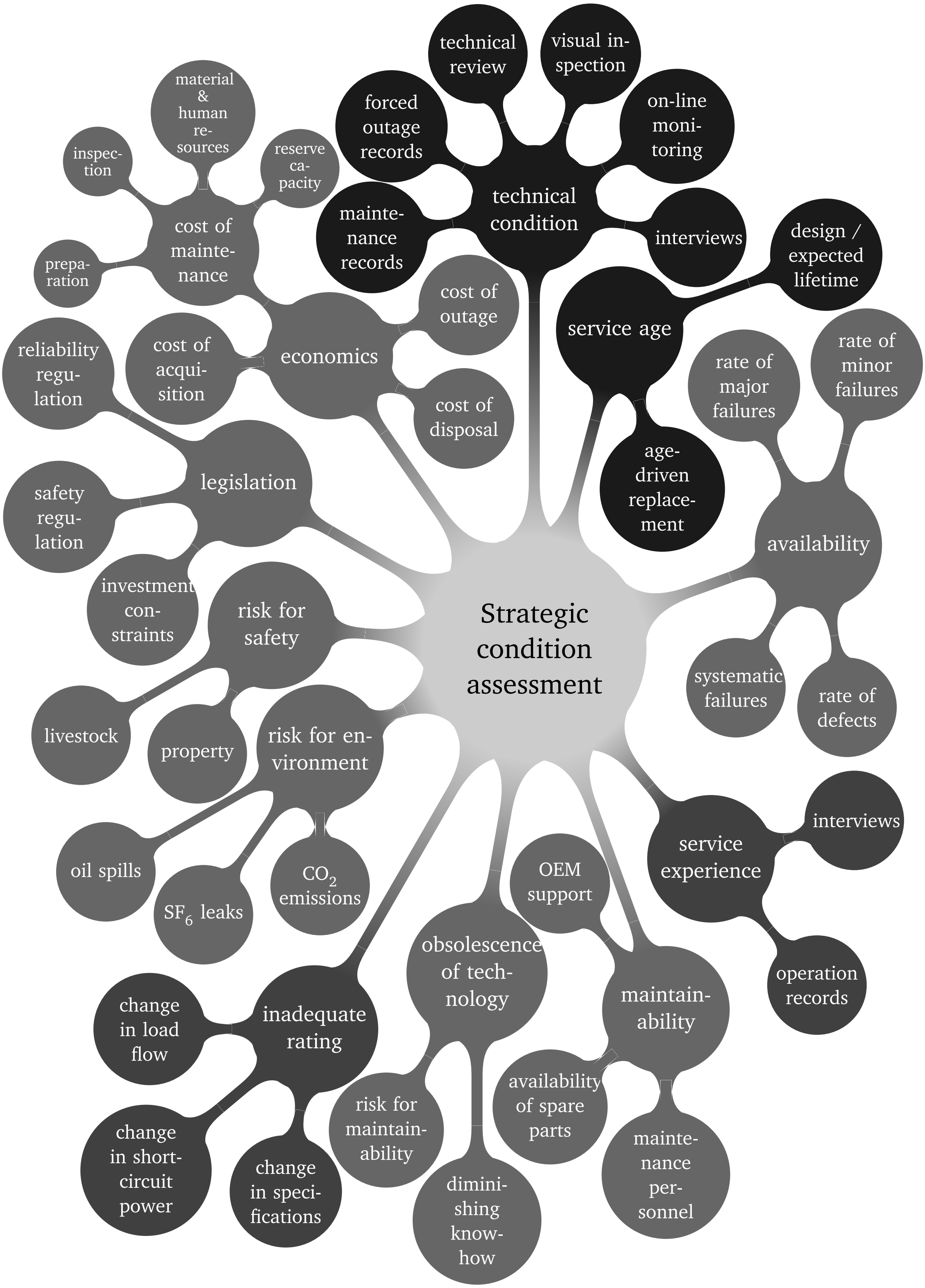


Figure 3.2.: Applicable condition indicators for strategic condition assessment. Dark colours denote device-specific information, light colours stand for type-specific information. Refer to page 48 for more information on the meaning of each indicator.

Technical condition: If the perspective of strategic condition assessment is device-specific, the technical condition of the equipment must be considered. Its determination is, however, performed at a lower-level within the scope of operational condition assessment, as will be shown in section 3.2.2. The information reflected in this CI originates primarily from the technical review of reports on inspection and maintenance activities as well as on forced outages. In case on-line monitoring systems are applied, the records of such systems must also be consulted. It is further recommended to conduct interviews with the maintenance personnel in order to capture unrecorded maintenance-specific knowledge.

Service age vs. expected lifetime: Despite the introduction of CBM as discussed in section 3.1, many utilities still base their decision on replacing a piece of equipment on its service age. Should it exceed the design or expected lifetime, the equipment is removed from service without considering whether it could be still operated and maintained. This rather reserved approach is the combined result of incomplete knowledge about failure mechanisms during the wear-out period with the general risk aversion of electric power companies. In case replacement is age-driven, this CI is of major importance for strategic condition assessment.

Equipment availability: This CI captures information on the rate of defects as well as minor and major failures. Since defects and failures are seldom events in electricity supply systems, average rates should be used with this indicator. This is the reason why it is seen as type-specific rather than device-specific. In this CI information of any systematic failures known to occur frequently for a specific type of equipment can also be captured.

Service experience: For the determination of the service experienced associated with a specific type of equipment or with a particular piece of equipment, interviews with the operators should be conducted. In addition, one should also consult any available operation records. This CI is of quite subjective nature, but should nevertheless be considered for strategic condition assessment since it reflects everyday satisfaction of operators with the equipment.

Maintainability: Maintainability of equipment is governed by several aspects, some of which can be influenced by the utility while others cannot. Factors that can be influenced by the utility are the preservation of important maintenance know-how in-house as well as the allocation of sufficient human and material resources for maintenance. On the other hand, the support of the Original Equipment Manufacturer (OEM) and the availability of spare parts are external factors, which however largely influence maintainability of equipment.

Obsolescence: A technology is regarded as *obsolete* if it is no longer state of the art and is not manufactured any more. Examples of obsolete technologies for high-voltage circuit breakers are bulk-oil breakers and air-blast breakers. The question of obsolescence is a central one for high-voltage equipment; due to its long lifetime and the continuous technological development in the field, every piece of equipment turns obsolete while still in service. However, equipment implementing obsolete technology may still perform well and respective maintenance skills may still be available within the utility. Nevertheless, obsolescence is a risk factor for maintainability, since OEM support could cease to exist in the future.

Inadequate rating: Changes in network topology, both with regard to load flow as well as short-circuit levels, can lead to situations at which a device is operated beyond its specifications. This effect is topology and thus device-specific. But also changes in standard specifications can lead to similar situations, only that this time all equipment of the same type is involved. In case of inadequate rating the equipment can be uprated, or, if this is not possible, it must be replaced; it can then be installed at some other location in the network or kept in cold backup for the event of an unplanned outage of similar equipment. The meaning of this CI is twofold: in a narrow sense it can be used to affirm or reject the question of whether the rating of a device is exceeded. In a broader sense it can reflect the risk that a specific type or a particular piece of equipment will be operated outside its specification in the future.

Risk for environment: This CI captures any potential negative effect of the equipment on the environment mainly in the event of a failure, but also during normal operation. Depending on the insulating system provided, catastrophic failures may cause oil spills (for oil-filled equipment where no oil containment is provided, typically for bulk-oil circuit breakers and instrument transformers) or SF_6 leaks (e.g. for gas-insulated switchgear). The aspect of CO_2 emissions due to power loss during normal service should also be addressed, although it is difficult to effectively assess emissions.

Risk for safety: Although safety is paramount, for the purpose of decision making it must be monetised and expressed as a risk. The CI summarises the risk exposure of the utility due to operation of the particular piece of equipment and compares this figure with the utility's target value for risk.

Legislation: Limitations defined by the regulatory environment may include upper bounds for the overall unavailability of the electric power system, penalties in case of service interruptions, or financial limitations with regard to the investment policy in the system. A more obvious example of the influence of regulation, however, is legal prohibition of materials used in equipment as with PCBs.

Economics: Economic analysis for the purpose of strategic condition assessment can be done at several levels e.g. for the cost of maintenance, cost of operation, cost of replacement etc. *Life-Cycle Costing* (LCC), a method widely used in the world of finance for determining the economic value of an investment, can be applied in order to sum up all cost factors over the complete lifetime of a piece of equipment. The life-cycle cost index can then provide a CI for strategic assessment. However, the investment for most devices installed in electric power systems has already been amortised, so that expenses are mainly driven by the cost of maintenance, both corrective (in response to unplanned outages) and preventive. Especially when assessing the cost of preventive maintenance activities care should be taken that all relevant cost factors are considered. These include [3.3]: the cost of preparation (switching and de-energising the equipment), the cost of inspections both visual and by means of measurements, the cost of measuring equipment, the cost of tools and spare parts, the cost of reserve capacity during the down-time of the equipment[8], and –most importantly– the cost of labour, accounting for approximately 75 % of the total cost of maintenance.

It is obvious that CIs for strategic condition assessment cover the whole range from technical to operational and financial indicators. It must also be stressed that some of the aforementioned CIs might overlap; for instance, the presence of systematic failures (e.g. increased partial discharges) for a specific type of equipment will influence not only its availability assessment,

8 For instance, disconnecting an overhead line for the purpose of preventive maintenance will cause the system to be operated off its optimal state, with subsequent power loss.

but also the associated service experience. However, when defining CIs one should strive to avoid such overlaps as much as possible.

The results of the international survey on end-of-life decisions by Cigré reported in [3.4] underlined the importance of four of the above CIs: When replacing equipment, most electric power utilities seem to be driven by a perceivable decrease in its availability or maintainability, an increase in the associated cost of service, or by a violation of its rating due to changes in the power system.

3.2.2 Indicators for operational condition assessment

Contrary to strategic condition assessment, operational assessment is performed at lower level with the purpose of supporting decision making for day-to-day maintenance. Possible objectives for decision making in this field could include: controlling the risk for unplanned outages, reducing the overall cost of maintenance, avoiding risk for safety or environment, implementing efficient schedules of upcoming maintenance activities, reducing or coordinating demand for spare parts, extending equipment lifetime etc. The scope of operational condition assessment thus accounts for the short and medium term and is rather device-specific than type-specific. In addition, the results of operational condition assessment are used as indicator for the technical condition of the equipment in the higher-level process of strategic assessment, as has been seen in section 3.2.1. The main actors in operational condition assessment are the service providers, collecting the information, and the asset manager, performing assessment and making decisions.

The general objective of the assessment is to understand the structural condition, performance, and progression of deterioration of the equipment (at the analytic stage) and express it by means of an index (at the synthetic stage which will be described in section 3.3). This section addresses the general approach for defining appropriate CIs for the purpose of operational condition assessment.

The sources of relevant information can be grouped into following categories: diagnostic tests of quantitative (measurements) or qualitative (visual inspections) nature, information about the stresses the equipment has been subjected to during service (loading profile), as well as quantitative and qualitative experience with maintenance of a specific type of equipment. Figure 3.3 graphically illustrates this categorisation. The different groups will be described here in brief:

Diagnostic tests: Diagnostic tests are measurements of a particular quantity of interest with the objective to detect abnormal or faulty conditions. The decision which diagnostic technique to use is very much equipment type-specific. For an example of common diagnostic techniques for high-voltage circuit breakers the reader can refer to section 5.2.1. Diagnostic tests are conducted either periodically in the course of maintenance or continuously by means of on-line monitoring systems. In order to account for effective data handling, many electric power companies have recently introduced personal digital assistants (PDAs) to substitute the older inspection forms. However, information on older measurements may still be on paper, and thus virtually unavailable for computer-aided condition assessment schemes.

Reports on visual inspections: Visual inspections[9] are qualitative diagnostic tests and their results is a *subjective* assessment of the equipment by the inspecting person. In order to

[9] A *visual inspection* is defined by IEC as an action which "identifies, without the use of access equipment or tools, those defects which will be apparent to the eye". On the other hand, a *detailed inspection* or simply inspection is

control the influence of the inspector on the inspection result, utilities usually have predefined inspection procedures which the maintenance personnel has to carry out and fill in, respectively. The results of visual inspections, although not as precise as diagnostic tests, are equally important for identifying failures and defects in service. As a matter of fact, the majority of failures in high-voltage power systems are detected by means of visual inspections.

Statistical information: Failure and maintenance statistics describe a quantitative approach to maintenance and service experience. Due to the low probability of minor and major failures in electricity supply systems, the information provided by failure statistics is averaged over many devices and is thus equipment type-specific rather than device-specific. Usually, the failure rate is expressed as a function of service time, although in some cases other correlations would seem to be more appropriate, as for example with circuit breakers where loading can be better expressed by the number of operations rather than by service time. Combined knowledge of statistical information and the loading profile of a particular piece of equipment (see below) can provide insight in its technical condition.

Experience of the maintenance personnel: Despite the efforts for systematic documentation in the field of maintenance, a significant amount of knowledge remains unrecorded. Interviewing the maintenance personnel allows for the integration of unrecorded knowledge

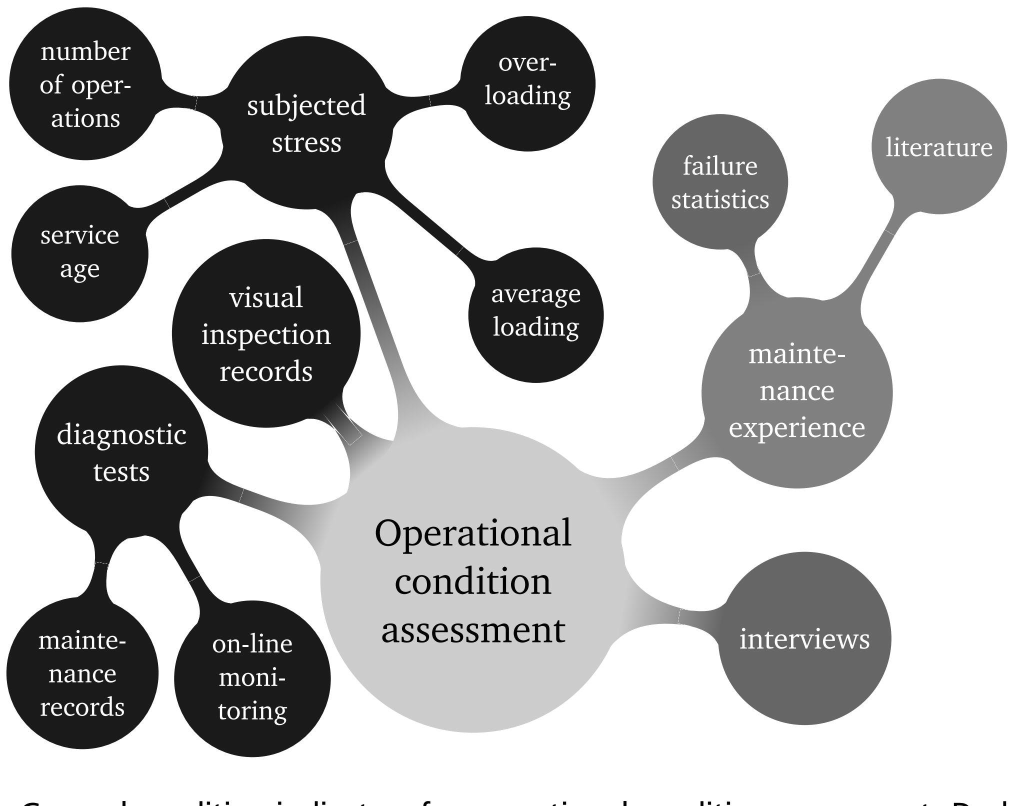


Figure 3.3.: General condition indicators for operational condition assessment. Dark colours denote device-specific information, light colours stand for type-specific information.

defined as an "action comprising careful scrutiny of an item carried out either without dismantling, or with the addition of partial dismantling as required, supplemented by means such as measurement, in order to arrive at a reliable conclusion as to the condition of an item". In this thesis, the term diagnostic test is used as equivalent to detailed inspection.

into the process of condition assessment. The personnel's point of view on common failure modes of the equipment, on life-limiting factors, or on the efficiency of diagnostic tests can prove to be an invaluable source of information[10].

Loading profile: The loading profile of a device is determined by the stress it has been subjected to during operation. An important indicator of accumulated stress, although by far not the only one, obviously is service age. This parameter is easy to determine and offers the advantage that it can be directly compared with the expected lifetime of the equipment. However, other sources of information might reflect accumulated stress more precisely. The average power loading of the equipment or the accumulated time during which the equipment has been operated very near to or beyond its specifications (overloading) are such examples. These parameters can be either estimated by an experienced operator or directly extracted from service statistics if available.

The process for defining valuable CIs for the purpose of operational condition assessment can be structured in two steps: First the most important or severe failure modes have to determined and then sources of information with regard to these failure modes must be identified. The

Identifying failure modes

Common failure modes
Which failure modes have been observed in the field?
Which of them have been most common?

Severe failure modes
Which failure modes pose a severe threat to safety and environment?
Which of them can be influenced by maintenance?

Life-limiting factors
Which are the most important life-limiting factors for the equipment?
Which of them are within the scope of operational condition assessment?

⇓

Identifying information sources for important failure modes

Diagnostic tests
What can be monitored?
What is being monitored?
What is the experience with the existing monitoring techniques (rate of fault detection)?

Loading profile
How does loading influence failure modes?
What information on loading is available?

Figure 3.4.: Identifying sources of information for operational condition assessment.

10 For example, in [3.19] a reliability model of a high-voltage circuit breaker is developed on the basis of interviews with the maintenance personnel about failure modes.

questions listed in figure 3.4 can assist throughout this process. In case a Failure Modes and Effect Analysis (FMEA) is available for the equipment, it can greatly assist in identifying the severity and relevance of failure modes. An example of FMEA applied to high-voltage circuit breakers can be found in [3.20].

3.3 Averaging information

The previous sections have addressed the process of analysis in condition assessment. Once appropriate CIs have been specified, the degree of compliance of the equipment with regard to each of the CIs can be evaluated. For condition assessment, these individual figures must then be aggregated into one single estimation by means of synthesis. Depending on the scope of condition assessment (strategic or operational) two terms are introduced here for this estimation:

Definition 3.3 *Asset condition index (ACI): The asset condition index is a composite index representing the result of strategic condition assessment.*

Definition 3.4 *Asset health index (AHI): The asset health index is a composite index representing the result of operational condition assessment.*

The above definitions largely adopt the point of view found in the literature regarding condition assessment. In particular, the term *asset health index* has already been used for this purpose [3.21–3.23]. In [3.16] an AHI is referred to as "one single overall indicator of the condition, derived from all available condition indicators, which expresses technical condition". Again in [3.14] the objective of AHIs is seen in "developing an understanding of the overall condition of the equipment". However, this perspective had to be broadened so as to also account for strategic condition assessment, since health strongly implies the equipment's technical condition. The decisions to introduce two distinct definitions for the result of condition assessment depending on its scope is mainly for reasons of clarification.

Generally speaking, AHIs are evaluated individually for every piece of equipment, while an ACI can be determined for a particular device, for a functional unit e.g. substation bay or even complete substation, or for a group consisting of devices of the same type. The practical implementation of synthesis in order to compute AHIs and ACIs is shown in the next sections.

3.3.1 The condition assessment matrix

The condition assessment matrix is a structured way of presenting CIs and computing the overall index from the individual degrees of compliance. It implements the concept of weighted averaging, featuring a weighting factor for each CI. The various CIs are arranged in the rows of the matrix, while the columns contain the individual degrees of compliance (or scores) c_i, the weighting factors w_i and the intermediate results $r_i = c_i \cdot w_i$ computed by the multiplication of the latter two. The basic layout of a condition assessment matrix is shown in table 3.3 for n condition indicators.

Sometimes the scorecards of the implemented CIs, i.e. the schemes for assessing the compliance of the equipment with them, are also included in the condition assessment matrix. In this way, the whole process of condition assessment can be represented within the matrix. Examples of condition assessment matrices for the assessment of high-voltage circuit breakers [3.4,

Table 3.3.: General structure of a condition assessment matrix featuring n condition indicators.

Condition Indicator	Score	Weight	Result
Condition indicator CI_1	c_1	w_1	$w_1 \cdot c_1$
Condition indicator CI_2	c_2	w_2	$w_2 \cdot c_2$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
Condition indicator CI_i	c_i	w_i	$w_i \cdot c_i$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
Condition indicator CI_n	c_n	w_n	$w_n \cdot c_n$

3.24] are given in appendix B.1, both for strategic as well as operational assessment (tables B.2 and B.1 respectively). In addition, the reader may refer to [3.25] for an overview of assessment matrices for equipment in the high-voltage electricity transmission network.

The resulting value for the composite index (AHI or ACI depending on the definition), is evaluated by the weighted mean, equation 3.1.

$$\text{composite asset index} = \frac{\sum_{i=1}^{n} w_i \cdot c_i}{\sum_{i=1}^{n} w_i} \tag{3.1}$$

It is further possible to include more than one level in a condition assessment matrix. In this case the score of each group of CIs at higher level is determined by the weighted mean of the corresponding CIs at lower level. An example for a multiple-level condition assessment matrix for strategic condition assessment of circuit breakers from [3.26] can also be found in appendix B.1, table B.3.

With regard to the values the composite asset index computed from equation 3.1 obtains, different approaches can be found in the literature. Some publications [3.24–3.27] request for the index to be in the range of 1–100, with 100 denoting the worst condition state, while others [3.16] define the index in the interval [0, 1] (or equivalently from 0 % to 100 %), with 1 being an indication of optimum condition. In this thesis the latter approach is chosen, since it is closer to most people's perception. The same scale is also used for the scores c_i with regard to each CI.

Obviously, condition assessment by means of an assessment matrix as in table 3.3 depends to a great extend on the choice of the weighting factors. The more CIs are involved, the more difficult it is to directly define the weighting factor for each CI. For this reason, pairwise comparison is usually applied in practice, as will be shown in the next section.

3.3.2 Determining weigths

The extent to which a CI influences the overall result of condition assessment depends on the weighting factor assigned to it: the higher the value of the weighting factor, the more influence does the particular CI exercise. While it would be easy for a maintenance expert to answer questions such as “which CI is most important to assessment?” or to distinguish between very important and not so important CIs, fine tuning the weighting factors is a difficult task, especially if the numbers of CIs to be considered is high.

A proven approach, originating from the research field of *multi-criteria decision analysis* (MCDA), is to compare two CIs at a time (pairwise comparison) and assess which one of them is more important and to what extent. This approach is used in the so-called *analytic hierarchy process* (AHP) which has been introduced by Saaty in the late 1970s. In the following the main features of AHP will be described; more detailed discussions can be found in [3.28–3.31].

Let us consider the comparison between the ith and jth indicator: If we already knew the weighting factors associated with them, we could find their ratio of importance a_{ij} as:

$$a_{ij} = \frac{w_i}{w_j} \tag{3.2}$$

A series of a_{ij} for all i, j is called *preference structure*. It can be expressed in matrix form as in equation 3.3.

$$\begin{array}{c c} & \begin{array}{cccc} \mathrm{CI_1} & \mathrm{CI_2} & \dots & \mathrm{CI_n} \end{array} \\ \begin{array}{c} \mathrm{CI_1} \\ \mathrm{CI_2} \\ \vdots \\ \mathrm{CI_n} \end{array} & \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} \end{array} = \begin{pmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{pmatrix} = \mathbf{A} \tag{3.3}$$

Performing right multiplication of $\mathbf{A}$ with the vector $\underline{w}$ containing the assumed weighting factors then yields:

$$\mathbf{A} \cdot \underline{w} = \begin{pmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{pmatrix} \cdot \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = n \cdot \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = n \cdot \underline{w} \tag{3.4}$$

Equation 3.4 represents a typical *eigenvalue* problem: if n is an eigenvalue of $\mathbf{A}$ then $\underline{w}$ is the *eigenvector* associated with it. On closer consideration of equation 3.3 we can observe that all rows can be expressed in linear dependence of only one of them, e.g. the first one. In other words, the rank of matrix $\mathbf{A}$ is one, and there exists only one non-zero eigenvalue λ, which at the same time is the principal[11] eigenvalue λ_{max}. The normalised principal eigenvector associated with it can be found by scaling vector $\underline{w}$ so that the sum of its entries equals one.

[11] The *principal* eigenvalue of a matrix is the largest eigenvalue, in case more than one exist.

A matrix as in equation 3.3 is said to be reciprocal, since $a_{ij} = 1/a_{ji}\ \forall i,\ j = 1,\ldots,n$, and consistent, since $a_{jk} = a_{ik}/a_{ij}\ \forall i,\ j,\ k = 1,\ldots,n$. The fact that **A** is consistent is not surprising, as we have assumed consistency when defining the ratios of importances in equation 3.2. During the practical implementation of AHP, however, the weights are not known a priori, so we have to assess each ratio a_{ij} according to our perception, belief, or expectation.

This will in general lead to inconsistency in the resulting matrix **A**. Some inconsistency is always inherent in multi-criteria decision analysis, so AHP generally allows it. In addition, AHP provides a measure of how inconsistent a preference structure is, called *consistency ratio* (CR). Its calculation is based on finding the distance between the principal eigenvalue λ_{max} of the –generally inconsistent– preference matrix **A** and its principal eigenvalue in case it were to be consistent (the latter is equal to the *size* of **A**, compare [3.31]). This figure is then scaled as $(\lambda_{max} - n)/(n-1)$ and compared to the same index obtained as an average over a large number of reciprocal matrices of the same order whose entries are random. The resulting ratio is then CR; if it is below 10 % inconsistency can be in general accepted.

The general procedure with AHP will be shown by means of a simple example.

Example 3.1 *Let us consider the preference structure given in following matrix* **A**. *We want to evaluate the weights associated with each CI.*

$$
\begin{array}{c}
 \\ \mathrm{CI}_1 \\ \mathrm{CI}_2 \\ \mathrm{CI}_3 \\ \mathrm{CI}_4 \\ \mathrm{CI}_5
\end{array}
\begin{array}{c}
\begin{array}{ccccc} \mathrm{CI}_1 & \mathrm{CI}_2 & \mathrm{CI}_3 & \mathrm{CI}_4 & \mathrm{CI}_5 \end{array} \\
\begin{pmatrix}
1 & 5 & 3 & 7 & 6 \\
1/5 & 1 & 1/3 & 5 & 3 \\
1/3 & 3 & 1 & 6 & 3 \\
1/7 & 1/5 & 1/6 & 1 & 1/3 \\
1/6 & 1/3 & 1/3 & 3 & 1
\end{pmatrix}
\end{array}
= \mathbf{A} \tag{3.5}
$$

The values in the above matrix have following meaning:

$a_{ij} < 1$: The i^th^ indicator is less important than the j^th^ one, and the smaller the value for a_{ij} the less important it is.

$a_{ij} = 1$: Both indicators are equally important for the assessment.

$a_{ij} > 1$: The i^th^ indicator is more important than the j^th^ one, and the larger the value for a_{ij} the more important it is.

Typically, factors from 1 to 9 are used, as behavioural studies have shown that human perception cannot differentiate between more than 7 ± 2 alternatives [3.31].

In the first step, we have to calculate the eigenvalues and eigenvectors of **A**. This can be done either by solving the characteristic polynomial of **A**, which however is not easy if the dimension of **A** exceeds four, or by using the method of power iterations. In our case we use MATLAB® and obtain –after normalising the eigenvectors– the results in table 3.4. The first column contains the principal eigenvalue and eigenvector of matrix **A** and is thus the answer to our question.

The principal eigenvalue of **A** is approximately equal to 5.23, compared to the theoretically feasible value of 5 if the matrix were to be absolutely consistent. In the second step we need to also calculate the value for the CR. The consistency index for matrix **A** equals:

$$\frac{\lambda_{max} - n}{n-1} \approx \frac{5.2294 - 5}{4} = 0.0749$$

Table 3.4.: Eigenvalue analysis for example 3.1. Only the principal eigenvalue and the corresponding eigenvector is considered.

Parameter	Solution 1	Solution 2 & 3	Solution 4 & 5
Eigenvalue	5.2994	$0.0115 \pm 1.1976\,\mathrm{i}$	$-0.1612 \pm 0.3659\,\mathrm{i}$
Weighting factor w_1	0.5018	$0.8905 \mp 0.4058\,\mathrm{i}$	$1.6925 \mp 0.5788\,\mathrm{i}$
Weighting factor w_2	0.1401	$-0.1105 \pm 0.2884\,\mathrm{i}$	$0.0765 \mp 0.4782\,\mathrm{i}$
Weighting factor w_3	0.2435	$0.3748 \pm 0.2009\,\mathrm{i}$	$-0.8704 \pm 0.8542\,\mathrm{i}$
Weighting factor w_4	0.0385	$-0.0373 \mp 0.0764\,\mathrm{i}$	$-0.1332 \mp 0.0971\,\mathrm{i}$
Weighting factor w_5	0.0761	$-0.1175 \mp 0.0070\,\mathrm{i}$	$0.2346 \pm 0.3000\,\mathrm{i}$

Averaging the respective index for 10^5 randomly generated preference matrices of size $n = 5$ returns a value of 1.0368. The consistency index is thus approximately equal to 7.22 %, which indicates sufficient consistency in the preference matrix. ■

The above example illustrates the procedure for computing weighting factors according to AHP. However, most assessment schemes found in the literature use simplified versions of AHP. In [3.26, 3.27] the preference matrix has a somehow different structure than the one above, with its parameters having values in the range between 1 and 5 with following meanings:

$a_{ij} < 3$: The i$^{\text{th}}$ indicator is less important than the j$^{\text{th}}$ one, and the smaller the value for a_{ij} the less important it is.

$a_{ij} = 3$: Both indicators are equally important for the assessment.

$a_{ij} > 3$: The i$^{\text{th}}$ indicator is more important than the j$^{\text{th}}$ one, and the larger the value for a_{ij} the more important it is.

In addition, the parameters in the main diagonal are all set equal zero. The weighting factors for each CI are then evaluated by summing up the entries in the respective row and then dividing by the total sum of the entries in the matrix, as shown in equation 3.6.

$$w_i = \frac{\sum_j a_{ij}}{\sum_{i,j} a_{ij}} \quad i, j = 1, \ldots, n \tag{3.6}$$

The main difference between this approach and the previously described AHP is that it does not consider indirect dominance of one CI over another. In other words, the mode of reasoning "if indicator i is more important than j and indicator j is more important than k, then indicator i is more important than k" cannot be implemented.

In [3.25] the approach is simplified even more by only counting the frequency of dominance of one indicator over another, and then dividing by the total number of pairwise comparisons (each comparison is counted only once, though). Equation 3.6 is again used, but parameter a_{ij} is now equal 1 if the i$^{\text{th}}$ indicator is more important than the j$^{\text{th}}$ one, otherwise zero.

At this point we shall revisit example 3.1 and investigate the results we would obtain with the two alternative approaches. For this reason, however, the preference structure must be adjusted accordingly, as can be seen in equation 3.7.

$$\mathbf{A}_1 = \begin{pmatrix} 0 & 4 & 3 & 5 & 4 \\ 2 & 0 & 3 & 4 & 3 \\ 3 & 3 & 0 & 5 & 3 \\ 1 & 2 & 1 & 0 & 3 \\ 2 & 3 & 3 & 3 & 0 \end{pmatrix} \quad \mathbf{A}_2 = \begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix} \tag{3.7}$$

The resulting weighting factors are given in table 3.5 in direct comparison with the values obtained before with the AHP. Although the ranking of the CIs in terms of their importance remains the same, the weighting factors differ a lot, and this will influence the assessment result. It should be further noted that the two simplifications presented here lack the well-founded discussion AHP has gone through. It is therefore recommended, when identifying appropriate weights for the CIs in the condition assessment matrix to use the original analytic hierarchy process.

Table 3.5.: Weighting factors for example 3.1, as obtained by the AHP and its simplifications.

CI	AHP	Alternative 1	Alternative 2
1	0.5018	0.2667	0.4000
2	0.1401	0.2000	0.2000
3	0.2435	0.2333	0.3000
4	0.0385	0.1167	0.0000
5	0.0761	0.1833	0.1000

However, some limitations are inherent to multi-criteria decision problems featuring a preference structure as in equation 3.3. This shall be illustrated on a theoretical basis by a brief excursion into the research field of multi-criteria decision analysis.

3.4 Excursus: multi-criteria decision analysis

The question of condition assessment is a problem of multi-criteria decision analysis (MCDA), with the CIs being the criteria and the composite index being the decision. Without delving into the research area of MCDA, this sections will highlight some important theoretical aspects in order to identify inherent limitations in condition assessment.

The discussion is largely based on the famous impossibility theorem introduced and proven in [3.32] by Kenneth Arrow, an American political theorist, economist and Nobel Prize winner in economics. In its initial notation it addresses the topic of *social welfare*, that is of the process of deriving a collective or social choice from individual values or preferences. The analogy to MCDA is obvious, since substituting the individual values by criteria and the social choice by decision defines a multi-criteria decision problem.

A common paradox of social choice is voting. Several voting paradoxes are known, with the example given by de Concordet being the most famous. De Concordet's paradox describes a situation, where collective preference is cyclic and thus non-transitive, although the preference of individual voters is not, as can be seen from table 3.6.

Let us have a closer look at table 3.6 and identify non-transitivity. If we assume that society decides by majority, we can see that alternative A is preferred to B by 2:1 votes. Majority further prefers alternative B to C also by 2:1 votes. Transitivity would require that alternative A is then preferred to C. However, this is not valid: in fact, the majority prefers alternative C to A by 2:1 votes.

Table 3.6.: De Concordet's voting paradox.

Voter	1st choice	2nd choice	3rd choice
1	A	B	C
2	B	C	A
3	C	A	B

Non-transitivity is not the only problem in social choices. For instance, another problem is the dependence of collective choice on irrelevant alternatives. This situation is also known from voting: in run-off elections, the withdrawal of a third candidate who was not preferred to neither of the remaining two can change the preference structure between the latter and influence the voting result.

In [3.32] Arrow shows that such problems occur due to fundamental limitations in social choices. He uses the term *social welfare function* to describe the process of aggregating individual preferences and assigns following properties to it:

Unrestricted domain: The function is universally defined. There are no certain preferences that individuals can have that cause the function to be indeterminate. For any set of individual voter preferences, the social welfare function should yield a unique and complete ranking of societal choices

Monotonicity or positive association of social and individual values: If any individual modifies its preference order in favour of an alternative, then the societal preference order should respond only by promoting that same alternative or not changing, but not by ranking it lower than before.

Independence of irrelevant alternatives (IIR): The societal ranking within a subset of alternatives should be the same as it would be for that subset within the complete set of alternatives. Adding or removing an alternative should not affect the ranking of other alternatives.

Citizens' sovereignty: The function has unrestricted co-domain: there are no societal preferences which cannot be achieved no matter what the individual preference orders are. This also implies that society cannot *impose* a preference on an individual.

Non-dictatorship: There is no individual preference that determines the outcome of the function regardless of all other individual preferences. The function is not allowed to simply mimic one person's preferences.

Arrow proves that for any social welfare problem involving more than two individuals and three alternatives, not all of the above properties can be satisfied at the same time. His proof is made by contradiction, but will not be presented here. The reader may refer to [3.32] for more information.

The main conclusion of Arrow's impossibility theorem is that "if we exclude the possibility of interpersonal comparisons of [satisfaction], then the only methods of passing from individual tastes to social preferences which will be satisfactory and which will be defined for a wide range of sets of individual orderings are either imposed or dictatorial."

Another way of formulating this conclusion is that there exists no fair (non-dictatorial and non-imposed) procedure for deriving a group preference from individual preferences by voting which is not independent of irrelevant alternatives. Exactly the question of IIR is a central one in MCDA. It is commonly referred to as *rank reversal* meaning that the overall preference structure can be influenced by adding or removing an irrelevant alternative. Generally speaking, this property is considered as inconsistent decision making and is undesired, although some researchers argue that it reflects reality[12].

Summing up our brief excursus, we have seen that the aggregation of more than one criteria has some inherent limitations which we by definition cannot get rid off.

3.5 Limitations of existing assessment methods

The theoretical discussion in the previous section showed that limitations in multi-criteria assessment originate from the process of synthesis, and not from the preceding analysis. In this section some practical examples are provided which illustrate the most important limitations of synthesis, as described in section 3.3. In particular, we shall examine the efficacy of condition assessment matrices when treating missing or uncertain information input.

3.5.1 Unavailable information

Situations where some source of information is unavailable is not uncommon in condition assessment. For instance, due to the periodic nature of visual inspections and diagnostic tests, information regarding a particular CI may be available only for some pieces of equipment, but not for all. Similar issues may occur when we wish to aggregate information from on-line monitoring systems (continuously available) and from diagnostic tests for which the time interval for information retrieval might amount up to one decade.

Another reason for missing information is incorrect data handling. Although power utilities strive to keep data bases complete and up-to-date, this seldom is the case: redundancy in data, fragmented data bases as well as inappropriate design of data bases (so that not all relevant aspects can be captured) will in general lead to errors introduced during data handling.

But even a faultless data handling system can only reflect the information entered; in many cases, however, information e.g. from visual inspections is available only on paper and not to a computer-aided information management system. Such “hidden” information is usually useless for condition assessment, as the decision maker cannot possibly delve into searching for individual records which might, or might not contain indications of the equipment’s condition.

The central question is whether and how the condition assessment matrix should react to missing information. Keeping in mind that information will be missing only for some, but not for all units, and that on the other hand the results of condition assessment are often used in order to compare the condition of different units among each other, the problem is even more

[12] For instance, Forman and Gass distinguish in [3.30] between two types of systems: in *closed* systems resources are limited so that scarcity is germane. In their opinion, when resources are scarce there cannot be any irrelevant alternative, since every alternative claims resources which are no more available for other alternatives. As an example, they describe a voting situation at which an independent candidate might appeal more to the voters of one of the two major parties, so that his candidature influences the outcome though his chance of being elected is negligible. Contrary to closed systems, in *open* systems resources are unlimited so that rank reversal due to irrelevant alternatives should not be allowed to occur.

complicated: Should there be *only one* condition assessment matrix or should the matrix be rather adjusted according to the input information available; and if yes, then how?

Obviously, the weighting factors play an important role here, since they describe the relative importance of each CI compared to every other CI. Let us therefore recall the procedure for determining weights, as described in section 3.3.2. We will consider only the AHP here, but the implications are valid for its simplifications as well.

Suppose that we have a preference structure as the one given in equation 3.8. By applying AHP we obtain the results shown in the first column of table 3.7 for the weighting factors. According to this table, the third and fourth CI are almost equally important, with the third one being marginally more important.

$$\begin{array}{c c} & \begin{array}{ccccc} \mathrm{CI}_1 & \mathrm{CI}_2 & \mathrm{CI}_3 & \mathrm{CI}_4 & \mathrm{CI}_5 \end{array} \\ \begin{array}{c} \mathrm{CI}_1 \\ \mathrm{CI}_2 \\ \mathrm{CI}_3 \\ \mathrm{CI}_4 \\ \mathrm{CI}_5 \end{array} & \left(\begin{array}{ccccc} 1 & 1 & 1/7 & 4 & 1 \\ 1 & 1 & 2 & 1/6 & 4 \\ 7 & 1/2 & 1 & 5 & 1/5 \\ 1/4 & 6 & 1/5 & 1 & 8 \\ 1 & 1/4 & 5 & 1/8 & 1 \end{array}\right) = \mathbf{A} \end{array} \tag{3.8}$$

Imagine now following situation: we want to assess the condition of two units by using a condition assessment matrix whose weights should be determined by the preference structure in equation 3.8. For the first unit the degrees of compliance with each of the five CIs have been evaluated, but for the second unit relevant information for determining the compliance with the first indicator was not available. For this reason, only the scores for CI two to five could be assessed. The question now is: which weights should be used for assessing the overall condition of each unit?

The first approach would be to use the weights as initially computed by the AHP (table 3.7, first column) and evaluate the weighted mean (equation 3.1). However, what value of the first indicator should we assume for the second unit? We could assume a value of $c_1 = 0$, but this would result to a significant bias in the result. Imagine for example that all other CIs indicate a flawless condition, i.e. $c_i = 1 \quad \forall i = 2, \ldots, 5$. The maximum value for the composite indicator of the second unit would then be:

$$\text{composite asset index} = \frac{\sum_{i=1}^{5} w_i \cdot c_i}{\sum_{i=1}^{5} w_i} = \frac{\sum_{i=2}^{5} w_i}{\sum_{i=1}^{5} w_i} = 0.8505 \tag{3.9}$$

By choosing $c_1 = 0$ (or any other arbitrary value) for the score of the first CI we introduce a bias into the composite index. Hence, comparing the condition of the two units by means of the composite index does no more make sense.

A second approach would be to “turn off” the CI for which information is missing when evaluating the composite index for the second unit. In this way, we can ensure that the co-domain of the composite asset index remains in the interval $[0, 1]$.

For this purpose equation 3.1 has to be modified to:

$$
\text{composite asset index} = \frac{\sum\limits_{i \neq 1} w_i \cdot c_i}{\sum\limits_{i \neq 1} w_i} \tag{3.10}
$$

This modified computation removes the bias and relieves us of the problem what value to choose for c_1. However, there is a –somewhat philosophical– question which remains: Does the preference structure we have provided in equation 3.8 still coincide with the modified weighting vector, which we obtain by just removing the entry for w_1?

The answer to this question is no, at least not necessarily. In order to prove this, we will re-run AHP on the preference structure of equation 3.8 after we have removed the row and column corresponding to the indicator for which information is missing. This is in accordance to the fundamental approach of AHP, where we pairwise assess the relative importance of criteria. Equation 3.11 shows the modified preference structure:

$$
\begin{array}{cc}
 & \begin{array}{ccccc} \cancel{\mathrm{CI}_1} & \mathrm{CI}_2 & \mathrm{CI}_3 & \mathrm{CI}_4 & \mathrm{CI}_5 \end{array} \\
\begin{array}{c} \cancel{\mathrm{CI}_1} \\ \mathrm{CI}_2 \\ \mathrm{CI}_3 \\ \mathrm{CI}_4 \\ \mathrm{CI}_5 \end{array} &
\begin{pmatrix}
\cancel{1} & \cancel{1} & \cancel{1/7} & \cancel{4} & \cancel{1} \\
\cancel{1} & 1 & 2 & 1/6 & 4 \\
\cancel{7} & 1/2 & 1 & 5 & 1/5 \\
\cancel{1/4} & 6 & 1/5 & 1 & 8 \\
\cancel{1} & 1/4 & 5 & 1/8 & 1
\end{pmatrix}
\end{array} = \mathbf{A}_{\sim 1} \tag{3.11}
$$

Condition indicator 1 is thus no longer of importance. Applying AHP on the above preference structure returns the modified weights listed in the second column of table 3.7. The same procedure has been applied by assuming that any other CI is removed one at a time, and the results are also listed there.

The findings are remarkable! We can observe that, although the third and fourth CI are almost equally important when all indicators are considered, removing any other indicator can change this situation in favour of one of them. This is the more likely to happen, the more inconsistent the assumed preference structure is.

We may reformulate this aspect by analogy to the question of irrelevant alternatives described in section 3.4: Removing an irrelevant alternative changes the rank of the remaining alternatives. The inherent problems associated with any multi-criteria decision problems are also evident in condition assessment. This is an important aspect one should always keep in mind when assessing the condition of equipment by means of a condition assessment matrix.

Table 3.7.: The problem of missing information during weight determination.

CI	all inputs	without CI_1	without CI_2	without CI_3	without CI_4	without CI_5
1	0.1495	–	0.1714	0.3644	0.1344	0.1810
2	0.1723	0.2046	–	0.1651	0.3742	0.2146
3	0.2586	0.2534	0.3292	–	0.2233	0.3834
4	0.2578	0.3613	0.2606	0.3771	–	0.2211
5	0.1618	0.1807	0.2388	0.0934	0.2681	–

3.5.2 The question of uncertainty

Another limitation of the condition assessment process, as it is applied in practice, is related to the structure used to compare information on a particular CI with the associated reference values. The result of this comparison is the degree of compliance c_i which is used in the assessment matrix. In section 3.2 we have already stressed the need for reference values as well as for an appropriate mechanism for comparison of available data with those, but we did not yet discuss the design of this mechanism.

The most common method of assessing the degree of compliance is by means of a *score card*. An example of a score card associated with the indicator "mean failure rate (minor and major) per annum" in condition assessment of circuit breakers is extracted from [3.26] and shown in table 3.8. The major advantage of score cards is that they represent the underlying knowledge and experience with the particular CI in a very compact and comprehensive way, so that misinterpretation can be avoided.

Table 3.8.: Example of a score card [3.26].

Failure rate p.a.	Score
$\leq 10\,\%$	1
$10 - 20\,\%$	2
$20 - 30\,\%$	3
$30 - 40\,\%$	4
$40 - 50\,\%$	5
$\geq 50\,\%$	6

However, they also have their drawbacks. The first limitation is related to the level of precision: The more detailed the analysis should be, the more classes must a score card implement. However, beyond a certain point analysis is turning to be more confusing, the more alternatives we introduce. Behavioural studies therefore suggest a maximum number of 7 ± 2 classes. In the words of Zadeh from the beginning of chapter 2: "As the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes".

This constraint with regard to the number of classes implemented in a score card brings us also to their second limitation, which will be described by means of a short example based on table 3.8: Imagine that we have three units whose failure rate we known as $h_1 = 19\,\%$, $h_2 = 22\,\%$ and $h_3 = 29\,\%$. According to table 3.8, the first unit would be rated with a 2, while units two and three would both receive a 3. From the scoring it would seem as if the condition of the latter two units were more alike, than the condition of the first and second unit. However, in reality the opposite is the case. This problem originates from the *sharp boundaries* of the classes in the score card [3.33].

The third drawback is related to the treatment of uncertainty by a scorecard. For instance, imprecise knowledge of the failure rate of a unit would prohibit us from choosing a score from table 3.8, although we could still have a general perception of the matter (we could e.g. regard the unit as having a rather low failure mode). Uncertainty could further originate from inaccuracy in measurement, this aspect being important when assessing the result of diagnostic tests by means of a score card.

In order to overcome the limitations of traditional condition assessment schemes, the introduction of fuzzy systems for this purpose is proposed in this thesis. The next two chapters provide case studies for the strategic and operational assessment of the condition of high-voltage circuit breakers based on fuzzy logic.

4 Strategic condition assessment of circuit breakers

> The underlying principles of strategy are enduring, regardless of technology or the pace of change.
>
> Michael Porter, Harvard Business School

One of the primary objectives of strategic assessment is to support decision making on major maintenance activities, mainly refurbishment and replacement. Such activities require a long lead project time and are associated with high cost. For this reason, asset managers use asset condition indices (ACIs) in order to rank the equipment and its needs; the ranking is then the basis for planning replacement or refurbishment as well as for claiming the necessary financial budget from the asset owner.

This chapter presents a fuzzy system for strategic assessment of the condition of high-voltage circuit breakers. The study has been conducted in cooperation with a German transmission system operator (TSO) in an attempt to extend the existing condition assessment scheme by fuzzy techniques. The existing scheme for strategic condition assessment in the particular TSO is carried through centrally by one maintenance expert with extensive knowledge of high-voltage switching equipment. It is equipment type-specific and assigns a value between 1 and 4 to the ACI of each type, with 1 being the best assessment result, and 4 being a recommendation for replacing all equipment of this type in the medium term. Information considered to be relevant to the process includes the availability of spare parts, the asset manager's satisfaction with the support by the manufacturer, known reliability issues for a specific type etc. These sources of information constitute the CIs for condition assessment; the corresponding degrees of compliance for each breaker type are determined manually by the maintenance expert.

Extending the condition assessment scheme by fuzzy logic shall assist in structuring the existing knowledge base and making it available to other participants in maintenance decision making throughout the utility. It should further help remove the limitations of condition assessment matrices discussed in the previous chapter.

The outline of this chapter follows the approach taken during the development of the fuzzy system. In the first section technological aspects of high-voltage circuit breakers are discussed and the different types of switching technology are assessed. Section 4.2 addresses service and maintenance experience with the various circuit breaker types and manufacturers. The last module of the fuzzy assessment scheme is described in section 4.3 and deals with the expected cost of maintenance for each breaker type. For each of the three modules a fuzzy rule base is defined; the final step of putting all parts together is described in section 4.4.

4.1 Assessing technology

A *circuit breaker* (CB) is defined by IEC 60050 as "a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit" [4.1]. The main function of circuit breakers is thus to establish or break connections in the electricity supply. This might be desired so as to control power flow in the system, clear system faults, or in order to de-energise an apparatus as a prerequisite for preventive maintenance actions. Practical applications of high-voltage circuit breakers (HVCBs) include switching of equipment (overhead lines, cables, power transformers, reactors and capacitors) as well as busbar switching.

Generally speaking, all HVCBs consist of five functional groups, no matter the technology applied. These are:

Drive (or operating) mechanism: responsible for storing the energy needed for switching, and converting this stored potential energy into kinetic energy, thereby moving the contacts of the circuit breaker,

Current-carrying (or live) parts: mainly the main contacts and the terminal connections, responsible for carrying the current when the breaker is in closed position,

Insulating system: providing both inner (when in closed position) and outer insulation (between phases and between phase and earth, both in open and closed position),

Interrupter: responsible for quenching the arc evolving during switching, and

Control unit: responsible for monitoring the state of the circuit breaker, and releasing the operating mechanism on command, thus initiating a switching operation.

The design of HVCBs is modular, and several interrupters can be connected in series so as to master higher voltages. State-of-the-art circuit breakers can switch system voltages up to 300 kV and short-circuit currents up to 50 kA with only one interrupter; for higher voltages and/or short-circuit currents more than one interrupters are required [4.2]. In this case voltage grading capacitors must be connected in parallel to the interrupters, since otherwise they would be unequally stressed by the electric field when the CB is in open position (for instance, the system-side interrupter of a two-stage live-tank[1] circuit breakers is stressed by approximately 80 % of the line voltage).

During a switching operation, the moving contacts of the interrupter must be closed or opened within a very short time interval, to ensure that the resulting arcing time and thus the wear of the contacts is kept at a minimum. The large amount of energy needed for the acceleration of the moving parts (in the range of several tens of kJ [4.2]) implies that it must have been stored as potential energy prior to operation. The main task of the operating mechanism is to store the required potential energy and –upon command– turn it into kinetic energy, thus accelerating the contacts. In addition, the energy stored within the operating mechanism at any time must

1 A *live-tank* circuit breaker has its interrupter(s) in a tank insulated from earth, for example inside a porcelain housing. On the other hand, *dead-tank* circuit breakers feature an earthed metallic tank enclosing the interrupter(s). Typical examples for live and dead-tank circuit breakers are air-blast and bulk-oil breakers, respectively (refer to sections 4.1.1 and 4.1.2). In general, the live-tank principle is widely accepted by European utilities, whereas in North America and Japan dead-tank breakers are more common.

suffice for at least opening the contacts autonomously i.e. without intermediately charging the energy storage. In this regard, IEC specifications define so-called *switching cycles* for HVCBs.

Over the past century, the technology both for interrupters and drive mechanisms has evolved significantly. These two aspects (switching and drive technology) are closely related, since the applied switching principle defines the amount of energy needed. Figure 4.1 graphically shows the evolution of switching principles in high-voltage engineering. As can be seen, HVCBs can be grouped into one of following categories: air-blast breakers, bulk and minimum-oil breakers, and single or double-pressure SF_6 breakers.

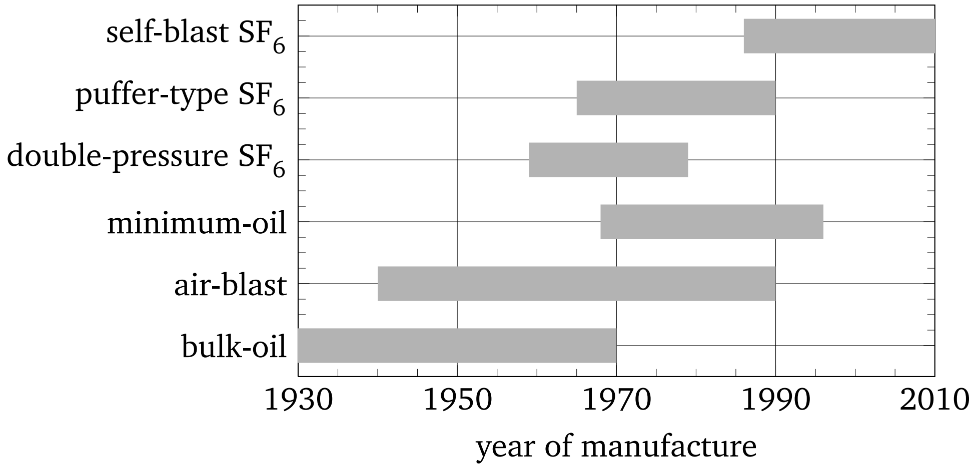


Figure 4.1.: Historical perspective of switching principles applied in high-voltage engineering. The bars denote the time periods during which circuit breakers implementing the particular switching principle have been manufactured; many of the devices, even of older technology, are still in service. Data collected from [4.2–4.4].

In the network of the particular TSO no circuit breakers of the bulk-oil type are installed. This technology will be therefore neglected in the following discussion. The remaining switching principles and the experience associated with them will be discussed in sections 4.1.1 to 4.1.3.

4.1.1 Air-blast circuit breakers

Air-blast circuit breakers are the oldest group of switching equipment installed in the German electricity transmission system. Their manufacture ceased in the late 1980s and no circuit breakers of this type have been installed since. Initially air blast circuit breakers displaced bulk-oil circuit breaker application in HV engineering, largely because of their higher continuous and interrupting current capability [4.3]. In the 1960s, air blast circuit breakers opened the door to higher voltage levels (system voltage 400 kV upwards). Nowadays, the air-blast switching technique is considered to be obsolete, although a significant number of devices are still in service, especially in the extra high voltage level.

The principal layout of air-blast circuit breakers is shown in figure 4.2. Arc quenching in air-blast circuit breakers is encompassed by a blast of compressed atmospheric air which is directed into the region of the arc. Expansion of the compressed air as well as the resulting air flow draw energy off the arc, thus cooling it down and deionising the air-break gap. Air-blast circuit breakers are double-pressure devices: The air flow is caused by a difference in pressure established before the opening operation of the circuit-breaker. For this purpose, atmospheric

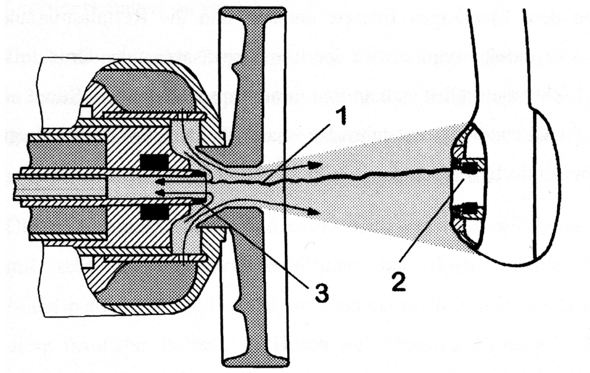


Figure 4.2: Arc quenching in air-blast circuit breakers [4.11]. Upon operation, compressed air is directed through a nozzle to the atmosphere thereby cooling down the arc.
Legend: 1 switching arc, 2 stationary contact, 3 moving contact.

air is compressed by an air-compressing unit and stored in a pressure tank at pressure level of up to 30 bar. When the command for switching is given, magnetic valves open and let the compressed air flow through a nozzle to the atmosphere. Compressed air stored in the main pressure tank is at the same time the source of energy for moving the contacts of the circuit breaker (pneumatic drive). In order to prevent condensation of the compressed atmospheric air, the main tank has to be heated.

The requirement for external pressure tanks as well as the need to connect several interrupters in series in order to master high short-circuit currents and high voltage levels make the layout of air-blast CBs rather complex, and have an adverse effect on overall reliability. The high noise emission during switching is a further disadvantage of air-blast CBs.

Their main drawbacks, though, are extremely high requirements for maintenance and servicing (off-line condition monitoring and diagnostic test are recommended in time intervals of three years [4.3]), partial unavailability of spare parts, and the dwindling maintenance know-how. For these reasons, the replacement of air-blast CBs is recommended.

4.1.2 Minimum-oil circuit breakers

From a historical perspective, oil circuit breakers have been the first design of a circuit breaker for high power applications [4.4]. Presently there are still many oil CBs in service, although the design has turned obsolete by the introduction of SF_6 technology.

The switching principle of oil CBs is quite simple. The energy dissipated by the switching arc decomposes the oil at very high temperatures (5,000–15,000 K), thereby generating hydrogen. The arc therefore burns within a hydrogen bubble, with the advantage that –due to the very good thermal conductivity of hydrogen in the aforementioned temperature range– it is effectively cooled and eventually extinguishes. This process can be further enhanced by means of appropriate design, which uses the energy dissipated by the arc to establish an oil flow in the switching chamber, as shown in figure 4.3. In the case of small interrupted currents, however, the energy of the arc is not sufficient to force an oil flow; for this purpose, a piston, directly connected to the moving contact, pumps the oil in the chamber during opening and supports arc quenching.

Oil circuit breakers in European electricity transmission systems have been primarily of the minimum-oil type: Contrary to bulk-oil CBs, minimum-oil breakers use oil only for the interrupting function while solid insulating materials are used to provide insulation to ground, this design being therefore a live-tank design.

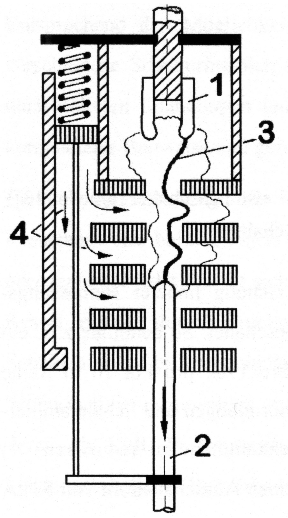


Figure 4.3: Arc quenching in minimum-oil circuit breakers [4.11]. The switching arc allows for the oil to vaporise and the increase in oil pressure forces the oil to circulate. The interaction of inflowing, cool oil with the arc causes the latter to cool down and finally extinguish.
Legend: 1 stationary contact, 2 moving contact, 3 switching arc, 4 oil flow by piston pump.

All types of drive mechanisms have been used for minimum-oil CBs. When the required energy for switching is not too high, spring-operated, mechanical mechanisms can be applied. They consist of closing and opening springs as energy storage, a charging motor and a charging ratchet to charge the springs, a cam disk which transforms the linear expansion of the springs into rotatory movement, and mechanical linkages to the contacts of the CB [4.12].

Minimum-oil circuit breakers are no longer installed in the high and extra high voltage level, and the devices in service feature a rather high service age. Spring-operated or hydraulic drive units used with minimum-oil CBs must therefore be regarded as inferior to drive units installed in modern SF_6 breakers, since they did not go through the recent progress in materials, engineering and manufacturing. Nevertheless, the overall reliability of minimum-oil CBs is fair, mainly due to the reliable spring-operated drive unit, the well-developed switching principle and the long service experience. Maintenance of minimum-oil breakers, on the other hand, is an issue. For instance, the dielectric strength of the insulating oil decreases due to its decomposition by the electric arc during switching, and must be determined by periodic tests. Due to the high number of minimum-oil CBs still in service, especially in 110 kV networks, maintenance know-how is still sufficient and does not pose a risk – at least not in the medium term.

4.1.3 SF_6 circuit breakers

Sulphur hexafluoride (SF_6) has been discovered in the beginning of the 20th century by the French chemist Henry Moissan. However, its potential for high-power switching applications remained undiscovered for another fifty years before first investigations have been conducted. They showed that SF_6 has a remarkable arc quenching ability, almost hundred times better than atmospheric air.

Following this studies, SF_6 circuit breakers were introduced in the late 1950s by simply taking over the design of air-blast CBs (double-pressure principle). Single-pressure breakers have been also introduced at this time, but only for low rated power. Over the years to follow, and with the invention of the single-pressure, self-blast principle, SF_6 breakers dominated the market of high-voltage circuit breakers and made the air-blast and oil design obsolete. Nowadays, SF_6 is increasingly applied also in the medium voltage level, where it is used as insulating medium in sealed-for-life gas-insulated switchgear.

Double-pressure SF_6 circuit breakers had the same operating principle as air-blast CBs introduced in section 4.1.1: during switching the arc is cooled down by a blast of SF_6 gas allowed to flow from a vessel at higher pressure (up to 17–18 bar [4.4]) into the switching chamber. Contrary to air-blast breakers, though, the switching chambers of SF_6 CBs is enclosed inside a housing, which is filled with SF_6 at lower pressure (usually 2–3 bar). After each switching operation, SF_6 gas is removed from the switching chamber, compressed and stored again in the high-pressure tank. Similar to air-blast breakers, double-pressure SF_6 CBs use a pneumatic drive.

Double-pressure SF_6 circuit breakers are capable of interrupting higher short-circuit currents with lower effort i.e. less interrupters than air-blast CBs due to the excellent arc quenching characteristics of the extinguishing medium. Nevertheless, they feature the same drawbacks regarding availability and maintainability as the air-blast design, so that a replacement in the short to medium term is recommended.

Puffer-type circuit breakers were the second generation of SF_6 breakers, and the first one of the single-pressure design. They use a piston pump to compress SF_6 during switching, which is then allowed to flow to the arc region, thus cooling the arc down until it eventually extinguishes (figure 4.4). Compared to the double-pressure design, this obviated the need for the high pressure tank, as well as for the complicated system of pipes and nozzles, leading to an increase in overall availability. The piston pump is directly attached to the moving contact of the circuit breaker, and compression takes place while opening.

The drive unit must therefore not only accelerate all masses involved (contacts as well as mechanical linkages between drive and interrupter), but also provide sufficient power for SF_6 compression. Because of this requirement for high power rating of the drive, puffer-type SF_6 HVCBs are equipped with hydraulic drive mechanisms. Their main components are a hydraulic pump for compressing the oil and a differential piston for the conversion of potential energy into kinetic energy. A nitrogen gas spring serves as energy storage. The operating mechanism is controlled and released by magnetic oil valves, which have to be connected as a cascade (i.e. the command is given to an auxiliary valve which, upon opening, causes the main valve to also open) due to the high oil pressure.

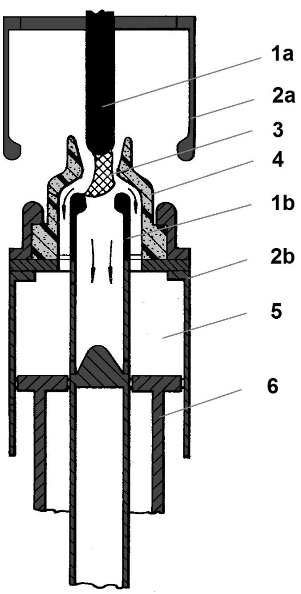


Figure 4.4: Arc quenching in puffer-type SF_6 circuit breakers. When opening, the moving contact moves downwards and SF_6 in the puffer volume is compressed. Energy dissipated by the arc and nozzle burn-off also contribute to an increase in pressure in the puffer volume. At the time of current zero crossing, compressed SF_6 flows upwards into the nozzle area and cools the arc until extinction [4.12].
Legend: 1 arcing contacts (a stationary, b moving), 2 main contacts, 3 switching arc, 4 nozzle, 5 puffer volume, 6 puffer piston.

Puffer-type SF_6 circuit breakers have been manufactured and installed until the mid 1980s, so that the majority of such equipment still in service are over 30 years old. This extensive service experience also implies deep knowledge of the equipment and sufficient maintenance know-how. Compared to double-pressure SF_6 breakers, puffer-type CBs are more reliable and maintenance-friendly, in particular regarding the design of the interrupter. The absence of a pressure tank also removes the requirement for other components (pneumatic valves, heating unit to ensure that humidity in the compressed SF_6 does not condense in the tank) and simplifies the overall layout. Nevertheless, hydraulic drive units are quite fault-prone mainly due to the high operating oil pressure of up to 300 bar: frequent minor faults are leaks at the oil circuit and at the nitrogen energy storage.

Finally, the third generation of SF_6 HVCBs are *self-blast* circuit breakers. In self-blast breakers, the energy dissipated by the electric arc during switching is directly used for its quenching, so that the energy the operating mechanism needs to supply is kept at a minimum. The arc quenching principle is shown in figure 4.5. Self-blast SF_6 breakers are single-pressure devices and their main difference to the aforementioned puffer-type breakers can be identified in the existence of a self-blast volume: as long as power is drawn from the arc and converted in heat, SF_6 pressure in the self-blast volume increases. At the time current crosses zero, generation of heat in nozzle region (where the arc is burning) decreases and the previously compressed SF_6 gas is allowed to flow back, thereby cooling down the arc until its extinction. In addition to the self-blast volume, a puffer volume as with puffer-type SF_6 breakers is also available in order to reliably interrupt small currents (compare also with minimum-oil breakers, figure 4.3).

The introduction of the self-blast principle lead to a significant decrease in energy the operating mechanism has to supply. Self-blast SF_6 breakers require almost half of the energy of puffer-type breakers with same ratings. This opens the scope of application also to other drive technologies than hydraulic drives: self-blast SF_6 HVCBs can be equipped with spring-operated mechanical drives (compare section 4.1.2) as well as with hydro-mechanical drives – a design where plate springs serve as energy storage and hydraulic oil is used for energy transmission from the storage to the contacts.

Nowadays, self-blast SF_6 circuit breakers are state-of-the-art in high-voltage engineering. From an operational point of view, they can cope with high transient recovery voltages and high short-circuit currents with a low number of interrupters. Also the maintenance experi-

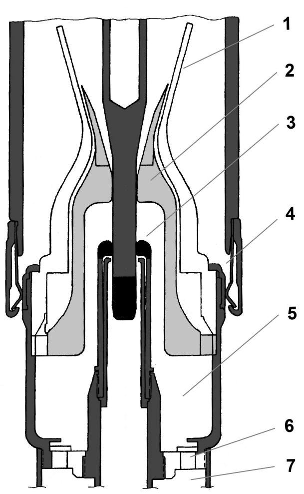


Figure 4.5: Arc quenching in self-blast SF_6 circuit breakers. In the figure, the CB is in closed position and current is carried by the main contacts. Upon opening, current commutates to the arcing contacts and the energy dissipated by the developing arc causes SF_6 pressure to rise. If pressure increase by the arc is low (small interrupted currents), a puffer cylinder, connected to the self-blast volume via valves, provides necessary SF_6 compression.
Legend: 1 grading electrode, 2 nozzle, 3 arcing contacts, 4 main contacts, 5 self-blast volume, 6 connecting valve, 7 puffer volume.

ence with self-blast breakers is good, as they have proven in the field to be very reliable and maintenance-friendly. Furthermore, and due to their prevalence in the market, maintenance know-how and OEM support are usually given.

Operating mechanisms of third-generation SF_6 CBs are in general more reliable than the drive units of second-generation breakers due to less mechanic energy used. However, reliability requirements for hydro-mechanical drives are very strict: Due to the short spring deflection of the employed disc spring package, oil pressure must be increased up to 500 bar [4.12], which poses high risk for oil leaks. For this reason, most circuit breaker manufacturers today tend to equip self-blast SF_6 HCVBs with spring-operated mechanical drives.

4.1.4 Rule base for technology assessment

Returning to the question of strategic condition assessment of HVCBs, the discussion in the previous sections can be used as a basis to establish an assessment scheme for the applied switching technology. Another source of information which can also be used is published data related to the general service and maintenance experience, as shown in tables 4.1 and 4.2. Failure rates listed in table 4.1 are per year and comprise both minor and major failures[2]. Compared with the values in table 4.2, obtained from a large international survey by Cigré, they are somewhat higher, probably because of the adverse climatic conditions in Canada [4.3].

The development of an assessment scheme for strategic assessment of HVCB technology should involve all maintenance experts with experience with HV switching equipment within the utility, so as to capture as much knowledge as possible. In the case study presented here, it has been adopted by the existing condition assessment scheme of the utility and is summarised in table 4.3. Based on this table, a fuzzy inference system has been designed and implemented in Microsoft® Excel®. Each row of the table defines a fuzzy rule featuring AND-connectives.

Table 4.1.: Maintenance experience of a Canadian utility with CBs of different switching technology [4.3].

Switching principle	Failure rate
Air-blast	18.0 %
Minimum-oil	7.0 %
SF_6 (double-pressure)	20.0 %
SF_6 (single-pressure)	7.0 %

Table 4.2.: Maintenance experience with CB operating mechanisms [4.3]. The entry “hydraulic” also accounts for hydro-mechanical drive mechanisms. Failure rates in the table are given in percent per year.

Drive technology	Minor failure rate	Major failure rate
Pneumatic	5.00%	1.42 %
Hydraulic	8.29 %	0.84 %
Mechanic	3.39 %	1.13 %

[2] By definition, a *major failure* is an event which leads to an immediate change in system conditions i.e. instantaneous equipment outage, while a *minor failure* leads to equipment outage within a short time interval, typically of one hour.

Table 4.3.: Rule base for strategic assessment of HVCB technology. The best and worst rating are denoted by A and D, respectively, with intermediate grades e.g. C+ being also possible.

Switching principle	Operating mechanism	Rating
Air-blast	pneumatic	D
Minimum-oil	mechanic	B
Minimum-oil	hydraulic	C+
Minimum-oil	pneumatic	C
SF_6 double-pressure	pneumatic	D
SF_6 puffer-type	mechanic	B
SF_6 puffer-type	hydro-mechanic	B–
SF_6 puffer-type	hydraulic	C+
SF_6 self-blast	mechanic	A
SF_6 self-blast	hydro-mechanic	B
SF_6 self-blast	hydraulic	B–

Combinations of switching and drive technology not listed in the table do not occur in practice: the FIS therefore returns an alarm output, as an indication that the input information is erroneous.

Obviously, there is no uncertainty with regard to whether a particular circuit breaker is, say, of the minimum-oil type or not. In other words all input variables are modelled as fuzzy singletons; it is in fact unnecessary to use a FIS for the assessment of technology. Nevertheless, this approach has been chosen because of two reasons: On the one hand, the remaining modules of the assessment scheme (maintenance and service experience as well as cost of maintenance) do model uncertainty, as will be shown shortly. In order to combine them with the assessment of technology, it is handy to express the result of the latter by means of linguistic variables as in table 4.3. On the other hand, a FIS offers an easy way to mathematically describe rules, even if the underlying variables do not contain any uncertainty.

4.2 Assessing service and maintenance experience

For the assessment of service and maintenance experience, following condition indicators are used: availability of spare parts, systematic failures of a specific type of CBs, OEM support, and available maintenance know-how. They will be described in more detail in this section:

Availability of spare parts: Availability of spare parts has a decisive influence on the overall availability of an apparatus. It is known from the practice that, when an unplanned outage occurs, the total down time (time for corrective maintenance) is mainly determined by the time needed to obtain the required spare part. But also the efficiency of preventive maintenance is enhanced by a secure supply with spare parts, since servicing and refurbishment of wearing parts can be better scheduled.

Three linguistic values are introduced for this CI: the safest scenario is spare parts stock keeping directly by the utility. However, an own warehouse is associated with yearly operational costs and might not always be the best choice, especially if the network extends over a large area. This scenario is denoted as "own stock keeping". Two more linguistic values are defined as "good availability" and "limited availability" depending on the average time needed by the subcontractor, typically the manufacturer, to deliver the required spare part. According to the maintenance expert of the cooperating TSO, the upper time limit for good availability should lie at one working day. The membership functions for the fuzzy sets are therefore defined as in figure 4.6.

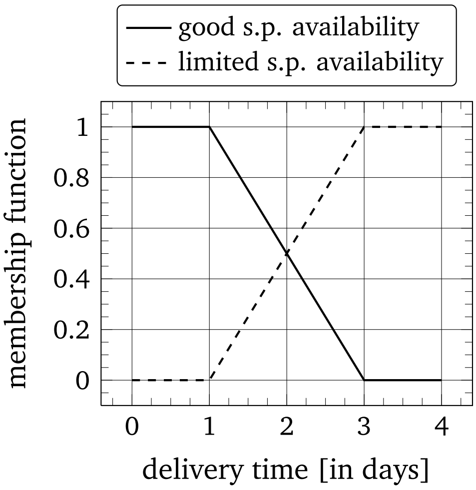


Figure 4.6: Membership functions for the condition indicator "availability of spare parts". The linguistic value "own stock keeping" is defined directly as either true or false and is regarded to be equal to "good availability".

Systematic failures: Root Cause Analysis defines systematic failures as such having their principal cause in the same design or manufacturing defects. In general, the manufacturer of the equipment is thus responsible for systematic failures; nevertheless, claiming guarantee is not always possible, especially when systematic failures occur only after prolonged service time. In some cases, for example in the case of repeated faults in installation or maintenance, the user of the equipment may as well cause systematic failures to occur.

In order to be able to identify systematic failures as such, a threshold for their rate of occurrence must be defined. Keeping the general reliability figures of HVCBs in mind, an appropriate choice for this threshold could be at 10 %, meaning that if 10 % of all type-like devices demonstrate a failure with the same root cause over their service lifetime then this failure mode is a systematic one.

When systematic failures are identified, not only do failed units have to be repaired, but also all other type-like devices must be preventively refurbished. The cost of these actions might be quite high, and should therefore be considered in the scope of strategic condition assessment.

Table 4.4 shows the resulting assessment scheme for the CI "systematic failures". The respective membership functions are shown in figure 4.7(b).

In order to evaluate the degree of membership to any of the three linguistic values, the cost associated with systematic failures must be known. Its computation is performed according to a two-stage approach: First the question whether systematic failures exist is answered. This is done by means of the fuzzification scheme shown in figure 4.7(a). The resulting degree of membership to fuzzy set "systematic failures apparent" is then multiplied by the expected cost of removal (per device) – a crisp value. The result of the multiplication is the input for the fuzzification scheme of figure 4.7(b).

OEM support: This condition indicator includes all aspects of service offered by the original equipment manufacturer after sale with the purpose of assuring customer satisfaction. Typical aspects of after-sale service are [4.13]:

- *Complaint management*: In case the acquired device does not fully fulfil the agreed specification, the after-sale department of the OEM should take care that the device is improved by refurbishment, overhauling and uprating, or –if this is not possible– initiate its replacement by another one, which fulfils the specification. The decision whether the device is still on guarantee or not must be fast and justified. In case of doubt, a service-oriented manufacturer would rather carry out the necessary improvement work at own cost than loose a customer.
- *Maintenance support*: According to the terms of contract, preventive maintenance is in the responsibility either of the manufacturer or of the buyer (or a subcontractor).

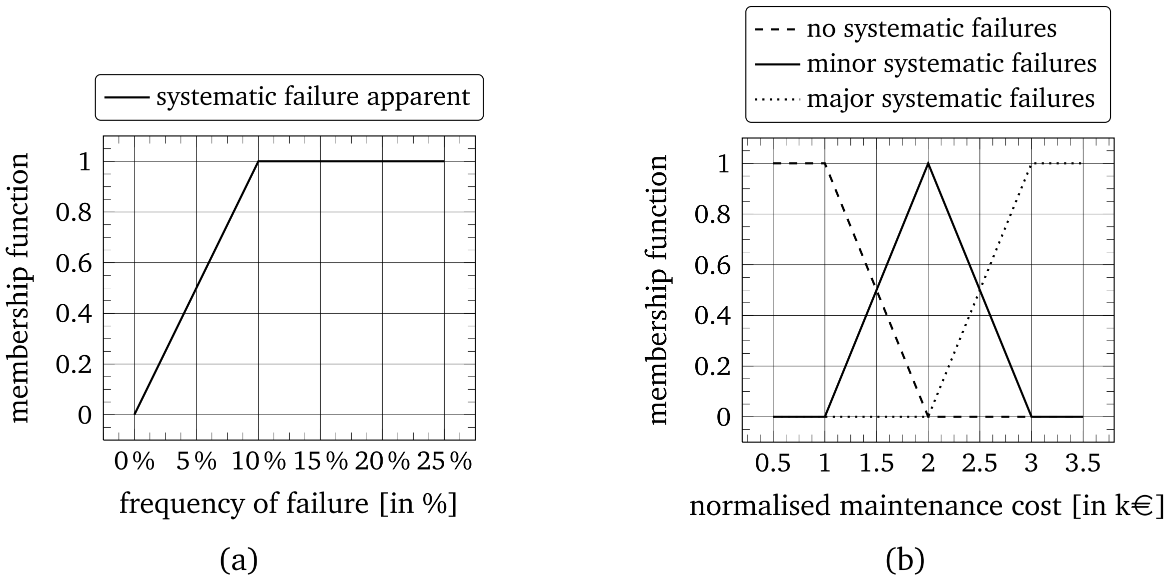


Figure 4.7.: Two-stage approach for the assessment of systematic failures. At a first stage, the frequency of recorded systematic failures is compared to the specified threshold, figure (a). The degree of membership to fuzzy set "systematic failures apparent" is then multiplied by the documented or expected cost of fault removal per device, and the result of the multiplication is used as input for the fuzzification at the second stage, figure (b).

Table 4.4.: Guidelines for the assessment of systematic failures.

Assessment	Remark
A	No systematic failures apparent or yet identified (failure rate associated with systematic failures is lower than the specified threshold)
B	Minor systematic failures (cost of removal per device lower than 2,000 € including man hours)
C	Major systematic failures (cost of removal per device exceeds 2,000 € including man hours)

In the electricity transmission and distribution business the latter approach is more common, since power utilities usually have own maintenance departments. Even in this case, support by the OEM in maintenance issues is very important. Some failures occurring in the field might be too complex for the user to remove or analyse; disassembly at the manufacturer's plant might be necessary or required by the user. The OEM's service department should make sure that this is done in a fast and inexpensive way.

- *Training*: From the buyer's point of view, a wide offer of seminars and training workshops by the OEM is indispensable, especially when a new type of equipment is introduced. Reputable manufacturers therefore run own training centres, where the customers' maintenance personnel can get acquainted with the equipment and can learn how to correctly perform maintenance.
- *Documentation*: Proper documentation is another prerequisite for effective maintenance and reliable operation. In addition to relevant technical drawings, a detailed handbook must be made available to the maintenance personnel of the buyer, including a well-defined maintenance schedule.
- *Feedback from users*: Besides all aforementioned aspects, a service-oriented manufacturer is characterised by the willingness to collect feedback on customer satisfaction and customer wishes and consider this feedback not only for assessing the performance of after-sale service, but also during the process of product development.

All aforementioned aspects have to be considered when assessing the satisfaction with the after-sale service of a particular manufacturer and a specific circuit breaker type. Due to the complexity of the topic, assessment should by made subjectively, and knowledge-carriers from several departments of the power utility should be involved so as to obtain a broad perspective. The resulting assessment should be given as a number between 1 (practically no support by the manufacturer) and 10 (all customer wishes are satisfied). Table 4.5 provides guideline for the assessment of OEM support. The result is the fuzzified according to figure 4.8.

Table 4.5.: Guidelines for the assessment of after-sale service offered by manufacturers. Intermediate values are also possible and should be used for finer classification.

Assessment	Remark
1	Device will be discontinued within the next five years (no support provided any more)
3	Insufficient documentation, no training facilities for maintenance personnel, known problems with complaints/guarantee claims (several statements are valid)
5	Insufficient documentation, no training facilities for maintenance personnel, known problems with complaints/guarantee claims (only one statement is valid)
10	Positive experience with complaint management, full support with maintenance issues, in-house training possible, complete documentation

Figure 4.8: Service & maintenance experience: assessment of after-sale service. The score used as input is determined according to table 4.5.

Maintenance know-how: The last, but not less important aspect of service and maintenance experience is the available know-how within the power utility. On the one hand, standard operating procedures must be defined and documented, on the other hand the maintenance personnel should have the capacity to carry out these procedures: tools, measuring equipment and skilled workers mus be available in sufficient numbers.

In the course of technological developments in the field of high-voltage engineering, some equipment e.g. air-blast HVCBs turns obsolete while still in service; the number of installed units decreases over time, and at some point only a few devices of this type are still installed. Keeping up tools and workforce for them becomes more and more expensive, so that a short-term replacement would be reasonable. In addition, the more seldom a specific type of equipment is in the system, the less workers will be acquainted with it; maintenance know-how diminishes.

An appropriate measure for this condition indicator is thus the number of devices of a specific type installed in the system. The same approach is recommended in [4.3] by BC Hydro, a Canadian utility. They label this CI “orphans” and set the respective threshold, under which equipment is regarded to be an “orphan” at five units. In this case study higher thresholds were defined in consultation with the co-operating TSO. They are shown in figure 4.9.

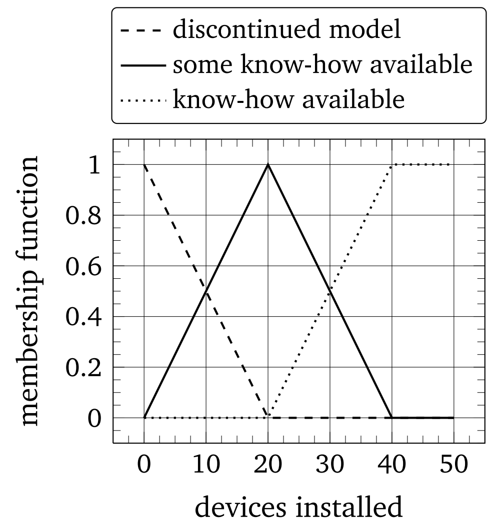


Figure 4.9: Service & maintenance experience: available know-how. For a specific type of equipment, the number of devices still in service is used as an indicator of the available maintenance know-how.

The aforementioned condition indicators (availability of spare parts, systematic failures, OEM support and maintenance know-how) are aggregated so as to assess the overall service and maintenance experience associated with a particular circuit breaker type. Aggregation is done by a fuzzy inference system the rule base of which is given in appendix C.1. Contrary to the assessment of technology discussed in section 4.1, linguistic variables used in this FIS are fuzzy, meaning that for a specific circuit breaker type several linguistic values will be true at the same time.

A closer look at the rule base in table C.1 reveals that the relative importance of each condition indicator to one another is not constant, but depends on the linguistic values applied. This is an importance difference to the standard condition assessment matrix presented in section 3.3.1. It allows for a more flexible assessment, by providing non-linear classification hyperplanes in the decision's input space.

The motivation for implementing a non-linear assessment scheme originates from the fact that the listed CIs influence both corrective and preventive maintenance. The efficiency of preventive maintenance is mainly determined by the expected down time and the ability to schedule all necessary actions. These aspects are directly related both to the availability of spare parts and the available maintenance know-how. OEM support is also important to preventive maintenance e.g. with regard to maintenance manuals, but to a lesser extent. On the other hand, corrective maintenance is influenced primarily by the availability of spare parts, since in the case of an unplanned outage the time needed to obtain the required part is a substantial component of total down time. Finally, there is also a correlation between the frequency and scale of systematic failures and OEM support. If a systematic failure mode is detected during service, this usually leads to complaints or even guarantee claims by the buyer. The reaction of the manufacturer upon the complaints will also determine how to proceed with the faulty devices.

4.3 Assessing the cost of maintenance

Decisions on refurbishment or replacement of equipment must also consider financial aspects. An international survey conducted by Cigré on end-of-life decisions for HV circuit breakers [4.3] identified the cost of maintenance to be the one of the primary reasons for replacement, especially for air-blast and double-pressure SF_6 breakers (refer also to section 3.2.1).

It is quite common for decision making involving long-term investments to apply the life-cycle costing method. The application of this method has been also proposed for the purpose of asset replacement in electricity supply systems e.g. in [4.14]. However, the result of such an analysis is largely dependent on the assumed probability and consequence of an unplanned outage. Since the information so far available regarding these aspects is not very reliable, the application of the life-cycle costing method should be questioned.

On the other hand, a cost aspect which is perceivable by an electric power company in the short and medium term is the cost of maintenance which is therefore used as a condition indicator in this case study. The determination of the total cost of maintenance for a circuit breaker type is quite a challenge, as many expenses for maintenance cannot be easily assigned to a particular device. The implementation of computer-aided enterprise resource allocation systems, as well as well-documented work flow management are important prerequisites if a utility wants to keep track of the cost of maintenance.

Experience so far has proven that, even if such information systems are implemented within a utility, it is still not easy to precisely evaluate the cost of maintenance for each unit installed. On the other hand, it is also known that almost 75 % of the overall expenses for maintenance are driven by labour, rather than by spare parts or required tools and measuring equipment [4.3]. An easy, but still effective way of assessing the cost of maintenance for a particular circuit breaker type is thus to consider the man hours needed for preventive and corrective maintenance along with its frequency. Putting this figure in relation for the different CB types will then reveal which breakers are expensive to maintain – and which are not.

This approach is handy because, even if data on the actual man hours spent is not captured by a work flow management system, it can be easily and quite precisely assessed by maintenance experts, at least for preventive maintenance actions. Although the cost of corrective maintenance is not easy to assess, this is not an issue, since the total cost of maintenance in electricity supply systems is primarily driven by preventive rather than corrective actions.

The assessment scheme for the condition indicator "cost of maintenance" is shown in figure 4.10. Instead of directly using the expected annual man hours, a benchmarking approach is taken: for each circuit breaker type, the annual maintenance labour required is first computed by multiplying the man hours for associated maintenance actions by their frequency. This figure is then averaged over all circuit breaker types to return a benchmark of what is assumed to be the "normal" cost of maintenance (corresponding to 100 % in figure 4.10).

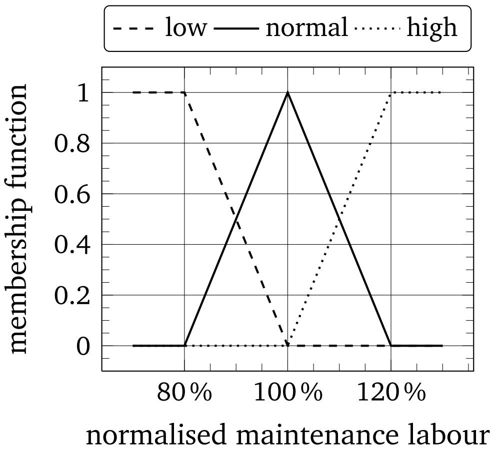


Figure 4.10: Assessing the cost of maintenance. The reference value is computed by averaging the expected annual need for maintenance labour.

4.4 Overview of the developed fuzzy system and discussion

The developed fuzzy inference system for strategic condition assessment of HV circuit breakers uses the intermediate results for the specified high-level condition indicators (technology, service and maintenance experience as well as cost of maintenance). Similarly to the assessment scheme applied by the co-operating TSO, it classifies circuit breaker types into four categories: perfect condition (A), normal condition (B), condition which justifies medium and long-term replacement or refurbishment (C), and condition which calls for short to medium-term replacement or refurbishment (D).

The complete rule base of the resulting FIS is shown in appendix C.2. It is obvious that intermediate linguistic values such as A+ or B–, defined as output of the fuzzy sub-systems for the assessment of technology and service & maintenance experience (tables 4.3 and C.1 respectively), are not included in this rule base. However, this does not mean that they were not considered: Every intermediate linguistic value can be translated into its adjacent "full" values by means of fuzzification, as can be seen in figure 4.11 for the example of B– and C+. The mo-

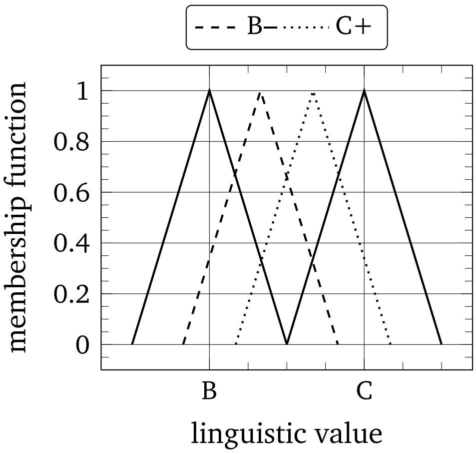


Figure 4.11: Definition of intermediate linguistic values. The degree of membership of each intermediate value to its adjacent "full" linguistic values is evaluated by means of fuzzification. For instance: $\mu_B(B^-) = 2/3$, $\mu_C(B^-) = 1/3$.

tivation for this approach has been to increase the classification accuracy at low level without increasing the required number of fuzzy rules at higher level.

The output of the fuzzy inference system so far is a set of degrees of membership to condition states A to D for each circuit breaker type. Defuzzification may take place in any of the following ways:

- The first possibility is to derive a numerical value for each HVCB type which considers the degree of membership to every condition state. By means of this asset condition index, it is possible to keep track of all circuit breakers in the system and compare to past values or some benchmark. The target space for defuzzification can be arbitrarily chosen e.g. between 0 % and 100 % as shown in figure 4.12.
- If however the objective is to rank the different types of circuit breakers in order to decide which type should be replaced first, it could be better to use only the degrees of membership to condition states C and D, rather than the complete fuzzy set. This mode of defuzzification is shown in figure 4.13.

Depending on the decision objective it is thus possible to represent the assessment result in various ways. This flexibility to obtain different indices from one and the same scheme is a major advantage of the fuzzy assessment scheme over the standard condition assessment matrix.

One should always keep in mind that replacement of a circuit breaker type takes place over an extended time interval which may amount up to one or two decades. This is due to the fact that the decision on and the implementation of a renewal within a substation bay will not focus

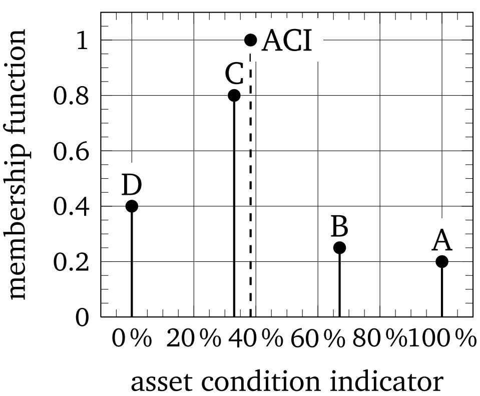


Figure 4.12: Evaluation of the asset condition index for a particular circuit breaker type. Defuzzification is done by the height method (section 2.2.2). Example:
A: ACI$(A) = 1$, $\mu_A = 20\,\%$
B: ACI$(B) = 2/3$, $\mu_B = 25\,\%$
C: ACI$(C) = 1/3$, $\mu_C = 80\,\%$
D: ACI$(D) = 0$, $\mu_D = 40\,\%$
$\Rightarrow$ ACI $= 38.3\,\%$

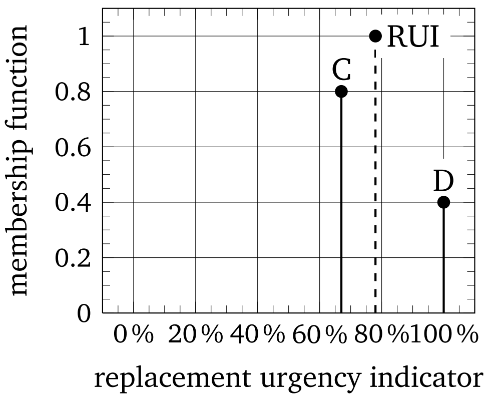


Figure 4.13: Evaluation of the replacement urgency index (RUI) for a particular circuit breaker type. Only condition states C and D are considered. Example:
C: RUI(C) $= 2/3$, $\mu_C = 80\,\%$
D: RUI(D) $= 1$, $\mu_D = 40\,\%$
$\Rightarrow$ RUI $= 78.0\,\%$

merely on the circuit breaker, but will also take into account other equipment as well, such as disconnectors, control and protection system, busbar support etc. Furthermore, constraints might exist regarding the access to the system, its current and future loading, or the general system design.

It is therefore recommended to extend the presented fuzzy system in a way that strategic condition assessment also considers the surrounding equipment as proposed in [4.15]. Another possible development could be to include further condition indicators for strategic assessment. Relevant indicators have been already discussed in section 3.2.1, figure 3.2. Nevertheless, the presented case study provides evidence of the applicability of fuzzy inference systems for strategic condition assessment.

Strategic condition assessment of equipment involves a great deal of vague technical-operational knowledge and experience which can be effectively modelled by fuzzy inference systems.

5 Operational condition assessment of circuit breakers

There's a fundamental distinction between
strategy and operational effectiveness.

Michael Porter, Harvard Business School

The general objective of operational condition assessment is to understand the structural condition, performance and progression of deterioration of the equipment and condense this information into an asset health index, which can be used for scheduling preventive maintenance activities in the short and medium term. For the purpose of operational condition assessment several information sources can be consulted: visual inspections and diagnostic tests give a good insight into ongoing deterioration processes, but are executed only on a periodic basis. On the other hand, on-line condition monitoring systems are rather expensive and are therefore employed to monitor the most crucial functions of the equipment. Furthermore, knowledge about the loading of the equipment and the stresses it has been subjected to during service can be gained by analysing service data.

However, the large number of relevant sources of information, and especially the various diagnostic techniques available on the market for high-voltage equipment, are both a blessing and a curse, since the information they provide might be contradictory. Engineering knowledge and experience is thus important for operational assessment, in order to understand stresses and analyse the influence they might have on deterioration processes.

Such engineering knowledge can be modelled by fuzzy inference systems, as has already been shown in the previous chapter. Contrary to strategic condition assessment, though, the construction of the fuzzy rule base for operational assessment in a hierarchic manner, where the maintenance expert explicitly defines all rules, might be quite tedious. For every linguistic variable introduced into a FIS, the size of its rule base grows exponentially[1]; at some point it is practically impossible to define the rules one by one.

This chapter therefore presents an alternative, two-stage approach for the design of fuzzy systems for operational condition assessment introduced in [5.1]. At a first stage, the equipment is divided into functional units, that is sub-systems which are responsible for one of the desired functions. The second stage then involves the assessment of the *entropy* (or content) of each available source of information with regard to each functional unit. In other words, for each information source the question is answered: to what extent can the information provide insight into the condition of the particular functional unit? In this way, it is possible to aggregate potentially contradictory information and derive an overall health index.

Similar to chapter 4, the approach is illustrated by means of a case study on high-voltage circuit breakers. However, since the scope of operational condition assessment is device-specific

[1] For instance, the complete rule base of a FIS featuring n linguistic variables (inputs) and k linguistic values (classes) for each variable comprises k^n fuzzy rules.

rather than type-specific, the fuzzy inference system can only be developed for a particular circuit breaker type. Due to their prevalence in the market, single-pressure SF_6 circuit breakers with spring-operated mechanic drives are considered here.

The outline of this chapter reflects the approach taken during the development of the fuzzy system. Breakdown of the CB in its functional units –the first stage of assessment– is performed in section 5.1. In section 5.2.1 diagnostic techniques available for SF_6 circuit breakers are presented and briefly discussed. Together with findings from visual inspections, the results of these techniques are the most reliable information available for assessing the technical condition of the equipment. However, this is not the only source of available information. General service data, combined with service and maintenance experience, can be equally important for assessment, especially if diagnostic tests have been performed long in the past. Section 5.2.2 describes the method used to aggregate service data with the results of diagnostic tests. The assessment of the information content for each condition indicator is shown in section 5.3. On its basis, the fuzzy system for operational condition assessment is designed.

5.1 Identifying functional units

As already discussed in section 4.1, every circuit breaker can be broken down to five functional units, no matter the technology applied: the drive mechanism, the current-carrying parts, the insulating system, the interrupter, and the control unit. The focus of the case study in this chapter is on *live-tank single-pressure SF_6 circuit breakers with spring-operated mechanic drives*. A general description of the switching and drive technology has been given in section 4.1.3. In this section some special aspects of this design with regard to reliability will be discussed.

The discussion here is based to a great extent on the findings of the second international survey on HVCB failures and defects in service, conducted by Cigré and reported in [5.2]. However, some adaptation has been necessary. In particular, statistical analysis in [5.2] considers only four sub-systems for the circuit breaker by aggregating the current-carrying parts (mainly the main contacts and the external terminals) with the interrupter (arcing contacts). For this reason, reliability data had to be restructured. This has been done by regarding the functional failure modes[2] defined in [5.2] and assessing the contribution of the five functional units to each of them, as can be seen in appendix D.1.

Table 5.1 shows the contribution of each functional unit to minor and major fault occurrence, as it has been determined after restructuring. As can be seen, the drive mechanism is definitely the most crucial component from a reliability point of view, since it dominates both minor and major failures. The control system is also responsible for a large share of major failures, most of which are related to failure to release the drive mechanism upon command. The high frequency of this failure mode has two reasons: on the one hand, many circuit breakers are operated rather seldom, so that static loading of bearings and deterioration of the lubricant's characteristics increase friction. The second and perhaps more important reason is that some other defect has been apparent for a longer time, but was only detected when the breaker failed to operate in response to an opening or closing command. The high share of the insulating system in minor failures is also noticeable. Its origin are minor leaks of SF_6 gas, mainly due to

[2] The difference between *functional* and *structural* failure modes is that, in the latter case, the failure can be assigned to a particular component of the apparatus, whereas functional failure modes describe only the effect of the failure on the general functionality of the device.

Table 5.1.: Cause of failure for live-tank single-pressure SF_6 circuit breakers with spring-operated mechanic drives. Values have been determined according to tables D.1 and D.2 [5.2].

Functional unit	Minor failure	Major failure
Drive mechanism	42.3 %	44.6 %
Current-carrying parts	3.9 %	5.9 %
Insulating system	25.1 %	6.6 %
Interrupter	7.4 %	11.4 %
Control unit	21.2 %	31.5 %

corroded flanges or damaged gaskets and seals. The much-discussed influence of faulty density monitors (refer to section 5.2.1) is indeed important, and approximately every third associated alarm leading to minor failure is actually a defect of the density monitor [5.2].

The data listed in table 5.1 is used by the fuzzy system for operational condition assessment during the process of synthesis, as will be shown in section 5.4. However, the condition of each functional unit must be assessed first.

5.2 Condition indicators for operational condition assessment

In this case study two groups of condition indicators are used for assessment: The first group comprises information obtained from diagnostic tests and visual inspections performed during preventive maintenance. Such information is most accurate and can provide deep insight in the progress of deterioration. In order to secure as much added value as possible, every diagnostic technique should be accompanied by a precise interpretation scheme. Section 5.2.1 gives an overview and a discussion of common diagnostic techniques for SF_6 circuit breakers.

The second group of condition indicators used here comprises easily-accessible service data. In the case of high-voltage circuit breakers these are: information on the location of the breaker, its service age, the number of switching operations performed etc. Such information can also provide an indication of the circuit breaker's condition, but is far less accurate than diagnostic tests and its interpretation requires extended maintenance experience. Nevertheless, there are situations were condition assessment should also be based on service data. This is especially the case when diagnostic tests or visual inspections have been performed in the long past and their significance could be therefore questioned.

As a result, the contribution of CIs based on service data to condition assessment should not be constant, but rather depend on the (varying) significance of diagnostic tests and visual inspections. Section 5.2.2 describes the approach proposed and implemented in this case study.

5.2.1 Common diagnostic techniques for circuit breakers

A comprehensive list of diagnostic techniques applied to high-voltage circuit breakers can be found in [5.3–5.5]. Based on these documents, this section provides a brief introduction to those techniques which are of particular relevance to condition assessment. An overview of the measured quantity, the most common measuring techniques and the frequency of measurement is given in table 5.2.

Table 5.2.: Common monitoring techniques for SF_6 high-voltage circuit breakers with mechanic drive [5.3, 5.5, 5.6]. Measurements are categorised as continuously or periodically accessible (denoted with c and p, respectively).

Measured quantity	Method for measurement	Frequency
SF_6 density	temperature-compensated pressure gauge	c
	uncompensated pressure gauge	c
	solid state gas sensor	c
SF_6 leak	sniffer	p
	infra-red imaging	p
SF_6 purity	gas chromatography	p
	infra-red spectroscopy	p
Moisture content	dew point	p
	solid state sensor	p
Partial discharge	UHF measurement (narrow & broad band)	c & p
	acoustic measurement	c & p
Insulation resistance	four-point measurement	p
Leakage current	residual current measurement	p
Power factor	four-point measurement	p
	polarisation/depolarisation current	p
Contact resistance	four-point measurement	p
Contact temperature	infra-red imaging	p
	optical fibre	c & p
	thermocouple	c & p
	compensated gas pressure gauge	c
Dynamic contact resistance	combined voltage and current measurement	p
Main contact's end position	contact position transducer (auxiliary switch)	c & p
Contact travel characteristics	resistance potentiometer	c & p
	optical position sensor	c & p
Operating time	galvanic contact	p
Vibration	accelerometer	c & p
Pole discrepancy	galvanic contact (synchronised measurement)	p
Charging power	motor current and voltage measurement	c & p
Motor running time	integrating counter	c
Coil current	current measurement	c & p
Minimum trip voltage	voltage sensor	p

Measurement of SF_6 density: Measurement of the density of SF_6 is the most common monitoring technique for SF_6 circuit breakers with respect to the insulating system, since it has a direct influence on the internal dielectric strength. The measurement is performed continuously by means of temperature-compensated pressure gauges. The gauges usually facilitate two outputs to report on density drops: if SF_6 density falls below a first threshold, an alarm is sent to the control station; in case the second threshold is reached, the circuit breaker is locked in its current position to prevent a potential internal flash-over during switching with potentially catastrophic consequences. An alternative way of measurement is to use uncompensated pressure gauges and measure the temperature of the gas separately; in this way SF_6 leaks can be identified easily from the control room. Recently, solid state sensors that directly measure the gas density have also become available. The reader can refer to [5.7] for more information on solid state sensors.

SF_6 leak detection: It is not uncommon for GIS-integrated SF_6 circuit breakers to check their tightness during regular field inspection. Detection of SF_6 leaks can be done by practical, hand-held gas detectors –typically referred to as *sniffers*– which detect leaks by measuring a reduction in the electric conductivity of the air, or by SF_6-sensitive infra-red imaging systems emitting laser light at a frequency characteristic for SF_6 [5.3].

Determination of SF_6 purity: Due to dielectric and thermal stress SF_6 is decomposed during service and the decomposition products can be found in the circuit breaker. As already discussed, in combination with moisture they can pose a risk for internal surfaces. Moreover, measuring the concentration of decomposition products also provides an indication on the stress the device has been subjected to during switching. Measurement is performed by means of gas chromatography and infra-red spectroscopy.

Measurement of moisture content: Moisture in SF_6 decreases the dielectric properties of the insulating system in two ways: First, due to temperature variations, moisture can condense on the surface of solid insulation materials thus increasing leakage current and significantly reducing the overall dielectric withstand. Second, water can react with existing decomposition products of SF_6 and form reactive compounds which then corrode the conductors' metallic surface. For this reason, moisture must be bound by moisture-absorbing scavengers and moisture content should be periodically checked. For the purpose of measuring moisture in gases two methods are used: The first method determines the dew point of the gas, that is the temperature at which the vapour condenses as liquid or frost. The second method employs solid-state sensors filled with hydrophilic materials. A change in moisture content can be measured by the variation of its electrical properties.

Measurement of partial discharges: Unlike free-standing units, circuit breakers within a GIS can be monitored by measuring the partial discharge activity, since the grounded metallic enclosure blocks off noise. For this purpose a significant number of antennas has to be installed inside the GIS, which record signals in the ultra high frequency (UHF) range. In modern GIS measurement of partial discharges is virtually a standard feature. Partial discharges can also be measured by detecting the resulting acoustic signals. In GIS these signals propagate as sound waves through SF_6 into the metallic enclosure and can be detected by using sensitive acoustic sensors mounted externally on the enclosure.

Insulation resistance measurement: Direct measurement of the insulation's resistance can provide some indication of surface contamination on solid insulators e.g. in the outer insulation. However, measurement is only possible if the equipment has been disconnected before.

Measurement of leakage current: Another possibility to assess the state of the solid insulation and detect excess contamination is the measurement of leakage current. In addition to disconnecting the device from the primary circuit, the connection of its exposed conductive parts with earth must also be broken for this measurement.

Power factor measurement: The power (or dissipation) factor $\tan\delta$ is a measure of the dielectric losses within the insulation and is commonly used as an indication for assessing the health of an insulating system. It can be measured off-line according to the four-point method or by comparing the polarisation and depolarisation current. However, the results of both methods are influenced by external factors such as temperature. For this reason, the power factor measurement alone should not be used for assessment. In case of live-tank circuit breakers with grading capacitors, the measurement of the dissipation factor of the capacitors is –together with the measurement of capacitance– the only practical diagnostic technique suitable to verify their condition.

Contact resistance measurement: The measurement of the resistance of the main contacts in the primary circuit is the most common diagnostic technique for evaluating the current carrying capability. It is carried out according to the four-point method by disconnecting the device from the primary circuit and then passing a measuring current from a separate source. Typical values of contact resistance for modern SF_6 circuit breakers are in the range $10 - 100\,\mu\Omega$. In order to minimise the measuring error, the injected current should not be less than one tenth of rated load current. Contact resistance measurement is primarily suitable for free-standing devices, where the current source and voltage probes can be easily connected, and not that much for equipment in GIS, where dismantling work is necessary.

Temperature rise: Measuring the rise of temperature due to load current can help identify faulty conditions in the primary circuit of a circuit breaker. In air-insulated substations (AIS) infra-red imaging is used extensively, since it provides a fast and non-invasive measuring method. In general, the accuracy of infra-red imaging systems is sufficient, and experienced operators can easily recognise noise signals e.g. due to sun radiation or fluorescent light bulbs. However, in case the sight line is blocked or interfered with –as for example with circuit breakers inside a GIS where induced ground currents in the enclosure generate heat– determination of the temperature rise of the internal current carrying parts is not feasible. Due to the high cost of infra-red imaging systems, they are employed only for periodic diagnostic testing. Other measuring techniques for determining temperature rise in the live parts of a circuit breaker include the use of distributed fibre optic sensors, and traditional thermocouples for localised temperature measurement. Disadvantages of localised sensors include the fact that a greater number of them is required to cover a component properly and that they can only be applied on grounded parts. This limits their application to measuring the overall temperature of the device, rather than the temperature at the current-carrying path.

A general problem of temperature rise measurements is that it is not easy to compare the measuring results with older data, since the loading state of the equipment as well as the ambient temperature have a dominant influence. This problem can be solved if gas pressure gauges, compensated against variations in loading and ambient temperature, are employed. Since an increase in temperature leads to an increase in gas pressure, it is possible to conclude on temperature by measuring SF_6 pressure; however, this type of measurement is integral, that is it cannot provide indication of localised overheating. In addition, the sensitivity of such measuring systems decreases with increasing gas volume, and is thus in general lower for equipment inside GIS than for free-standing live-tank circuit breakers.

Dynamic contact resistance measurement: The wear of arcing contacts can also be assessed by measuring contact resistance throughout a closing or opening operation. For the purpose of dynamic resistance measurement, the device is taken out of service and a high d.c. current is injected at low voltage. The tripping command is then sent to the circuit breaker and the resistance is recorded over time. Excessive arcing contact wear can be detected as changes in the resistance characteristics: for instance, in case of severe wear, the arcing time (identified within the transition stage between continuous very low resistance i.e. closed position and continuous very high resistance i.e. open position) will appear to be shorter. Nowadays, dynamic contact resistance measurements are increasingly applied as a periodic diagnostic test on circuit-breakers, very often in combination with measurements of contact travel [5.3].

Main contact's end position: Single-pressure SF_6 circuit breakers comprise two sets of contacts: arcing contacts, responsible for the switching operations, and main contacts, responsible for carrying the load current. When the circuit breaker reaches its end position, the current path must have commutated to the main contacts and insertion of the moving contact (male jack) into the stationary contact must ensure sufficient contact pressure. Otherwise load current will continue to flow through the arcing contacts causing overheating and severe thermal stress. If the settings of the circuit breaker's end position is found to deviate from normal during maintenance, it is adjusted accordingly. However, knowledge of the fact that the breaker has been operated under faulty conditions is important for assessing the condition of the current-carrying parts. The most commonly used position sensor type is an electromechanical auxiliary switch connected directly to the operating mechanism, in which case contact position is measured indirectly. It should be therefore kept in mind that failures or incorrect adjustments in the mechanical linkage between the contacts on high-voltage potential and the position transducer on ground can give misleading readings.

Measurement of contact travel: The term *travel characteristics* (synonyms are: travel curve, position-time characteristics and circuit breaker timings, although the latter term is also used for the determination of contact closing and opening times – see below) implies the measurement of the position of the contacts as a function of time during operation. When the contact position is known as a function of time, it is easy to compute contact velocity and acceleration, which are also relevant parameters for the purpose of condition assessment. Travel curves contain information about several important aspects of the mechanical operation of the contacts, and consequently, a number of abnormalities that may occur can be detected from a careful analysis of travel curves [5.3, 5.8, 5.9]. To these belong the detection of abnormalities in the release mechanism (e.g. due to poorly lubricated release latches), reduced energy in operating mechanism, poor damping (e.g. due to defective dash pot), and incorrect settings leading to decreased insulation distance of the contacts when in open position.

The most common sensors for measuring contact travel characteristics are analogue resistance potentiometers and digital optical position sensors. Resistance potentiometers are available in both rotational and linear versions and are attached directly to a moving part of the switching device. The analogue d.c. voltage output is then proportional to the rotational or linear movement. On the other hand, optical sensors use a ruler (linear sensors) or disk (rotational sensors) equipped with one or more tracks of light barriers, reflectors, strip codes or other types of digital codes that are recorded by the optical sensing system.

Preferably, the travel sensors should be connected directly to the moving contacts. In case they are installed at service potential their electrical output signal must then be converted into an optical one. When the sensor is mounted on some location between the moving contact and the operating mechanism, the recorded characteristic is not necessarily the travel curve of the contact due to the intermediate system of mechanical linkages. Usually, manufacturers of measuring equipment specify where to attach the transducer and some also provide conversion tables for the most common circuit breaker models.

Due to the high mechanical forces and vibrations during switching operations, the requirements for on-line monitoring systems for measuring contact travel curve are strict. It is also for this reason that recording of travel curves for diagnostic purposes is primarily applied on a periodic basis using temporarily mounted sensors. The interpretation of travel curves requires experience with the switching device being considered, but valuable information can also be found simply by comparing travel curves from several breakers of the same type or by comparing actual data with older measurements at the same device. Nowadays, manufacturers of circuit breakers usually provide information about how the contact is supposed to move and this can assist in the interpretation of the measurements.

Measurement of operating time: Measuring the opening and closing time of a circuit breaker[3] is a simple alternative to travel curve recordings. The closing and opening time is determined by the galvanic contact in each pole which implies that the device has to be taken out of service. Information obtained by this measurement gives an indication of the condition of both the drive and the interrupter unit.

Distinguishing between normal and abnormal timings is largely based on the experience of the maintenance personnel. In addition, some manufacturers include operating times with allowed tolerances in the specifications of their circuit breakers; this information can assist in interpreting timing measurements. When no defect or fault exists, the variation in operating times of modern SF_6 circuit breakers is very small (for spring-operated breakers in the range $1-2\,\mathrm{ms}$ [5.3]). If discrepancies in opening or closing time are found, it is recommended to apply additional diagnostic techniques, like travel curve measurements, in order to determine their cause.

Vibration measurement: Vibration analysis is an established diagnostic technique for rotating machinery, where it is used to detect defects such as mass imbalance or poor bearing lubrication. In principle, the application of vibration analysis to circuit breakers is possible, but its interpretation is difficult due to the high complexity of the breakers' mechanical part. This is also the main reason why vibration analysis is not widely implemented for circuit breaker diagnosis. The interpretation of results obtained from vibration measurement at a particular circuit breaker is done according to the "fingerprints" method, that is by comparing the pattern of the results with some reference pattern. The reference can be an earlier recording from the same breaker, the pattern of another breaker of the same type, or even the measuring results obtained from another pole of the same breaker in case every pole has its own drive unit [5.11, 5.12].

3 According to IEC *closing time* is the interval of time between the initiation of the closing operation and the instant when the contacts touch in all poles, while *opening time* is the interval of time between the specified instant of initiation of the opening operation and the instant when the arcing contacts have separated in all poles [5.10].

Detection of pole discrepancy in operating times: Contrary to the measurement of the circuit breaker's opening and closing time described above, the detection of pole discrepancy calls for synchronous measurement at all three poles of the device; the general measuring procedure is the same as above. IEC specifications regarding pole discrepancy of circuit-breakers state that the discrepancy in both opening and closing time should be less than one half cycle of the rated frequency; however, many manufacturers or utilities have stricter requirements e.g. maximum acceptable deviation in opening times of 5 ms [5.3].

Measurement of motor charging power and motor running time: Both the charging motor and its connecting gear may fail from time to time. Minor defects or faults will lead to an increase in charging power and running time per charging cycle. The resulting increase in temperature thermally stresses the insulating system of the motor's armature winding and may eventually lead to motor failure. In order to monitor the state of the motor in particular and of the charging system in general, the charging power of the motor can be determined by measuring motor current and voltage. Another possibility is to measure the operating time of the motor per charging cycle. In contrary to circuit breakers with hydraulic drives, where measuring the number of motor starts provides an indication of leakages in the energy storage system, for spring-operated units this information is of little value.

Measurement of coil current: Recording the current profile of the coils provides information about the condition of bearings and latches in the operating mechanism. Defects in the release mechanism are not uncommon for circuit breakers which are rarely operated; this measurement can detect the most frequently occurring problems. Some experience with this technique is, however, required in order to interpret the results. The reader can refer to [5.9] for a description of coil current patterns corresponding to different faults in the release mechanism. Coil current measurements are primarily applied for periodic diagnostic testing, with standard current measurement techniques such as shunts and Rogowski coils being applied.

Minimum trip voltage measurement: The measurement of the minimum voltage required to trip the release coils also provides indication of the condition of the release mechanism. According to IEC specifications, the circuit breaker's release mechanism should be able to perform its operation reliably as long as the supply voltage is above 70 % of its nominal value. Due to its simplicity, this method is widely used. The requirement to use a varying supply voltage, however, implies that it can only be applied during periodic maintenance, for the connection of the control system to the supply network must be broken.

It has to be noted that the above list is confined to diagnostic techniques of relevance for operational condition assessment. Some common monitoring techniques for circuit breakers such as measurement of stored energy, measurement of the control system's supply voltage, or continuous testing of the continuity of the control system are therefore not listed here. Such diagnostic and monitoring techniques identify failure modes which have to be corrected immediately. Consequently, the information they provide is not relevant to the process of condition assessment, since the defect will then have been removed.

5.2.2 Treating missing or obsolete data

Diagnostic tests and visual inspections are performed in a periodic manner, and the time interval between successive measurements can be significant. For instance, in [5.2] a time interval of eight years between scheduled maintenance has been found to be common; in [5.4] maintenance intervals of even up to 14–16 years have been reported. Obviously, findings of diagnostic tests dating so far in the past should not alone be used as a basis for condition assessment, no matter how accurate the tests themselves are. In this thesis, we shall refer to such data as *obsolete* data.

A problem quite similar to that of obsolete data is the one of *missing* data or information. In practice it can happen that, for some reason, a source of information initially intended to be considered for condition assessment is not accessible – at least not for all devices. We have already seen in 3.5.1 that the standard approach to condition assessment, the assessment matrix, cannot effectively account for this situation. No matter whether obsolete or missing, the more data from diagnostic tests is unavailable, the more should the assessment be based on experience and information on the loading of the equipment.

Following aspects are related to the loading profile of high-voltage circuit breakers in service and can be assessed by analysing service data: the location of the breaker, its service age, the frequency of switching, the number of interrupted short-circuit currents, the continuous current loading or temporary overloading as well as the dissipation of energy in the interrupter during arcing.

Location: The location of a circuit breaker has been found by many surveys to be related to its overall unavailability. High-voltage circuit breakers can be installed either indoors or outdoors, with the latter approach being most common for live-tank breakers. As can be seen from table 5.3, unavailability of circuit breakers located outdoors is generally higher, mainly due to corroded flanges and damaged gaskets and seals, leading to SF_6 leakage. Although corrosion is recognised by utilities as an influencing factor, ambient temperature is not considered to contribute to failures of circuit breakers installed outdoors: more than 95 % of utilities participating in the second Cigré enquiry stated that ambient temperature is a negligible stress factor [5.2].

Service age: Service age is still one of the most important condition indicators used by electric power utilities. Generally speaking, service age can provide indication of those ageing and deterioration processes which are not so much related to wear, but rather depend on time to evolve. This is why it is mainly significant in the wear-out phase, i.e. when the device reaches or exceeds its expected lifetime. Older circuit breakers deserve more attention than newer ones, because of many reasons: First, the older the device, the more limited is

Table 5.3.: Failure rates of single-pressure SF_6 circuit breakers with mechanic drive in dependence of their location [5.2]. Rates are in % per annum.

Location	SF_6 leakages	Minor drive failures	Major drive failures
Indoors	0.83 %	0.05 %	0.21 %
Outdoors	2.04 %	0.45 %	0.28 %

the service experience related to it, since the number of installed devices of the same type in an electric power system decreases with increasing service age. Unknown or not yet fully understood failure modes may exist, calling for special maintenance actions. Second, deterioration processes during the wear-out phase are in general faster. Retaining long time intervals between successive maintenance activities could allow for incipient failures to evolve, eventually leading to unplanned outage. Finally, older devices are usually more difficult to maintain, since not all maintenance workers have the required experience and skills.

Number of operations: The number of operations is commonly used for condition assessment purposes, especially when combined with knowledge and experience with the circuit breaker considered. Many utilities plan inspection and maintenance according to this parameter. The underlying assumption is that mechanical and electrical wear of the breaker generally increases with use. However, experience shows that this simple relationship between number of operations and overall condition is not valid in many cases. For instance, breakers that are rarely operated show a higher probability for defects or faults, especially with regard to the drive unit.

Continuous load current: Although the measurement of load currents in a power system mainly serves control and protection purposes, it can also provide information on the loading level of a circuit breaker. This is particularly important in case the device has been operated beyond its specifications for a limited period of time.

Interrupted short-circuit current: The number of short-circuit current interruptions is perhaps the strictest constraint in circuit breaker operation. Due to their extremely high magnitude, short-circuit currents pose a major stress to high-voltage circuit breakers, although CBs are actually intended to make, carry and break such currents. The components primarily stressed are the interrupters, due to the energy dissipated by the arc, but also the operating mechanisms must overcome significant forces. For this reason, manufacturers generally recommend a complete dismantling of the circuit breaker after a maximum of seven short-circuit current interruptions per pole.

Arcing energy: The Joule integral over the arcing time[4] has been proven by experiments to be a good indicator of the wear of arcing contacts. However, contact wear due to the dissipated energy during arcing does not seem to be a significant problem for modern circuit-breakers: Dismantling and inspection of the contacts of circuit-breakers that have been in service for many years reveals that the arcing contacts are virtually as new. Accurate assessment of arcing energy calls for precise measurements of the waveform of the current so as to identify the arcing time. On-line measuring systems can satisfy the requirement for high accuracy, but are rather expensive so that their application in the field is not common. A simpler approach is to estimate the accumulated arcing energy by simply counting the number of circuit breaker operations and using average values for the arcing time and interrupted current. The average arcing time and interrupted current can be found by means of power system simulation as shown in [5.17, 5.18].

[4] The *arcing time* is defined as the time interval between initiation of the arc (for an opening operation: instant of contact separation of the arcing contacts) and final arc extinction in the interrupter of a circuit breaker.

In the previous section we have already identified a total of twenty diagnostics-based condition indicators (table 5.2 on page 88); the six service-based CIs presented here should be added to them. The method to combine these two groups of indicators has been introduced in [5.1] and will be presented here in brief.

The main idea is to define a *maximum usability period* (MUP) for each diagnostics-based CI, which describes the temporal significance of the respective information. Every time data is assessed in order to evaluate the degree of compliance with a particular CI, the result of the assessment should obtain a time stamp. In case condition assessment is performed at a later stage, these time stamps have to be compared to the respective MUPs so as to identify potentially obsolete data. The maximum usability period is thus a “best before” indication for condition assessment.

Let t_i be the time of information retrieval regarding the i^{th} condition indicator, MUP_i be the maximum usability period for this CI, and t_{as} be the time at which condition assessment is performed, $t_{as} \geq t_i \quad \forall i = 1, \ldots, n$. The *usability factor* u_i then describes the temporal significance of the respective condition indicator, as show in equation 5.1:

$$u_i(t_{as}) = \max\left\{\frac{t_{as} - t_i}{\mathrm{MUP}_i}, 0\right\} \quad \forall i = 1, \ldots, n \tag{5.1}$$

Obviously, the usability factor takes values in $[0, 1]$, with 1 meaning that the information expressed by the respective CI is absolutely up-to-date, and 0 implying that the data is obsolete and should not be used for assessment. The degree to which service-based CIs should be implemented can be found by aggregating over all n diagnostics-based condition indicators. However, before this can take place, the information content of each CI must be assessed, as will be shown in the next section.

5.3 Assessing the information content of CIs

In the previous sections, 26 condition indicators have been identified for the purpose of operational condition assessment of circuit breakers. Obviously, establishing the rule base of a fuzzy system with this amount of input information in a direct way is not feasible: even if only two linguistic values per input are considered, the complete rule base of such a system would amount several ten millions of rules!

On a closer look, however, one can notice that most indicators are related only to some of the functional units defined in section 5.1. The approach proposed here is therefore to use simple rules and connect each condition indicator to each functional unit in a direct way. The resulting rules would then feature only one fuzzy variable in the antecedent (the CI) and one fuzzy variable in the conclusion (the assessed condition of the functional unit). Combinations of the fuzzy variables in the input space would thus be neglected and the size of the fuzzy rule base would depend only linearly from the dimensionality of the problem.

In principle, the condition of each functional unit is then assessed in direct relation to the outcome of a diagnostic test: if the outcome of the test is positive, then the assessment result is also positive. A limitation of this approach is that, in case of contradictory information e.g. when the result of diagnostic test i is positive while the finding of diagnostic test j is negative, both condition indicators would be given the same importance so that one could not say whether the condition of the functional unit should be assessed in a positive or negative way. The result would be complete uncertainty of the output variable – a rather unsatisfactory outcome.

However, not all condition indicators possess the same information content when it comes down to assessing the condition of the individual functional units. For instance, the measurement of SF_6 purity is expected to provide good insight into the condition of the inner insulation of the circuit breaker, but would be of little value for the assessment of the operating mechanism. For this reason, the concept of *information content* (or entropy) of a CI is introduced. The information content β_{ij} is a measure of how much information about the condition of the j^{th} functional unit is included in the i^{th} condition indicator.

Experience with the particular circuit breaker and deep knowledge of the underlying failure modes is required in order to effectively assess the information content of the various CIs. The results of a failure mode and effect analysis can be a very useful source of information in this process. The approach taken in this thesis is summarised in figure 5.1.

First, a table should be compiled in two copies, featuring the condition indicators as rows and the functional units as columns. Following questions should then be answered – one by one:

1. *Assuming there is a defect at component level, will this defect be reflected in an alarming outcome of the diagnostic test?* Or equivalently: *Does a positive outcome of the diagnostic test ensure that the functional unit is in good condition?*

2. *Assuming the results of the diagnostic test are alarming to what extent could they originate from a defect within the functional unit?*

The above questions are different perspectives of the correlation between positive or negative outcomes of the diagnostic test on the one hand and good or poor condition of the functional

Preparation

Compile the assessment table (two copies):

- condition indicators are listed in the rows
- functional units are listed in the columns

Assess necessity

For each functional unit fill in vertically by answering the question:

Assuming there is a defect at component level, will this defect be reflected in an alarming outcome of the diagnostic test?

Assess likelihood

For each condition indicator fill in horizontally by answering the question:

Assuming the results of the diagnostic test are alarming to what extent could they originate from a defect within the functional unit?

Figure 5.1.: Assessment of the information content of condition indicators. For the assessment results refer to appendix D.2.

unit on the other hand. In particular the first question investigates *necessity,* that is the conditional probability of the outcome of the test given the underlying condition of the functional unit, while the second question investigates the *likelihood* of the underlying condition given the outcome of the test.

By applying this approach, the information content has been assessed for all specified condition indicators. The results are summarised in tables D.3 and D.4. As can be seen there, most condition indicators are related to one or two functional units at a time. It is also noticeable that service-based CIs do not possess any information content with regard to necessity. This is reasonable, since service-based indicators express only an expectation, but no causality.

On the basis of tables D.3 and D.4 a fuzzy inference system is designed in order to assess the condition of functional units. Its main features are:

- Each condition indicator defines a fuzzy input variable x_i which may take following linguistic values: "findings better than reference", "findings according to reference", and "findings worse than reference". The linguistic values are represented respectively by fuzzy sets A_i^{in}, B_i^{in} and C_i^{in}.
- The condition of each functional unit defines a fuzzy output variable c_j which takes following linguistic values: "good condition", "moderate condition", and "poor condition". The linguistic values are described by fuzzy sets A_j^{out}, B_j^{out} and C_j^{out}, respectively.
- The inference rules for the assessment of the j$^{\text{th}}$ functional unit on the basis of the i$^{\text{th}}$ condition indication are defined automatically according to following general scheme:

$$\text{if } x_i = A_i^{in} \text{ then } c_j = A_j^{out} \quad \forall i, j \tag{5.2a}$$

$$\text{if } x_i = B_i^{in} \text{ then } c_j = B_j^{out} \quad \forall i, j \tag{5.2b}$$

$$\text{if } x_i = C_i^{in} \text{ then } c_j = C_j^{out} \quad \forall i, j \tag{5.2c}$$

The above scheme treats all condition indicators equally: their influence on the assessment result is not limited according to their significance. The above rule base is therefore adapted by introducing the information content, as it has been assessed before. In this section we will denote by β_{ij}^{ℓ} the degree of likelihood related to combination of the i$^{\text{th}}$ CI and the j$^{\text{th}}$ functional unit, and by β_{ij}^{n} the respective degree of necessity.

By closer examination of the first question in figure 5.1, it is obvious that all fuzzy rules whose output is "good condition" should be limited by the corresponding degree of necessity. On the other hand, the second question implies that all rules with an outcome "poor condition" should be limited by the corresponding degree of likelihood. Finally, fuzzy rules whose outcome is "moderate condition" can be assessed by using each of the two question; they should by therefore limited by the union of necessity and likelihood. We can now re-write the above fuzzy rule set in a way that accounts for the information content of each condition indicator:

$$\text{if } x_i = A_i^{in} \text{ and } \beta_{ij}^{n} \text{ then } c_j = A_j^{out} \quad \forall i, j \tag{5.3a}$$

$$\text{if } x_i = B_i^{in} \text{ and } \left(\beta_{ij}^{n} \text{ or } \beta_{ij}^{\ell}\right) \text{ then } c_j = B_j^{out} \quad \forall i, j \tag{5.3b}$$

$$\text{if } x_i = C_i^{in} \text{ and } \beta_{ij}^{\ell} \text{ then } c_j = C_j^{out} \quad \forall i, j \tag{5.3c}$$

So far, we have not discussed the fuzzification process used in order to evaluate the degree of membership of element x_i to fuzzy sets A_i^{in}, B_i^{in} and C_i^{in}. Although this aspect is important for the assessment result, it is more a question of interpretation of the diagnostic results, rather than an issue of condition assessment. For this reason, it will not be covered here. In brief, every interpretation scheme compares the actual outcome of the diagnostic test (measuring result) with some reference value and determines whether there is any abnormal deviation. Reference values for some of the condition indicators identified for HVCBs can be found in appendix D.3.

The rule base in equation 5.3 does account for the information content of condition indicators, but still neglects the question of temporal significance. In section 5.2.2 we have already discussed this issue and introduced the concept of maximum usability periods and usability factors in order to treat missing or obsolete information. We shall now integrate this concept into the rule base.

First, the n CIs have to be grouped into n_d diagnostics-based and n_s service-based indicators. For each diagnostics-based CI its usability factor u_i ($i = 1, \ldots, n_d$) is then determined according to equation 5.1. In a last step, the *contribution factor* u_j^f of service-based CIs for each functional unit is evaluated according to equation 5.4.

$$u_j^f = 1 - \underset{i}{\perp} \top \left\{ u_i, \perp \left[\beta_{ij}^n, \beta_{ij}^\ell \right] \right\} \quad \forall j \tag{5.4}$$

The meaning of this equation is following: "For each functional unit, identify the diagnostics-based CI with the highest contribution to the assessment result. Then use its negation in order to limit the contribution of all service-based CIs". When assessing the condition of a particular functional unit, the evaluated contribution factor must therefore be applied to each service-based CI. The final rule base is summarised below:

Diagnostics-based condition indicators:

$$\text{if } x_i = A_i^{in} \text{ and } \beta_{ij}^n \text{ and } u_i \text{ then } c_j = A_j^{out} \quad i = 1, \ldots, n_d \quad \forall j \tag{5.5a}$$

$$\text{if } x_i = B_i^{in} \text{ and } \left(\beta_{ij}^n \text{ or } \beta_{ij}^\ell \right) \text{ and } u_i \text{ then } c_j = B_j^{out} \quad i = 1, \ldots, n_d \quad \forall j \tag{5.5b}$$

$$\text{if } x_i = C_i^{in} \text{ and } \beta_{ij}^\ell \text{ and } u_i \text{ then } c_j = C_j^{out} \quad i = 1, \ldots, n_d \quad \forall j \tag{5.5c}$$

Service-based condition indicators:

$$\text{if } x_i = A_i^{in} \text{ and } \beta_{ij}^n \text{ and } u_j^f \text{ then } c_j = A_j^{out} \quad i = 1, \ldots, n_s \quad \forall j \tag{5.6a}$$

$$\text{if } x_i = B_i^{in} \text{ and } \left(\beta_{ij}^n \text{ or } \beta_{ij}^\ell \right) \text{ and } u_j^f \text{ then } c_j = B_j^{out} \quad i = 1, \ldots, n_s \quad \forall j \tag{5.6b}$$

$$\text{if } x_i = C_i^{in} \text{ and } \beta_{ij}^\ell \text{ and } u_j^f \text{ then } c_j = C_j^{out} \quad i = 1, \ldots, n_s \quad \forall j \tag{5.6c}$$

The above rule base can be easily implemented in a computational programme e.g. in MATLAB® in order to set up a fuzzy inference system. Before implementation, all fuzzy rules for which at least one of the limiting factors equals zero should be eliminated, since they do not contribute to the output. However, one module of the fuzzy inference system is still missing: the accumulation of the individual functional units so as to evaluate the composite asset health index.

5.4 Overview of the developed fuzzy system and discussion

According to the discussion in chapter 3, any assessment scheme for operational condition assessment should use available information about the technical condition of the equipment as input and return an asset health index as output. The fuzzy inference system defined by the rule base in section 5.3 fulfils the first requirement, but its output are estimates of the condition of the individual functional units. The last step is thus to accumulate these estimates into a (numerical) asset health index. For this purpose, the findings of section 5.1 are used.

Due to the great importance of the operating mechanism for the overall reliability of high-voltage circuit breakers (both with regard to minor and major failures), its contribution to the AHI should be higher than for the other functional units. The remaining functional units should preferably contribute to the AHI in some way similar to their share of minor and major failures. Following approach has been therefore taken for the construction of the rule base, which infers the AHI from the condition of the functional units.

In case all functional units are assessed to be in good or moderate condition, the AHI is computed by taking their weighted mean. The values listed in table 5.1 are used as weighting factors for averaging. This is expressed mathematically as:

$$\mu_A(\mathrm{AHI}) = \frac{\sum_j w_j \cdot \mu_{A_j}(c_j)}{\sum_j w_j} \qquad \mu_B(\mathrm{AHI}) = \frac{\sum_j w_j \cdot \mu_{B_j}(c_j)}{\sum_j w_j} \tag{5.7}$$

where $\mu_A(\mathrm{AHI})$ and $\mu_B(\mathrm{AHI})$ are the degrees of membership of the composite asset health index to the output fuzzy sets A and B, representing the linguistic values "AHI is good" and "AHI is moderate", respectively, and w_j is the weighting factor of the j^{th} functional unit from table 5.1. In order to account for both minor and major failures it is recommended to take the average of the values listed there.

A different approach is taken for assessing the AHI when at least one functional unit has been found to be in "poor condition" (fuzzy set C_j). In particular, a complete fuzzy rule base is established for this case according to the guidelines given in table 5.4. The resulting rule base comprises thus 31 fuzzy rules which can be easily implemented.

It must be however stressed, that both modes of reasoning work in parallel. In other words, during assessment both the weighted averaging rules of equation 5.7 above as well as the rule base derived from the guidelines of table 5.4 will be usually activated to some extent.

Table 5.4.: Fuzzy rule base for AHI determination in case at least one functional unit is assessed to be in poor condition.

Rule's antecedent	Rule's conclusion
At least one functional unit, but not the drive, is in poor condition	AHI is C+
At least two functional units, or the drive unit alone, are in poor condition	AHI is C
Three of more functional units, or the drive and at least another unit, are in poor condition	AHI is C–

After accumulating over all rules, the AHI is still described by a fuzzy variable, i.e. by the degrees of membership to each linguistic value "good", "moderate" and "poor" (represented by fuzzy sets A, B and C respectively). The last process is therefore defuzzification, which returns a crisp numerical value for the asset health index between 0 % and 100 %. Similar to the FIS presented in chapter 4, several possibilities exist. If all linguistic values are considered during defuzzification, the resulting AHI can be used in order to rank the various circuit breakers in the electric power system. On the other hand, if a measure of urgency of maintenane is asked for, then it would be more appropriate to consider only linguistic value "poor" when defuzzifying. Refer to section 4.4 for more information on the defuzzification process.

The previous sections have shown how a fuzzy inference system for the purpose of operational condition assessment can be designed. The procedure proposed here consists of breaking the equipment down to its functional units (analysis), identifying relevant condition indicators as well as their information content with regard to each functional unit, and then aggregating the assessed degrees of compliance with each condition indicator (synthesis) in two stages so as to finally evaluate the composite asset health index. In this way the major obstacle for setting up a fuzzy system for operational condition assessment –the high dimensionality of the input space– can be cleared, while at the same time available maintenance engineering knowledge is captured in a systematic way.

Moreover, the fuzzy inference system developed in this case study is capable of treating missing or obsolete data in a consistent way, since the underlying rule base is not defined by means of pairwise comparisons between the various condition indicators. Even more, its adaptive structure enables the substitution of missing or obsolete information from diagnostic tests by indicators of the equipment's loading profile and the general service experience.

> *In conclusion, fuzzy inference systems can be helpful for the purpose of operational condition assessment, in particular when the sources of information involved are obsolete or contradictory.*

The case study in this chapter has shown how a fuzzy inference system can treat uncertainty in operational condition assessment. An important aspect is, however, the source of such uncertainty – especially the uncertainty which rises from the interpretation of diagnostic tests. This aspect as well as the potential of fuzzy logic to incorporate uncertainty during diagnostic analysis will be discussed in the second part of the thesis.

6 Introduction to Dissolved Gas Analysis

> This marriage of oil and paper has almost perfect intimacy. They are the two cheapest insulating materials available, but their combination is the best yet known and gives an electric strength much higher than either separately.
>
> E. T. Norris, 1963

Oil-impregnated paper insulating systems traditionally play an important role in high-voltage engineering. Their main field of application covers both instrument and power transformers as well as power cables (although oil-filled power cables are increasingly substituted by modern cross-linked polyethylene cables). This chapter provides a historical and theoretical background of oil-impregnated paper insulating systems, with special focus on cellulose-based papers and mineral insulating oils.

For condition assessment purposes of oil-filled power apparatus, dissolved gas analysis (DGA) is widely employed. The second part of this chapter provides the necessary theoretical background on DGA. An unpublished review of DGA history is also given. Chapters 7 and 8 will then demonstrate the use of DGA for high-voltage instrument and power transformers, respectively.

6.1 Oil-impregnated paper insulation

In the beginnings of high-voltage engineering, various fibrous materials, both cellulosic and non-cellulosic, were used for electrical insulation purposes. Examples of such materials include cotton rag, silk, jute etc. Around 1920, blends of kraft wood fibres and manila hemp fibres began to be used for telephone cable insulation [6.1]. In the following years, much research has been performed on the dielectric improvement of oil-impregnated paper insulation [6.2–6.5].

Apparently, the combination of kraft paper and insulating oil (mainly mineral) as impregnant was introduced on a wide base in transformer engineering by the late 1920s and early 1930s [6.1]. At the same time in Switzerland, Weidmann developed the first pressboard made from kraft pulp without any use of binders. This new product, known under the commercial name “transformerboard”, could be easily fabricated into formed items, and these were ideal for high-stress areas [6.6]. Since the 1940s, transformerboard has also been used in the main, inter-winding insulation.

In the mid 1960s thermally upgraded paper has been introduced in the USA. The purpose of upgrading is to increase the insulation life, or –in case the lifetime is kept constant– to reach higher utilisation by operating at higher temperature. The most successful formulas for upgrading agents used amine compounds, particularly dicyandiamide. Outside the United States most countries still use non-upgraded kraft paper insulation, and a 98 °C hottest spot temperature [6.1].

Further development came with the introduction of mixed dielectric materials in the late 1950s: such mixtures of cellulosic and synthetic materials, using oil as impregnant, began to replace the traditional oil-paper insulation in power cables and capacitors. In [6.7] the use of a synthetic, polymer-based paper impregnated with oil is described. The results of this study indicate that the physical and electrical properties of these oil-impregnated polypropylene webs are quite adequate to make the webs a promising replacement for kraft paper in high-voltage insulation systems. The mechanical properties, although lower than those of kraft paper, may well be sufficient for cable applications. In the following sections, the oil-impregnated paper insulating system is described in more detail.

6.1.1 Dielectric papers and boards

Dielectric papers and boards may be produced from a variety of materials, including wood pulp, cotton and jute rag, manila hemp, linen and other organic fibres, as well as glass, ceramic and mica [6.8]. The most common materials are sulfate wood pulp derived from softwood trees, also known as *kraft* wood pulp (from the German word *Kraft*, meaning strength), and manila hemp. The latter is used for manufacturing manila paper, a semi-bleached chemical sulfate paper featuring lower rigidity and roughness than kraft paper.

Although the distinction between dielectric paper and board is not clear, paper is usually thinner than 30 μm, while boards consists of several layers adding up to 80–130 μm [6.9]. As a result, boards are used where an insulation structure is needed, e.g. for inner-winding insulation purposes. On the other hand, dielectric paper is usually used for inner-turn insulation. Insulating boards are also referred to as pressboard, fuller board and transformerboard [6.8].

In the following, we shall concentrate on cellulose-based dielectric papers and boards, especially kraft paper and transformerboard, as these are the main solid insulating materials in power system equipment considered in chapters 7 and 8.

Cellulose is a high-molecular-weight polymer with the general molecular formula $(C_6H_{10}O_5)_n$. The cellulose molecule is presented by a chain of glucose rings, the number of which is of the order of one thousand, as shown in figure 6.1. The polar hydroxyl groups provide cross-linking of the molecules resulting in crystalline areas embedded in amorphous areas [6.8, 6.9]. This results into the known fibrous structure with average capillary diameters of approximately $0.01 - 0.1\,\mu$m and a high internal surface. The latter aspect also accounts for the hygroscopic behaviour of cellulose. Through a manufacturing process called *cyanoethylation*, this moisture-absorbing tendency of cellulose is reduced [6.8].

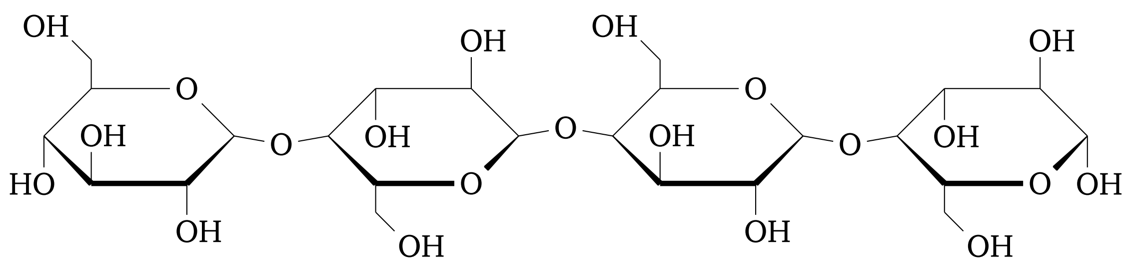


Figure 6.1.: Cellulose molecule.

The most important process steps in kraft paper production are [6.8]:

1. At first, undesirable components are removed by boiling wood particles with a solution of sodium sulfite and sodium hydroxide under pressure. Such undesirable components include lignin and hemicellulose, both significant components of soft wood with a concentration of approximately 20–30 % and 10–15 % by weight, respectively.
2. The resulting slurry is chopped in a rotating drum (the so-called *beater* or *refiner*) equipped with closely spaced sharp knives.
3. The pulp is then diluted to contain over 98 % water, the mixture then being mechanically and magnetically filtered so as to remove grit and magnetic particles.
4. In several process steps, the mixture is successively rolled by felt-covered rollers and a series of heated drums, leaving approximately 4 to 6 % by weight moisture in the paper.

Especially the last process step of drying is of high importance for the dielectric and mechanical properties of insulating paper. Too high a moisture content in the cellulose leads to increased dielectric loss resulting in accelerated ageing, as will be shown shortly. On the other hand, extensive drying at higher temperature would already cause significant ageing of the cellulose during manufacturing [6.10]. The temperature should therefore remain below 120 °C throughout the drying process in order to avoid paper ageing [6.9].

Several standards deal with cellulose-based paper production. In general, they may be divided in two main categories: i.) standards considering wood pulp composition and characteristics, and ii.) specifications regarding mechanical strength properties, physical properties and electrical behaviour. In appendix E.3 an overview of the most important standards on dielectric papers and boards by the International Electrotechnical Commission (IEC) and the American Society on Materials and Testing (ASMT) is provided.

Electrical permittivity of untreated kraft paper is lower than the permittivity of cellulose (approximately 2.8 compared to 6.1, respectively [6.9, 6.10]), due to the capillary structure of paper characterised by voids between the individual fibres. The dissipation factor is rather high

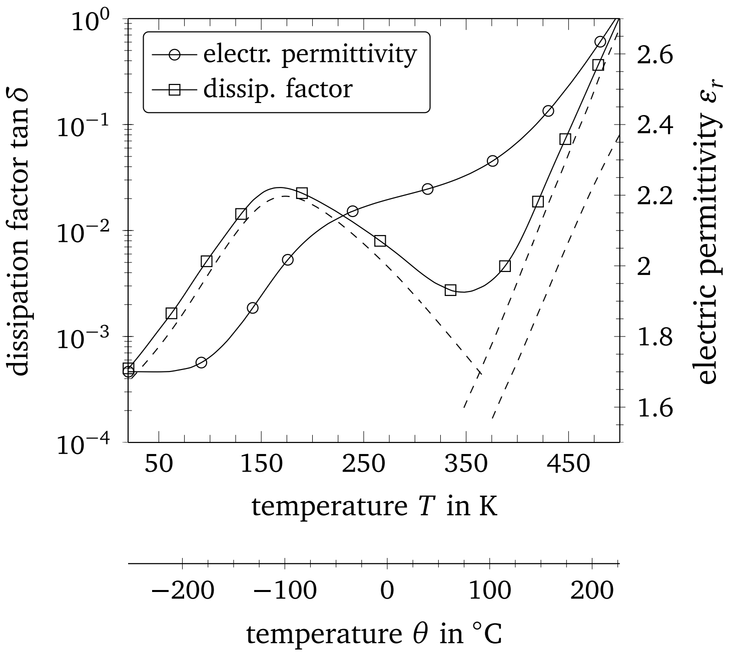


Figure 6.2: Dissipation factor of dielectric paper as a function of temperature, measured at a cylindrical paper sample of 0.7 mm thickness and water content amounting 0.5 % by weight (redrawn from [6.9]).

for an insulating medium and amounts to 0.2–0.5 % for dry papers [6.10] and sharply increases when the moisture content exceeds 0.1 % by weight, as will be shown later [6.9]. Figure 6.2 shows the dependance of the dissipation factor on temperature for a paper sample [6.9]. Several processes can be identified in this figure: the influence of electrical (ionic) conductance, starting at temperatures around 350 K, as well as two polarisation mechanisms (in the region 0–300 K and in the region 400 K upwards).

Some theoretical background on dielectric properties of insulating materials, both liquids and solids, can be found in appendix E.1. In general, dielectric behaviour of any material may be described by means of its electrical permittivity ε_r, electrical conductivity σ, dissipation factor tan δ, and dielectric strength E_{50}. These properties are not constant, but depend on various parameters, mainly temperature T, electric field strength E, and moisture content w.

The resistivity of dry cellulose is quite satisfactory for insulating purposes (approximately $4\times10^{10}\,\Omega$m) and is not sensitive to sufficiently small deviations from complete dryness [6.11, 6.12].

Regarding their mechanical properties, dielectric papers and boards are usually characterised by their degree of polymerisation or their tensile strength. The *degree of molecular polymerisation* (DP) is the average number of glucose rings of the cellulose molecule. It is obtained by a measurement of the viscosity of a solution of paper in an appropriate solvent. There is a close relationship between the DP and the mechanical properties of the paper. A new case study on the correlation between the DP of cellulose and its mechanical strength is given in [6.13]. Generally speaking, the lower the DP the lower is the mechanical quality of the paper. The DP of new kraft paper ranges from 1000 to 1400 [6.1, 6.10, 6.14], but decreases over time due to ageing. With this reduction in the DP of cellulose, there is a decrease in mechanical strength.

Summing up, untreated cellulose insulating papers and boards have dielectric strengths little better than air, high dielectric loss factors and poor mechanical strength [6.8]. Their greatest weakness is their high affinity to moisture. However, when treated by impregnation or coating with resins and varnishes (low-voltage applications) or by impregnation with liquid dielectrics (high-voltage equipment), paper and boards become widely useful as will be shown in section 6.1.3.

In 1960, Fabre already described in detail the deterioration mechanisms acting on kraft paper [6.15]. Deterioration seems to commence by hydrolysis and continues by oxidation, with a breakdown of the molecular chains and the opening of the glucose rings with the elimination of water. The DP decreases continuously down to about 100. The main deteriorating agents for kraft paper are:

Temperature/heat: several chemical reactions contribute to degradation (mainly *oxidation*, *pyrolysis* and *hydrolysis*). As a rule of thumb, for every 6–10 °C rise in temperature, reaction rates double [6.14].

Oxygen: cellulose oxidises readily and directly to carbon oxides. The carbon oxides found in oil-filled electrical equipment result primarily from the cellulose material (refer also to section 6.2).

Moisture: the rate of thermal deterioration of paper is proportional to its water content. This approximate law is valid for water contents in the range 0.3 % to 7 % and for states of final deterioration which are relatively average [6.15]. Figure 6.3 shows the moisture content of craft paper at equilibrium as a function of the relative humidity in air at room temperature [6.16].

Acids: cellulose can by degraded by *hydrolysis*. Hydrolysis is a chemical reaction during which molecules of water (H_2O) are split into hydrogen cations H^+ and hydroxide anions OH^-, the latter used to break down the cellulose polymers, thus decreasing the degree of polymerisation. This process is catalysed by acids produced from the oil as a result of oxidation.

It is generally agreed that deterioration of dielectric paper is primarily mechanical and not electrical. In order to assess the mechanical condition of cellulose, the best method seems to be in comparing its tensile strength [6.13]; dielectric stress, on the other hand, was found to be no criterion by which to judge the degree of mechanical ageing already in 1939 (refer to the discussion in [6.17]).

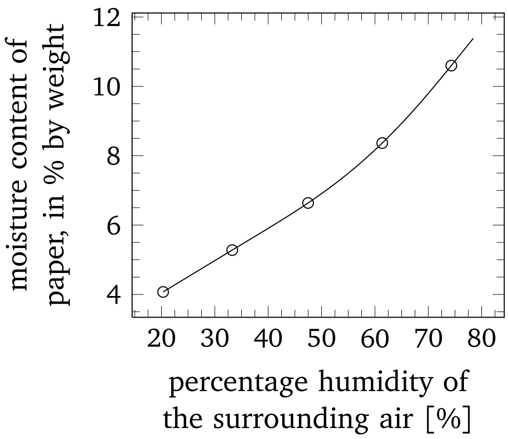


Figure 6.3: Moisture content of kraft paper as a function of the relative humidity of the ambient air at room temperature (redrawn from [6.16]).

6.1.2 Mineral oil

In combination with solid dielectrics, insulating oils[1] fulfil a threefold function [6.18]: First, they provide the necessary *electrical insulation* in the solid-free space and impregnate the solid dielectric, thus filling potential voids within the latter and enhancing its insulating properties. Second, insulating oils assist in transferring excessive heat to the surrounding medium. This requirement for *heat dissipation* is of particular importance in power transformers where power loss leads to localised heating of winding and core. Generally speaking, the thermal design of oil-filled power apparatus mainly depends on the heat transfer capability of the applied oil. The third, sometimes neglected, although equally important function of insulating oils is of *diagnostic* nature: the condition (both electrical and chemical) of the oil reflects the general operational condition of the electrical device and can provide evidence of potential ongoing deterioration processes inside its internal insulation system [6.14].

The chemical, physical and electrical properties of the oil will affect its compliance with the (application-specific) requirements for electrical insulation and heat dissipation. Table 6.1 gives an overview of the most important properties of insulating oils, which shall be described in the following paragraphs.

[1] The term “insulating oil” is used in this thesis as equivalent to all insulating liquids used in high-voltage power apparatus, including e.g. natural and synthetic esters, other synthetic liquids etc. In case only mineral insulating oil is referred to, this will be explicitly denoted.

Table 6.1.: Chemical, physical and electrical properties of insulating oils and their influence on the required functions (electrical insulation, thermal dissipation and diagnostic purposes). In general, chemical properties affect the ageing behaviour, electrical properties the insulating capacity and physical properties both heat dissipation and insulating capacity. The last column accounts for general operational and design aspects such as e.g. fire hazard or material compatibility.

property	insulation	heat dissipation	diagnostics	other aspects
chemical properties				
oxidation stability	✓	✓	✓	
acidity	✓		✓	✓
gassing tendency	✓		✓	
water solubility	✓		✓	✓
ionic contamination	✓			
physical properties				
thermal conductivity		✓		
density	✓	✓		
viscosity		✓		✓
solvent power				✓
vapour pressure	✓		✓	✓
flammability				✓
electrical properties				
dielectric strength	✓		✓	
electrical conductivity	✓		✓	
dissipation factor	✓		✓	

The chemical stability of insulating oils is particularly important, since they have to fulfil their required functions for a long period of time, preferably over the complete lifetime of the equipment. In general, the ageing behaviour of a material is mainly influenced by its resistance to *oxidation*. In the case of mineral oils –the most common insulating liquids– oxidation proceeds by a free-radical-initiated chain-reaction mechanism[2] [6.19]. Oxygen concentration and temperature are the main parameters influencing the rate of oxidation. Furthermore, oxidation is accelerated by the presence of metallic catalysts e.g. copper or iron and slowed down in case oxidation inhibitors or passivators[3] are used.

[2] For the example of straight paraffinic hydrocarbons molecules, oxidation follows three successive chemical reactions: at first, the hydrocarbon reacts with oxygen to generate a hydroperoxide, which in turn transforms to a ketone by loosing water. Finally, the ketone reacts with oxygen to produce a carboxylic acid [6.19].

[3] *Oxidation inhibitors* are naturally present in small amounts in mineral oils, e.g. as sulphur compounds, or may be intentionally added so as to slow down oxidation. They react with the free radicals or peroxides, initially generated by oxidation, and bind them into inactive, stable molecules, thus terminating the chain mechanism [6.20]. By doing so, they are used up over time and eventually have to be replaced. The most common oxidation inhibitor is butylated hydroxytoluene (BHT) [6.21] which is added to mineral oils in a 0.3 % by weight concentration [6.22]. On the other hand, *passivators* prevent metallic catalysts form accelerating the

The products of oxidation are acids, solids (referred to as *sludge*) and water, all of which adversely affect the oil's electrical properties [6.8, 6.19]. In addition, sludge deposited on windings and cooler ducts[4] of transformers impairs heat transfer and results in increased temperature and oxidation rate. In order to assess oxidation, it is therefore sufficient to determine the total amount of acids and sludge.

However, acids in an insulating oil are not only due to to oxidation, but may be initially present in traces. High acidity can lead to corrosion of metals or other materials (e.g. cellulose) in contact with the oil. The *neutralisation value*[5] is used as a measure of acidity. Acidity of an oil is also described by the *saponification value*, although determination of the latter also includes esters reacting with boiling alcoholic alkali (in contrary to the neutralisation value, where only acid compounds are neutralised).

The *gassing tendency*, both under normal and excess stress conditions, is a further important chemical property of an insulating oil. Formation of gas bubbles in the oil reduces its dielectric strength [6.23, 6.24] and the higher electric field inside the gas space may lead to partial discharges. The gas bubbles themselves may result from pressure or temperature variations, from trapped gases in voids within the solid insulation, or from gases produced by thermal degradation e.g. hydrogen. The type of gases generated by the oil when stressed is characteristic for its chemical composition and the applied stress. A more detailed description of the gassing behaviour of mineral insulating oils is given in section 6.2.

The solubility of water in the insulating oil is another important chemical property. It is strongly temperature dependent and varies with the constitution of the oil. In particular, water solubility increases with ongoing oxidation due to the greater attraction of the polar and ionic oxidation products [6.19]. Generally speaking, water within oil can exist in three states: in a dissolved state (most common), chemically bound to oil molecules, or free in case its concentration exceeds the saturation level. Water has a negative influence on the electrical properties of the insulating oil, since it increases its electrical conductivity and reduces its dielectric strength (refer to appendix E.1). It has to be stressed out that it is the *percentage saturation*[6] of water in oil which affects its dielectric strength rather than the absolute water content [6.25]. In the case of oil-impregnated paper insulating systems, the water solubility of the oil plays a significant role for the moisture equilibrium between paper and oil, as will be shown in section 6.1.3. Water in oil is measured in *parts per million* (ppm) using the weight of water divided by the weight of oil ($\mu g/g$).

Ionic contamination of insulating oils is usually caused by manufacturing processes. Potential ionic contaminants affect the oil's electrical properties, especially its electrical conductivity and dissipation factor, in a negative manner.

On a first sight, the physical properties of an insulating oil can be divided into such affecting general operating requirements and such influencing its heat dissipation capacity. The latter

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oxidation rate. Their mode of action relies upon forming a protective layer on the metallic surfaces so that they do not come in contact with the oil.

4 The solubility of sludge in oil is lower at lower temperature, and sludge deposits preferably on cooler surfaces. In the case of power transformers, sludge will be therefore found mainly in the oil ducts of radiators. As a results of sludge deposits, the effective duct diameter is decreased, leading to lower cooling power.

5 The *neutralisation value* is the amount of potassium hydroxide in mg KOH/g of liquid needed to neutralise the acid compounds of the liquid.

6 The relative humidity, or percentage saturation of water in oil, is defined as the ratio of the vapour pressure to the saturation vapour pressure. It is obtained by determining the dew-point of water vapour which has been transferred from the oil to a small volume of air [6.19].

group is mainly composed of the properties of *thermal conductivity*[7], *specific heat*[8], *density*, and *kinematic viscosity*[9].

The density of an oil, together with its specific heat capacity, determine the amount of energy per unit volume which is necessary to change the temperature of the oil to a specific degree. Consequently, these properties are important for transient phenomena, where heat generation due to power loss and heat dissipation to the surrounding medium are not balanced. On the other hand, thermal conductivity and kinematic viscosity mainly determine the rate at which heat is dissipated. They are therefore important properties regarding the type of cooling to be used (refer to table 8.1 for cooling systems used for power transformers).

It has to be noted that all aforementioned physical properties are not constant for an insulating oil, but change with temperature and oil composition. The dependence on temperature is important and has to be taken into account when designing an oil-filled power apparatus. Special care has also to be taken with respect to the expansion of oil at higher temperature. This effect is governed by the *coefficient of thermal expansion*. By specifying the acceptable temperature and pressure variation inside an oil-filled device and under consideration of the coefficient of thermal expansion it is possible to determine the free space required in the oil tank. Another important aspect related to the temperature-dependant behaviour of oil is the significant increase in its viscosity at low temperature. This phenomenon is quantified by the *pour point*[10] of the oil. The pour point is thus an important property for cold climate applications. IEC 296 defines three classes of insulating oils with respect to density and pour point [6.26].

In addition to the temperature dependence described above, physical properties as viscosity, density, thermal conductivity and specific heat are also influenced by the oil composition. For example, paraffinic mineral oils have higher viscosity and lower thermal conductivity than naphthenic oils [6.19]. Also, acids and sludge produced by oxidation change the oil's properties. In general, for an oil to be a good cooling medium, viscosity and pour point should be as low as possible, while thermal conductivity, specific heat and density should be as high as possible.

Solvent power, vapour pressure and flammability constitute the second group of physical properties; they are important with respect to general operational requirements of oil-filled power apparatus. The *solvent power* (or solvency) of an insulating oil describes the attractive forces between oil molecules and molecules of other materials. It is therefore of special importance in relation with the compatibility of oil with other insulating or conducting materials used within oil-filled power equipment [6.19].

The *vapour pressure*[11] of insulating oils has some influence on their electrical properties, in particular on the dielectric strength. An oil with high vapour pressure behaves in a gas-absorbing

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7 *Thermal conductivity* describes the ability of a material to conduct heat. It is measured in W/K·m and expresses the amount of heat conducted through a unit cube (with all edges equal to one meter) if a temperature difference of one Kelvin is applied to two opposite faces.

8 *Specific heat* or *specific heat capacity* describes the amount of energy needed to change the temperature of a material per unit mass. It is measured in J/kg·K.

9 The *viscosity* of a liquid describes its resistance to flow. Instead of the absolute viscosity (measured in $N{\cdot}s/m^2$), usually the *kinematic viscosity* is used. It is determined by dividing the liquid's absolute viscosity by its density. The measuring unit of kinematic viscosity is the Stoke (m^2/s).

10 The *pour point* of a liquid is the lowest temperature at which it will still continue to flow. Further decrease in temperature leads to flow cease.

11 The *vapour pressure* (more precisely: equilibrium vapour pressure) of a liquid/solid is the pressure of vapour above the liquid/solid phase in a closed system, at a given temperature. It is a measure of the tendency of particles to escape from the liquid/solid.

manner such as discharge inception voltage is increased [6.19]. This effect enhances dielectric strength (the breakdown mechanism in oil is briefly discussed below).

From an operational point of view, perhaps the most important physical property of an oil is its *flammability*. It is usually measured by the *flash* and *fire point*[12]. The safe operation of oil-filled equipment requires an adequately high flash point of the oil. Specific applications e.g. built-in distribution transformers or a high fire hazard call for the employment of oils with even higher flash points. IEC 60076-2 distinguishes between insulating oils with flash point lower than 300 °C (class O) and such with flash point above 300 °C (class K) [6.27].

Finally, the electrical properties of a liquid are obviously important in its function as an insulating medium. Here the properties of dielectric strength, electrical conductivity and dissipation factor will be briefly discussed. A more detailed theoretical description may be found in appendix E.1.

The *dielectric strength* of an insulating oil is measured according to IEC 156 [6.28]: two mushroom-shaped electrodes with an intermediate gap of 2.5 mm are used and a sinusoidal 50 Hz voltage is applied at 20 °C oil temperature. Usually, for new mineral insulating oils a breakdown voltage above 45 kV is required. Breakdown in insulating liquids under electrical stress has been a topic of intensive research in the past [6.23, 6.24, 6.29]. The mechanism of breakdown is rather complicated, but, can be described briefly by the following processes: under the influence of an electric field, contaminants into the oil migrate in the area between the electrodes and form "strings" which eventually bridge the gap [6.19]. Contaminants are always present in the oil (in the case of oil-impregnated paper insulating systems mainly in form of cellulose fibres) and usually attract water [6.29]. After the formation of these "strings" of contaminants, discharge inception leads to generation of gas bubbles along them. Ionisation eventually progresses until final breakdown. Water in the oil plays an important role in breakdown [6.18]; even small amounts significantly reduce its dielectric strength. Other parameters influencing the dielectric strength are pressure and temperature[13] as gases dissolved in the oil[14].

Electrical conductivity is another important property of insulating liquids (refer to appendix E.1 for a brief theoretical discussion). The main parameter influencing conductivity is the application time of the electric field, as this is related with the absorption of charge carriers [6.10, 6.30, 6.31]. Accordingly, one distinguishes between two characteristic values: the *ac* conductivity and the *dc* conductivity. Oil temperature and the strength of the applied electric field also have an influence on conductivity, although to much lesser extent than field application time. The measurement of dc conductivity is considered to be of greatest value for monitoring oil in service, as it has been shown to be reasonably proportional to oxidation acids and other contaminants e.g. water [6.19].

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12 The *flash point* of an oil is the temperature at which the vapour above its surface ignites spontaneously [6.20]. On the other hand, the *fire point* is the temperature at which the oil itself will ignite and continue burning. It is usually about 25 % above the flash point.

13 In the case of mineral insulating oils, the effect of pressure on dielectric strength has been found to be independent of the type of oil [6.24]: increasing pressure leads –in general– to higher dielectric strength. The temperature dependence, on the other hand, is not unambiguous; the dielectric strength of heavy, viscous oils falls with increasing temperature, since contaminants and particles are allowed to move more easily due to the lower viscosity. This, however, is not true with light, low-viscosity transformer oils: here, experiments showed that in the range of 25 °C to 100 °C dielectric strength is enhanced with increasing temperature [6.24]. This behaviour can be explained with proper consideration of the relative density of gases dissolved in oil [6.23].

14 In case of large temperature or pressure variations, gases dissolved in the oil could form bubbles and enable discharge inception.

The *dissipation factor* (also called *power factor*) of an oil[15] describes its tendency to absorb energy when an alternating electric filed is applied. It is analogous to the electrical conductivity and is affected by the same factors. However, the power factor test is not unambiguous, as there seem to be no established correlation between power factor and moisture, dielectric strength and acidity [6.16]. In general, the power factor of the oil is no guide to the power factor of the oil-impregnated paper [6.32]. High values of the dissipation factor lead to heat generation within the insulation oil and –if the excess heat is not effectively transferred to the surrounding medium– can result in thermal breakdown, since increased temperature further increases the oil's electrical conductivity and dissipation factor. The value of the dissipation factor of mineral oils is largely influenced by the water content, with dry oils having values in the range of 0.1 %, whereas moisted oils in practice could reach values above 5 % [6.10].

The development of insulating oils commenced with the introduction of the first oil-filled power transformers in the early 1890s. These first transformers, introduced both in Europe and the USA, featured mineral oil as insulating and cooling medium. By the end of the 19th century, commercial production of mineral oils specifically designed for power transformer applications had already started [6.33]. At the same time, investigations of natural ester liquids as a potential insulating medium for electrotechnical purposes have also been performed, but such plans were abandoned quickly, since ester liquids proved to have inferior oxidation stability, higher pour point and higher viscosity than mineral oils at that time [6.20].

Generally speaking, mineral insulating oils have always been the standard solution for power transformers from the early beginnings until now, mainly because of their low price, good insulating and cooling properties and ready availability [6.19]. Alternatives to mineral oils have also been investigated and introduced when more stringent requirements concerning fire resistance (flash point), electric permittivity, gas absorption or pour point are dictated by the particular application e.g. for railway traction transformers or built-in distribution transformers. Table 6.2 gives a brief historical overview of the development of insulating oils from the very beginnings up to now [6.19, 6.33, 6.34], described in more detail in appendix E.2. From here on, we will focus on mineral oils only, since they are and have always been the standard choice for oil-filled power apparatus.

Mineral insulating oils are produced by distillation and refining of crude petroleum. In a typical refinery which produces a full range of products, crude petroleum is distilled at atmospheric pressure to remove its low boiling contents, and these are used as fuels and solvents after appropriate refining. The residue is then distilled under vacuum to give stocks for the production of dielectric and lubricating oils [6.19, 6.22]. These are in turn refined by one or more of the following methods: solvent extraction[16], hydration (or hydrogeneration[17]), sulphuric acid extraction[18] and earth filtration[19]. The purpose of refining is to remove or reduce unstable or

[15] Refer to appendix E.1 for a theoretical discussion of the dissipation factor.

[16] *Selective solvent extraction* is a physical process and relies upon the selective solubility of oil components. In particular, aromatic compounds, being more soluble than paraffinic or naphthenic molecules, migrate more easily into the solvent [6.22].

[17] *Hydrogeneration* is a modern refining process in which the oil is refined in the presence of catalysts and hydrogen. During refining, aromatic hydrocarbons and unstable, reactive molecules react with hydrogen to form saturated, stable compounds [6.22].

[18] During *sulphuric acid extraction*, aromatic hydrocarbons react with sulphuric acid and generate sulphonic acid, which then deposits in form of resin and has to be extracted by centrifugation and/or earth filtration [6.22].

[19] *Earth filtration* is a physical process in which unwanted particles within the mineral oil are absorbed from a fuller's earth filter.

Table 6.2.: Historical development of the most important insulating liquids for electrotechnical applications [6.19, 6.33, 6.34]

Year	Developments in the field of insulating oils
1892	General Electric® produces the first-known application of mineral oil in a distribution transformer.
1899	Commercial production of mineral oil specifically designed for transformers starts.
at the same time	Trials with natural ester fluids (vegetable oils) demonstrate inferior oxidation stability and higher pour point, electric permittivity and viscosity compared to mineral oils. Application of natural esters for electrotechnical purposes is abandoned.
1930s	Commercialisation of PCB-filled transformers.
mid – late 1970s	PCBs are identified as toxic through a series of incidents. Banning of further production and commercialisation of PCBs in many industrial countries.
mid 1970s – early 1980s	Introduction of silicone oils as substitute for PCBs.
mid 1980s	Introduction of mineral-oil-based high molecular weight hydrocarbons (HMWH).
at the same time	Synthetic esters (most commonly polyol esters) are used in compact railway traction transformers.
early 1990s	As a result of environmental regulations, extensive R&D effort is put into the development of natural esters.
since mid 2000s	Pilot application of natural esters in large power transformers.

reactive compounds from the mineral oil, since these compounds would react with oxygen at higher temperature, resulting in increased generation of sludge and acids [6.14].

The blend of compounds that is present in a particular mineral oil depends not only on the distillation/refining process described above, but also on the source of the crude petroleum [6.14]. Since the composition of crude petroleum varies even within small geographical areas, so does also the composition of insulating mineral oils. The classification of crude petroleum is not easy or stringent, however one generally distinguishes between paraffinic and naphthenic petroleum. These two hydrocarbonic compounds –together with some aromatic and polyaromatic compounds– are found in different ratios in all mineral oils [6.35]. In particular, mineral oils consist of [6.22]:

paraffins (or n-alkanes, C_nH_{2n+2}): saturated, straight or branched hydrocarbons. Branched molecules are called *isoparaffins*. Paraffins are fairly inert compounds, and paraffinic oils have rather high viscosity due to the long molecular chains.

naphthenes (also called cycloparaffins or cycloalkanes, C_2H_{2n}): saturated, cyclic compounds. They may consist of only one ring comprising five to six carbons atoms, or of several rings attached to each other (condensed naphthenes). They may also have attached paraffinic compounds.

olefines (or alkenes, C_nH_{2n}): unsaturated compounds, both linear or cyclic, featuring double bonds between carbon atoms. Olefines are rather reactive due to their double bonds.

aromatic compounds based on benzene (C_6H_6): unsaturated cyclic compounds with three double bonds in a six-atom ring. Very reactive.

other (non-hydrocarbonic) compounds: typically, mineral oils will contain other compounds, such as sulphur, nitrogen or oxygen, in small amounts. Some of them may act as oxidants, accelerating oil ageing.

Figure 6.4 shows the main compounds of mineral insulating oils. Depending on their concentration in a particular oil, it is classified as naphthenic or paraffinic.

Appendix E.5 lists the specifications of a typical naphthenic mineral oil with high oxidation stability (uninhibited). Its main use is in transformers of high to extreme high voltage ratings as well as in instrument transformers [6.36]. Finally, appendix E.4 contains a list with national and international standards of relevance for manufacturing and testing insulating mineral oils.

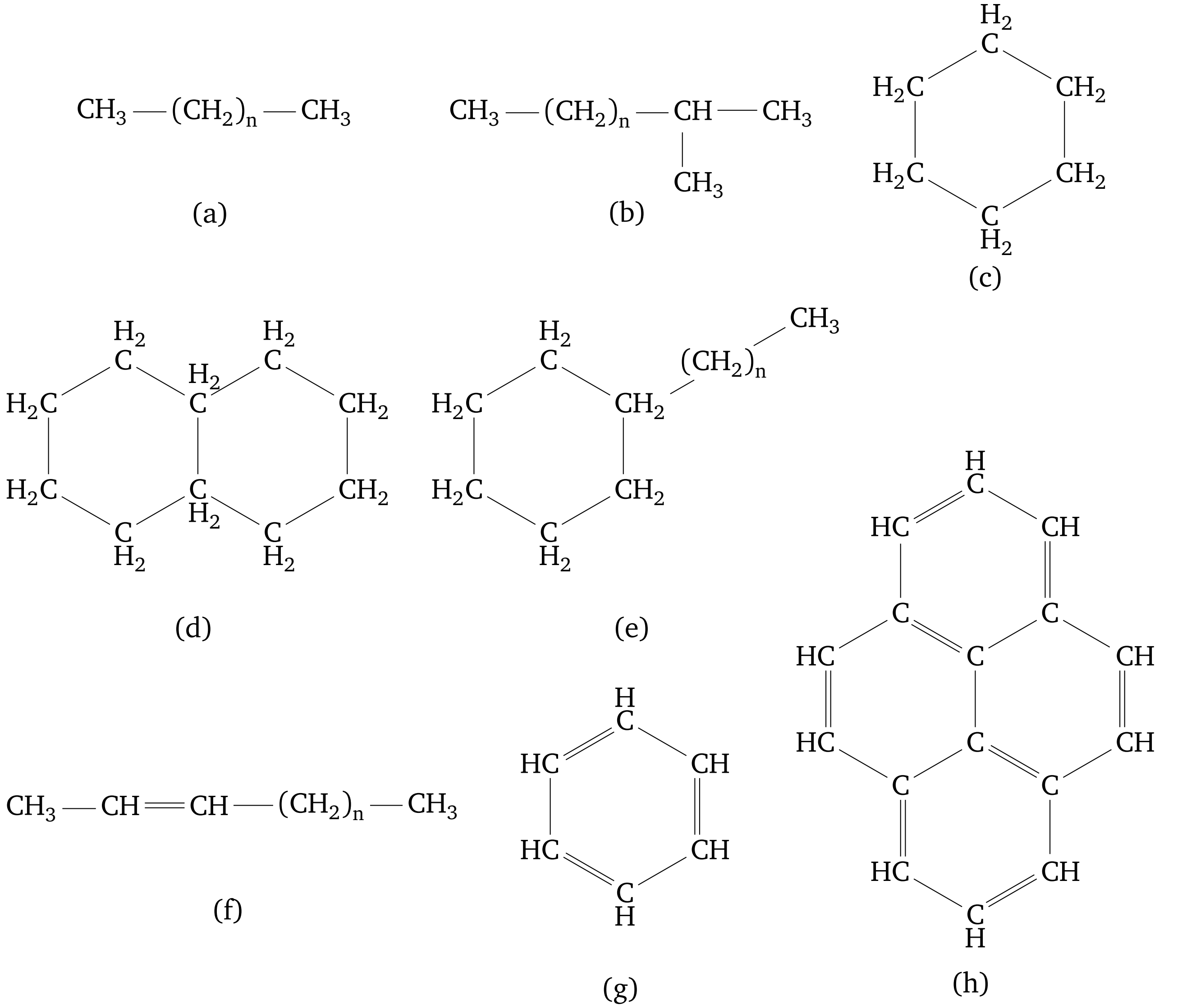

Figure 6.4.: Examples of hydrocarbons present in mineral oils, based on [6.10, 6.19, 6.22]: (a) straight paraffin, (b) branched paraffin (isoparaffin), (c) single-ring naphthene, (d) condensed naphthene, (e) single-ring naphthene with attached paraffin chain, (f) olefine, (g) single-ring aromatic (benzene), (h) peri-condensed, multi-ring aromatic.

6.1.3 Oil-impregnated paper

As already stated in the beginning of this chapter, the combination of kraft paper with mineral insulating oil was introduced, developed and tested by the early 1930s. It was shown that oil-impregnated paper is superior to its components with respect to both electrical and thermal properties. In 1936, Race wrote: "the combination of specially treated mineral oil and wood pulp paper from which water, oxygen and other contaminants very carefully have been removed makes the best flexible high voltage insulation yet discovered" [6.2]. This statement is, in general, still valid up to date.

The good insulating properties of oil-impregnated paper results from the fact that, during impregnation, voids within the paper –inherent in the paper's capillary structure– are filled with mineral oil. Consequently, the electric field is distributed more uniformly inside the insulation system; its dielectric strength is enhanced. As a rule of thumb, the dielectric strength of oil-impregnated paper is approximately ten times higher than that of oil and paper separately [6.16]. This is true as long as the oil's viscosity and the hydraulic pressure applied ensure that no voids inside the paper occur as a result of temperature variations[20] [6.4].

Other relevant electrical properties of oil-impregnated paper insulation systems are similar to that of untreated kraft paper: for example, electrical conductivity remains constant after impregnation (approximately 2.8×10^{-11} S/m [6.37]), but might rise in the case of many paper layers, due to interfacial effects in the paper-oil interface [6.38, 6.39]. For this reason, boards feature slightly lower conductivity than dielectrics papers when impregnated. Contrary to electrical conductivity, the paper's electrical permittivity is significantly lower after impregnation (in the range between 3.9 and 4.8 [6.10, 6.37]), but still higher than that of mineral oil.

But also the thermal properties of dielectric paper are enhanced when impregnated with mineral oil [6.40, 6.41]. Untreated kraft paper belongs to class Y materials according to IEC 60085; however, after impregnation with oil, it can be operated at higher temperature up to 105 °C, and is categorised under class A materials [6.42] (table 6.3). However, even after impregnation, the thermal limit of the oil-paper combination is determined by the paper and not by the oil.

The impregnation process of dielectric paper and pressboard is usually combined with the preliminary treatment for achieving the basic elements of dry cellulose and clean dry oil [6.16]. Accordingly, the typical manufacturing procedure of oil-filled power apparatus comprises following processes: after assembly, the internal paper insulation has to be dried. This is done by applying heat under vacuum[21]. For this purpose the device is placed into a furnace and –in case of large units e.g. high-voltage power or instrument transformers– the windings may also be additionally heated by applying a direct current through them. The vacuum is important, so as to remove the water vapour generated during drying. As stressed out in section 6.1.1, the temperature should not exceed 120 °C, since this would lead to significant deterioration of the cellulose. Prior to impregnation, the insulating oil has to be filtered and degassed. Applying heat and vacuum is of advantage for the degassing process. Once the paper insulation has been dried and the oil degassed, impregnation may begin. In practise, the impregnating oil is entered pressurised in the bottom part of the device and vacuum is sucked from the top of the device.

[20] The effect of loading cycles, resulting in large temperature variations, is especially important for oil-filled high-voltage cables.

[21] During the drying process, it is necessary to reach a temperature of at least 100 °C at atmospheric pressure, before starting the vacuum; if the temperature is too low or the drying process is too fast, ice can form in deeper parts of the insulation [6.43].

Table 6.3.: Thermal classification of solid insulating materials used in oil-filled power apparatus, according to IEC 60085.

Thermal class	Maximal temperature	Insulating materials
Y	90 °C	untreated organic fibrous materials (paper, wood, cotton, etc.); polyvinyl chloride (PVC)
A	105 °C	impregnated organic fibrous materials; nitrile rubber
E	120 °C	polyester foil; wire enamels
B	130 °C	epoxy resin; wire enamels
F	155 °C	cast resin; glass fibre reinforced plastics
H	180 °C	silicon resin fibre glass; polyamide enamels

The purpose is to ensure that no voids or gas bubbles remain trapped in the paper insulation. A vacuum pressure below 1 mbar is generally recommended [6.6]. Application of heat also accelerates impregnation: increasing the temperature from 20 °C to 90 °C can shorten impregnation time by a factor of ten [6.6]. For large oil-filled devices e.g. for high-voltage power transformers the use of holes for drying and impregnation purposes at appropriate locations of the paper and pressboard insulation is highly recommended.

The electrical breakdown mechanism of oil-impregnated paper insulating systems has been found to be similar to that of mineral oil. In a series of experiments [6.2–6.5], Race demonstrated that breakdown of impregnated paper is preceded by gaseous ionisation, with gas evolution resulting from localised heat generation. A higher amount of gases dissolved in oil was found to promote the formation of gas bubbles [6.3]. Also, temperature variations can cause void formation within the paper and initiate ionisation [6.4]. This effect is especially important for cable insulating systems, due to pronounced temperature load cycles. The use of low-viscosity insulating oils is recommended in this case.

Electrical breakdown of oil-impregnated paper is also influenced by impurities or water in oil and paper. Even small impurities (e.g. moist cellulose fibres) can provide sufficient ionic current to produce a gas-evolution rate at the electrode which exceeds the gas-solution rate [6.44]. If water is present in oil or paper, vapour also arises by its electrochemical decomposition [6.45]. This explains the large dependence of dielectric strength on the moisture content: up to a water concentration of 1 % to 2 % by weight, the dielectric strength of oil-impregnated paper is rather constant. Above this value, it falls dramatically, and no electrical insulation is given when water concentration exceeds 10 %. But also in the case of completely dry impregnated paper, breakdown is initiated by the formation of gas: at a certain critical electric field strength, the current density at the electrode due to electron emission is sufficiently high to cause local vapourisation of the oil.

Nevertheless, the life-limiting factor of oil-impregnating insulating systems is not its dielectric strength, but rather its mechanical strength. The latter is mainly influenced by chemical deterioration. Temperature, moisture and the presence of oxygen, acids and catalysts determine the chemical and consequently mechanical lifetime of impregnated paper. Here, we shall focus mainly on the effect of *temperature* and *moisture*.

Montsinger [6.46] published early ageing data and made an observation about the ageing rate of oil-impregnated paper which has been widely used over the years. He noted that the rate of deterioration of mechanical properties doubled for each 5 K to 10 K increase in temperature. The doubling factor was not a constant, but varied from about 6 K in the temperature range 100 °C – 110 °C to about 8 K for temperatures above 120 °C. However, the doubling factor is usually remembered as a constant and the present IEC loading guide of oil-immersed power transformers (IEC 60076-3) uses a constant value of 6 K [6.48]. Up to now, the validity of the Montsinger's rule has been demonstrated only for class A insulating materials (table 6.3).

At temperatures exceeding 140 °C, oil-impregnated paper will be additionally decomposed by pyrolysis [6.49]. Pyrolysis of paper can be easily detected by high generation of carbon monoxide and carbon dioxide, but is usually of no great importance for fault-free operation.

Beside temperature, the presence of water will also increase the rate of degradation. We have already described the process of hydrolysis in section 6.1.1 and its effect on the paper's electrical and mechanical properties. In general, the mechanical life of the insulation is reduced by half for each doubling in moisture content [6.15]. Water is inevitably introduced into new oil-impregnated paper insulating systems through the cellulose, due to its high affinity to water. For this reason, dielectric papers and pressboards have to be carefully dried prior to impregnation, as described above. A water content of no more than 0.5 % is generally recommmended for new oil-filled devices [6.14]. However, water is also introduced into the insulating system during service because of the ongoing oxidation of the cellulose. Furthermore, water might be absorbed from the atmosphere, depending from the applied oil preservation system[22]. In order to fully understand the deteriorating effect of water in oil-impregnated paper insulating systems, we have to investigate first its distribution in oil and paper in more detail.

In the case of oil-impregnated paper, water is distributed unevenly between cellulose and oil. In general, the cellulose has a greater affinity to water and will attract most of it (the oil in a power transformer will typically contain only about 0.01 % of the total water [6.32]). On the other hand, the solubility of water in mineral oil is not constant; rather, its increases markedly

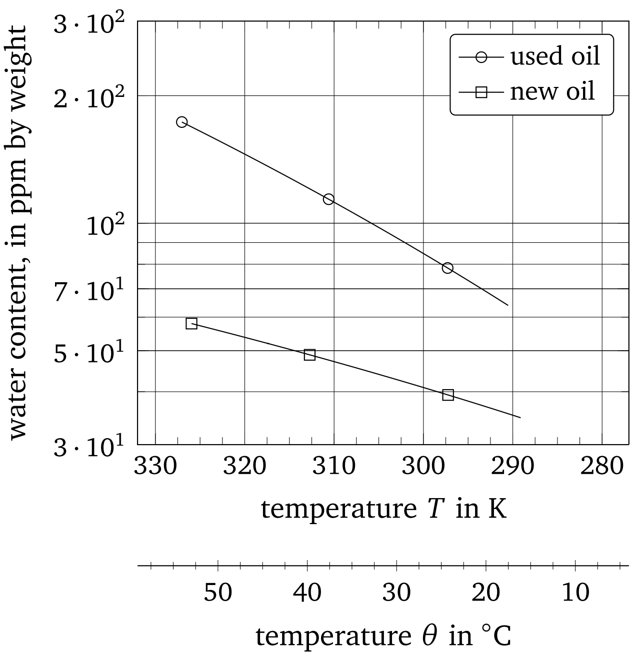

Figure 6.5: Solubility of water in mineral oil as a function of temperature (redrawn from [6.32]).

[22] Refer to section 8.1.2 for a description of oil preservation systems.

with temperature. This means that, with rising temperature, a small amount of water moves from the paper into the oil.

In a multi-component system consisting of oil and paper (and possibly air as surrounding medium), the equilibrium between the water contents of the components is such that the respective degrees of saturation are equal [6.32].

Definition 6.1 *Degree of saturation: The degree of saturation of a material with water at a given temperature is defined as the ratio of its water content to the maximum absorbable water content at 100 % ambient relative humidity:*

$$\text{degree of saturation} = \frac{\text{weight of water absorbed/dissolved in the material}}{\text{maximum weight at 100\% ambient rel. humidity}} \tag{6.1}$$

The degree of saturation with water is a combined index and reflects more than merely the material's water content, since maximum absorbability/solubility is a function of pressure and especially of temperature[6.32].

Keeping this in mind, it is possible to determine the distribution of water within paper and oil at equilibrium conditions. Over the years, many scientists have reported such moisture distribution curves[23]: they are derived by considering the moisture content of cellulose as a function of ambient relative humidity (figure 6.3) and the solubility of water in mineral oil at different equilibrium temperatures, as illustrated in figure 6.5.

The combination of these two information sources with definition 6.1 finally yields the known moisture distribution curves of figure 6.6 [6.53]. With the aid of such curves it is possible to determine the water content of the cellulose by measuring the oil's water content – provided that the system is in equilibrium and the temperature is known.

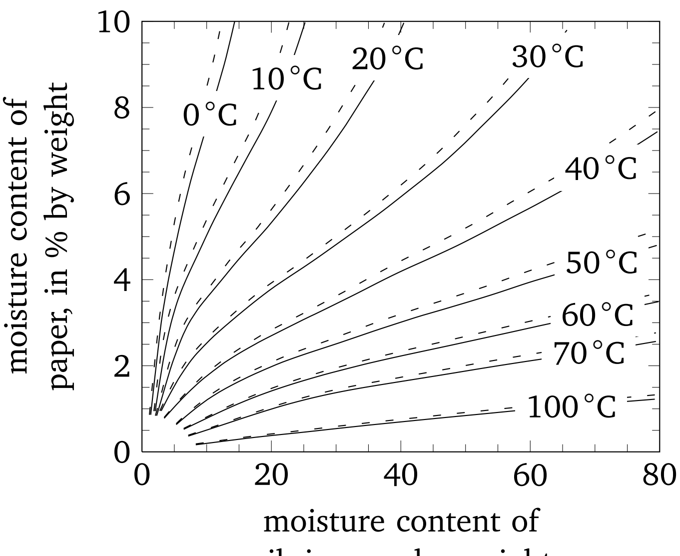

Figure 6.6: Moisture distribution curves for oil-impregnated paper insulating systems at equilibrium, published by Oommen (redrawn from [6.53]). Dashed lines indicate desorption curves (diffusion of moisture out of the cellulose), whereas solid lines stand for adsorption curves (diffusion of moisture into the cellulose). The moisture concentration in paper is given by the weight of moisture divided by the weight of the dry, oil-free paper, in %.

23 Relevant publications have been made by Piper (1946), Jeffries (1960), Fabre and Pichon (1960), Stannett(1962), Norris (1963) and Oommen (1984) [6.15, 6.16, 6.32, 6.51–6.53]. An interesting review of relevant research work is also provided in [6.35]. Moisture distribution curves for mineral oil-impregnated paper insulating systems are sometimes referred to in the literature as "Piper's charts", "Norris' curves" or "Oommen's curves", although Farbe and Pichon were the first to publish some.

The requirement for equilibrium is the major limitation of Oommen's curves: for example, for power transformers in service, the significant changes in loading and ambient temperature, the large temperature gradients within the device (even with constant loading and ambient temperature) as well as the relative slow diffusion of moisture within the paper and the even thicker pressboard result in large deviations from the thermodynamic equilibrium [6.54]. In addition, aged oils demonstrate an increase in water absorbing capacity (compare figure 6.5), thus shifting the curves in figure 6.6 downwards.

Summing up, ageing of oil-impregnating paper insulating systems is governed by quite the same factors as does ageing of each component separately. Special features, though, are the uneven moisture distribution as well as the fact that ageing products of one component may act as catalysts of deterioration processes within the other component (the most pronounced example are acids due to oil oxidation which act upon the cellulose and accelerate ageing of the latter).

6.2 Dissolved gas analysis

The most relevant ageing processes for oil-impregnated paper insulating systems –namely oxidation, hydrolysis and pyrolysis– have been briefly described in the previous section. The main life-limiting factor has been found to be the decrease in mechanical strength of the cellulosic solid insulation, rather than the deterioration of its dielectric strength. Obviously, the most reliable way to assess the mechanical strength of dielectric papers and pressboards is to directly measure its tensile strength or, equivalently, its degree of polymerisation. However, this is not always possible in the case of oil-filled power apparatus: the cellulose is not easily accessible from the outside, as the internal paper insulation is usually submersed in the oil. Therefore, in order to take a sample, the device would have to be de-energised and opened. But even in this case, the sample would not provide a reliable, representative result, since the regions of highest thermal and electrical stress are in the inner paper layers directly adjacent to the electrodes (conductors) and are, thus, not accessible.

It is for this reason that other, non-invasive monitoring techniques have to be applied so as to assess the condition of the internal insulation. Extensive knowledge of the presence and severity of ageing processes within the equipment offers significant advantages:

- First to mention is the identification of pronounced, critical reactions which could lead to short-term outage with severe or even catastrophic consequences unless immediate action is taken. By means of timely detection of such critical conditions it is possible to prevent unplanned outages, thus enhancing the overall reliability of the power system. It is furthermore possible to limit the consequences of an outage and keep repair cost low.
- But also the detection of incipient faults and slow-progressing ageing processes offers significant advantages. From an operational point of view, early fault detection allows for planned removal from service, so that appropriate maintenance actions can be taken. By engaging at an early stage, the cause of potential faults can be mitigated at low cost, and the risk of sudden, unplanned outages can be controlled to a large extent.
- Finally, non-invasive monitoring techniques are suitable for application during operation, that is, without any service interruption. If, in addition, localisation of potentially faulty components is provided by monitoring, the down time for maintenance actions can also be minimised to improve the total availability of the equipment.

Non-invasive monitoring techniques for oil-filled power equipment extract information about the condition of the internal insulation mainly from the oil[24] and sometimes from the gas space above it. The oil contains reaction products both due to ageing of the oil itself (e.g. sludge and oxidation acids) as well as due to ageing of the paper (mainly water). Monitoring the oil's neutralisation and saponification value as well as its water content is therefore highly recommended. In addition to sludge, acids and water, the thermal and dielectric stresses imposed to oil-filled equipment during service also lead to the generation of gases. In the previous section we have seen that the formation of such *fault gases* is an integral process in the mechanism of electrochemical and thermal decomposition of oil-impregnated paper insulating systems.

Exactly this observation of increased fault gas generation during internal faults motivated Max Buchholz to introduce his well-known protection relay[25] in 1925 [6.56]. The Buchholz relay is perhaps the most reliable, simple and yet effective monitoring device for oil-filled power apparatus. It is therefore not surprising that it quickly found broad acceptance and has soon been regarded as an indispensable protection component.

At the same time it was realised that, if gases evolving from the oil due to an acute fault were to operate the Buchholz relay, then slowly developing faults would also be producing gases which would be dissolved in the oil and only appear in the relay at the end of a complicated system of interchange between gases contained in bubbles rising to the surface and the less soluble atmospheric gases dissolved in the oil [6.57]. In the next thirty years to follow its introduction, research concentrated on analysing the gases collected in the Buchholz relay, so as to detect hydrogen, acetylene and carbon monoxide, and thus distinguish between normal ageing, oil decomposition by low-energy mechanisms, oil decomposition at high-temperature conditions and decomposition of solid insulating material (paper) [6.19]. However, it was only after the invention of gas chromatography in the early 1950s that analysis of fault gases was launched in large scale. In the beginning, interpretation of the results was done only case-specifically, since no representative data bases existed. The wide introduction of fault gas analysis, though, quickly resulted in significant amounts of valuable data, and by the late 1960s the first systematic interpretation methods emerged. Table 6.4 gives an overview of milestones in the historical development of fault gas analysis in oil-filled power apparatus. A description of the most important interpretation methods will be provided in section 6.2.3.

One should note that fault gas analysis[26] may be done in two different ways: the first possibility is to use the *free gases* collected in the Buchholz relay or in the gas space above the oil. The main disadvantage of using free gases is that the fault gases must first saturate the oil and

[24] Due to its significance as information source for ongoing ageing processes within the internal insulation, Duval drew an analogy between the insulating oil of oil-filled equipment and the blood of living organisms: "like a blood test [oil analysis] can warn you about an impendent problem, give an early diagnosis, and increase the chances of finding the appropriate cure" [6.55].

[25] The *Buchholz relay* is used for protection purposes mainly at oil-filled power transformers. In case of an internal fault, gases are generated by decomposition of the oil and by evaporation of potentially present water. If the concentration of such fault gases exceeds their respective solubility limit in the oil, they travel in form of bubbles upwards to the gas space above the oil. This is typically the case when arcing with high power density is involved. In conservator-type (also called breathing, compare section 8.1.2) transformers, the tank is completely filled with oil and the generated fault gases have to travel –through the Buchholz relay– to the conservator. Depending on the rate of gas evolution, two alarm signals are sent by the relay: in case of extremely high gas evolution rates (potential internal short-circuit) the transformer has to be immediately de-energised, whereas, at lower gas evolution rates, further investigation is recommended.

[26] Throughout this chapter, the terms "fault gas analysis" and "dissolved gas analysis" are considered to be equivalent. Other common wordings are: "gas-in-oil analysis" and "dissolved gas-in-oil analysis".

Table 6.4.: Milestones in the historical development of dissolved gas analysis of oil-filled power equipment. Only the most significant interpretation methods are included in this table.

Year	Developments in the field of dissolved gas analysis
1925	Invention of the Buchholz protection relay [6.56]
mid 1920s – mid 1950s	Detection of hydrogen, acetylene and carbon monoxide from free gases collected in the Buchholz relay with simple gas analysers [6.58]
mid 1950s	Development of headspace gas chromatography by Archer Martin and Erika Cremer
mid 1950s – mid 1960s	Power utilities deploy first research projects for analysis of fault gases dissolved in the oil of oil-immersed transformers as well as of free gases collected in Buchholz relays [6.59–6.61]
mid 1970s	Thermodynamic studies on the thermal decomposition if mineral insulating oils [6.62–6.64]
1973	Introduction of the ratio method by Rogers for DGA interpretation [6.57]
1974	Dörnenburg's ratio method for DGA interpretation [6.65]
1974	Duval's triangle for graphical DGA interpretation [6.55]
1975	Introduction of the DGA nomograph for interpretation purposes [6.66]
1978	First standard by the International Electrotechnical Commission: "Mineral oil-impregnated electrical equipment in service: Guide to the interpretation of dissolved and free gases analysis" (IEC 60599), revised in 1999 and 2007 [6.67]
in the same year	First standard by the Institute of Electrical and Electronic Engineers: "Guide for the detection and determination of generated gases in oil-immersed transformers and their relation to the serviceability of the equipment" (IEEE C57.104[a]), revised in 1991 and 2008 [6.68]
recently	Further Cigré activities with the purpose of updating typical gas concentration values in various oil-filled power apparatus [6.69] as well as to adapt traditional DGA to equipment filled with non-mineral oils [6.70]

[a] After its first revision in 1991, the title of IEEE C57.104 was reduced to "Guide for the interpretation of gases generated in oil-immersed transformers".

diffuse to the surface before accumulating in the Buchholz relay or in the gas blanket above the oil. This method was applied mainly prior to the invention of the liquid-gas chromatography. The second approach, which is being widely followed nowadays, is based on the analysis of *gases dissolved in the oil*. Extracting the gases directly from the oil allows for the earliest possible detection of an incipient fault. No matter which approach is chosen for the purpose of fault gas analysis, extensive knowledge of the gassing characteristics of oil-impregnated paper insulating systems under electrical and thermal stress is essential. The following paragraphs are therefore dedicated to the gas evolution mechanisms for mineral oil and kraft paper.

6.2.1 Gas evolution in oil-impregnated paper insulating systems

Decomposition of mineral insulating oils under thermal and electrical stress may progress according to two different reaction schemes: *electrochemical decomposition* results from applied electrical stress at low temperature, whereas *thermal decomposition* occurs due to pyrolysis or disruptive discharges (arcing) at higher temperatures, typically exceeding 400 °C [6.71]. The distribution of discharge energy and temperature in the neighbourhood of the fault, together with the time duration of the applied thermal or electrical stress, plays a decisive role on evolution of gases in the course of oil decomposition. Generally speaking, the rate of gas evolution is proportional to the magnitude of the fault, whilst the composition of the gases is related mainly to the type of the fault, although the composition of the oil also plays and important role. In the following paragraphs we shall, thus, differentiate between three types of faults: electrical faults with low energy (predominantly partial discharges), thermal faults (overheating of oil or cellulose), and electrical faults of high energy.

Discharges of the *cold-plasma type* (also called *corona discharges*) impose high electrical stress at the oil-gas interfaces[27] in the insulating system. In the course of electronic bombardment of the oil-gas interface, the oil is electrochemically decomposed at low temperature, with free radicals being formed (e.g. methyl, $CH_3^{\bullet}$, and atomic hydrogen, $H^{\bullet}$). The type and energy[28] of the discharge, the applied frequency, the nature of the gas phase as well as the temperature at the location of the fault determine the reaction [6.19]. In general, decomposition processes comprise the liberation of molecular or atomic hydrogen (scission of the carbon-hydrogen bonds of the hydrocarbons in the oil), chain and ring scission of carbon-carbon bonds with formation of free hydrocarbonic radicals (e.g. methyl), polymerisation, condensation and rearrangement.

In case separate atomised gas is already present and dissolved in the oil, it can react with the gas phase and recombine (gas absorption[29]). The gas-absorbing capability of mineral oils under discharge conditions is enhanced by a higher content of aromatic hydrocarbons or other appropriate additives [6.74]. Depending on their composition, mineral insulating oils under low-energy electrical stress can, thus, behave in a gas-evolving or in a gas-absorbing manner. Nevertheless, most oils used in oil-filled power equipment are gas-evolving and, when subjected

27 The gas phase may consist of oil or water vapour produced by voids in the insulation due to changes in temperature or pressure, trapped air or air bubbles moving out of the cellulose or gas produced elsewhere in the insulating system by thermal degradation (usually hydrogen) [6.19].

28 In [6.72], Borsi showed that the absolute concentration of hydrocarbons evolving from the decomposition of oil by non-disruptive discharges increase linearly with increasing discharge energy.

29 The gas-absorbing behaviour of an insulating oil has been, however, found to be dependent on voltage and temperature [6.73]. In particular, increase in either voltage or temperature can induce gas evolution in an oil which, by normal definition, is gas-absorbing.

to electrical stress by low-energy discharges, will tend to generate hydrogen and –to a lesser extent– methane.

Markedly different decomposition processes occur when the oil is thermally stressed: Although dehydration (scission of carbon-hydrogen bonds), decomposition (scission of carbon-carbon bonds) and recombination (polymerisation and condensation) reactions are still pronounced, they result from pyrolysis rather from ionisation. Conventionally, the *thermal decomposition* of hydrocarbons is divided into primary and secondary reactions. Primary decomposition is dominant at lower temperatures, where the most unstable compounds of the oil, namely alkanes [6.64], are attacked. Dehydration and decomposition lead to the formation of low-weight hydrocarbon radicals, mainly methyl as well as atomic hydrogen. These radicals can combine with each other to form molecular hydrogen, methane, saturated hydrocarbons of higher order e.g. ethane, and –to a much lesser extent– unsaturated hydrocarbons e.g. ethylene. Examples of primary decomposition reactions are the following:

$$
\begin{aligned}
C_nH_{2n+2} &\leftrightharpoons H_2 + C_nH_{2n}\\
C_nH_{2n+2} &\leftrightharpoons CH_4 + C_{n-1}H_{2(n-1)}\\
C_nH_{2n+2} &\leftrightharpoons C_2H_4 + C_{n-2}H_{2(n-2)+2}
\end{aligned}
$$

One should note that the above reactions occur simultaneously so that a mixture of gases is generated by primary decomposition.

On the other hand, if temperature exceeds 400 °C–500 °C [6.62, 6.71], rapid pyrolytic decomposition of the oil takes place. This *secondary decomposition* includes not only the oil's initial compounds, but also all products of primary decomposition, further decomposed and rearranged by heat. Due to the higher thermal stress, reaction products comprise condensed, unsaturated low-weight hydrocarbons. Typical secondary decomposition reactions include for example [6.64]:

$$
\begin{aligned}
C_2H_4 &\leftrightharpoons C_2H_2 + H_2\\
2\,CH_4 &\leftrightharpoons C_2H_4 + 2\,H_2
\end{aligned}
$$

If, furthermore, temperature exceeds 1200 °C [6.62], local carbonisation of the oil occurs; under such high thermal stress, methane produced during primary decomposition is broken down to its components hydrogen and carbon. The latter may either deposit in form of carbon black or recombine with oxygen to produce carbon oxides.

By proper consideration of the partial pressure of each gaseous product dissolved in the oil as a function of temperature, thermodynamic models can be provided for the equilibrium state. The most known theoretical thermodynamic model for mineral oils was prepared for the UK Central Electricity Research Laboratories by Halstead in 1973 [6.62]; similar considerations are also published in [6.64]. The main insight provided by thermodynamic models is that the proportion of each gaseous hydrocarbon produced by the decomposition of the oil varies with the temperature of the fault location. This insight was the main motivation for introducing ratios of gas concentrations for the purpose of DGA interpretation, as will be shown later in section 6.2.3. As can be seen in figure 6.7, the gases generated at most with increasing temperature are in turn methane, ethane, ethylene and acetylene. Nevertheless, the thermodynamic approach also has its limitations [6.68]: the assumed ideal, isothermal equilibrium in the region of the fault does not exist in practise, and there is no provision for dealing with multiple faults occurring simultaneously.

Finally, *high-energy electrical stress* due to disruptive discharges (commonly referred to as *arcing*) causes the oil to decompose to a large extent. Extreme temperatures at the location of the fault (up to 3,000 °C [6.71]) produce high amounts of hydrogen, ethylene and acetylene. Contrary to thermal faults, where acetylene remains unstable and recombines to methane, in the case of severe arcing acetylene is quickly cooled down at the oil-plasma interface and can therefore by traced in the oil.

In addition to the gases released from the oil by electrical and thermal faults, some mineral oils will tend to generate excessive amounts of gases even when no fault exists. This behaviour is labelled as *stray gassing*; Cigré defines stray gassing in [6.69] as: "the formation of gases from insulating mineral oils heated at relatively low temperatures (90 °C–200 °C)".

Several mechanisms contribute to stray gassing. Oxidation of the oil produces small amounts of carbon oxides, which can, however, accumulate over time to significant concentrations. Due to the accompanying formation of sludge and acids, oxidation can be easily distinguished from stray gassing. On the other hand, if hydrogen or gaseous hydrocarbons are released by stray gassing, it can be mistaken for excessive gassing at modest temperatures. This can occur for example in case of incompatibility between the oil and other materials used in oil-filled power apparatus. The most pronounced effect in this regard is the catalytic action of stainless steel [6.63] which stimulates the production of hydrogen even at normal operating temperatures.

The impact of stray gassing has been found to depend mainly on two factors: temperature and type of oil. In particular the temperature of the hottest spot[30] in the equipment will determine the rate of stray gassing. Accordingly, the contribution of stray gassing is significant only at high-load or overload conditions. The second parameter influencing stray gassing is the type of the oil itself. Newer, highly refined oils have demonstrated a pronounced stray gassing behaviour. Cigré identified in [6.69] large variations between different types of oils, and even different

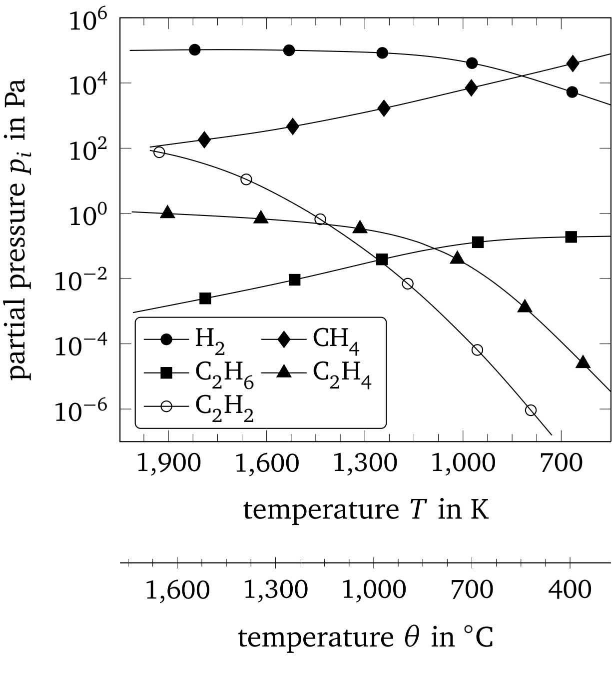

Figure 6.7: Partial pressures of different low-weight gaseous hydrocarbons dissolved in oil as a function of temperature, at equilibrium (redrawn from [6.62]).

[30] Typical ANSI and IEC hot spot temperatures at nominal load are 110 °C and 98 °C, respectively.

batches of the same branch of oil may have rates of stray gas formation varying by a factor of one to five.

In order to assess the stray gassing behaviour of mineral insulating oils, several procedures have been proposed recently [6.69, 6.75, 6.76]. Two different testing temperatures are used: at low temperature (120 °C) stray gassing produces mainly hydrogen and methane, whilst at higher temperature (200 °C) mainly methane and ethane are generated. Accordingly, Cigré recommends the use of the ratio of methane to hydrogen concentration in order to identify stray gassing.

So far, only gases generated from the oil have been examined. In case of a fault occurring in the vicinity of the *paper insulation*, the cellulose will also decompose and release fault gases. Since the temperature thresholds for oxidation and pyrolysis of the cellulose are much lower than for the oil (at approximately 105 °C and 140 °C, respectively – compare also table 6.3), decomposition of the paper insulation will define the gassing behaviour in this case: the carbon-oxygen bonds in the glucose rings break, and carbon oxides are released. If, furthermore, the temperature at the fault location exceeds 300 °C, excessive pyrolysis sets in leading to local carbonisation of the paper. Generally speaking, the presence of high amounts of carbon oxides dissolved in the oil indicates either a thermal fault with paper involvement (e.g. overheating of paper-wrapped conductors) or a highly-aged oil.

6.2.2 Measuring gases dissolved in the oil

As already stated above, fault gas analysis can be performed either on the basis of free gases collected in the Buchholz relay[31] or by considering the gases dissolved in the oil. Traditionally, only simple gas detectors are used when analysing free fault gases, with the purpose of determining the total concentration of combustible gases (TCG) as will be shown later, though a more thorough analysis is also possible. In order to link the amount of free gases above the oil with the concentration of dissolved gases, *Henry's law* can be applied. It states that, at equilibrium, the concentration of a gas dissolved in a liquid is directly proportional to its partial pressure:

$$c_n = k_n \cdot p_n \tag{6.2}$$

where c_n is the concentration of the n$^{\text{th}}$ gas in the oil by volume, k_n is the Henry's law constant for the particular gas and liquid combination, and p_n is the partial pressure of the respective gas. One should note that Henry's law constants vary significantly with temperature.

The first step in fault gas analysis obviously involves sampling the gases: in the case of free gases, sampling is done directly, however, if gases dissolved in the oil should be analysed, an oil sample has to be taken first, and the fault gases must be then extracted from the oil. In order to incorporate direct sampling of free gases, the Buchholz relay is fitted with a suitable sampling point. A detailed procedure for gas sampling from the Buchholz relay is provided in [6.22], pp. 82–83. But also in sealed equipment, provisions for sampling free gases are provided, with the main difference that fault gases will be in mixture with the medium of the gas blanket above the oil (usually nitrogen). In such equipment periodical or on-line sampling of free gases is widely used for the evaluation of TCG concentration. Guidance on direct sampling free gases from transformers is provided in ASTM D 3305 and ASTM D 2759 [6.77, 6.78].

31 For sealed and positive-pressurised equipment, free gases are sampled from the gas space above the oil – compare section 8.1.2.

On the other hand, taking samples of oil from oil-filled power apparatus for the purpose of dissolved gas analysis is slightly more complicated. Special care has to be taken regarding the choice of appropriate containers for the oil sample: both the material and construction of the container as well as the type of its cap must withstand temperature variations without allowing contamination by atmospheric air. The use of aluminium or glass containers with snap or screw caps is widely accepted, plastic containers are on the other hand unsuitable since they are not hydrogen-tight. Containers with constant volume have two drawbacks: if the oil is sampled at temperature higher than the ambient one, the resulting negative pressure during cooling can cause atmospheric air to leak into the container and contaminate the sample. But even if the tightness of the container cap is sufficient to prevent air from entering the container, the negative pressure leads to the formation of local vacua. Gases dissolved in oil will then diffuse into this low-pressure gas phase and the concentration of gases dissolved in the oil will thus be falsified [6.79]. In order to account for this effect, the sample must be heated up to its initial temperature at the time of sampling before further analysis can be performed in the laboratory. A better solution is the use of sampling syringes with variable volume.

The procedure for sampling oil for the purpose of dissolved gas analysis is defined in IEC 60567 and ASTM D 923 [6.80, 6.81]: a hydrogen-tight hose is connected to the main tank of the oil-filled device at appropriate location[32] and sufficient amount of oil is allowed to flow through it, washing out any contaminants. The hose is then inserted into the container down to its bottom and the container is filled with oil. Oil of approximately one to three times the container's volume is allowed to overflow, and the cap is then secured without leaving any air above the oil in the container. It is important to store the sample out of light, as the interaction of gaseous hydrocarbons with oxygen under the influence of light would cause them to oxidise into non-gaseous compounds [6.79].

Once the oil has been successfully sampled, the dissolved gases have to be extracted. Traditionally, the *headspace method*[33] has been applied for this purpose. The oil sample is injected into a glass vessel, where vacuum has been previously established. With the help of a Toepler pump[34] a high level of vacuum is provided in the headspace. As a result, the gases dissolved in the oil diffuse in the headspace according to Henry's law. The level of vacuum, the surface of the oil-vacuum interface as well as the applied temperature will influence the degassing performance. Generally speaking, virtually the complete gas content can be extracted from the oil with the headspace method (degassing is higher than 99 % [6.83]).

Another possibility to extract gasses dissolved in the oil is by means of the *stripping method*. Instead of using a vacuum pump, a carrier gas –usually argon– is allowed to bubble through the oil sample in a closed loop. Due to the high difference in partial pressure, the gases dissolved in the oil diffuse into the bubbles of carrier gas. The stripping method is especially suitable for oil samples of small volume and can provide quick gas extraction (the total time for DGA using the stripping method is below twenty minutes [6.84]). Since no vacuum pump is necessary, it can

32 The position of the sampling point must ensure that the sampled gas concentrations are representative for the device. In particular, sufficient circulation of the oil is important.

33 The term *headspace* refers to the volume of gas or vacuum above a liquid or solid in a closed container.

34 A *Toepler pump* consists of a quarz glass-cylinder equipped with a mercury piston. In order to avoid any contamination in the primary circuit, magnetic valves are implemented. The main advantages of using mercury for the piston result from its extremely low gas-absorbing behaviour and form the excellent tightness of the mercury-glass cylinder construction. The Toepler pump is shown at the left of figure 6.9. Recently, mercury-free pumps, implementing solid mechanical pistons instead of mercury pistons, have been introduced into the market, showing good accuracy and reliability [6.82].

be integrated into the gas chromatograph. However, the degassing performance of the stripping method is lower than that of the traditional headspace method, as is the overall accuracy [6.79].

In general, two types of analyses can be performed once the fault gases have been collected either by direct sampling or by extraction from an oil sample. The simplest analysis consists of determining the *total concentration of combustible gases*, which is usually preferred for sealed and quasi-sealed equipment. For this purpose three detection methods are applicable [6.68]:

- The first method uses *thermal conductivity detectors*: by comparing the thermal conductivity of the gases sampled from the oil-filled equipment with the thermal conductivity of the medium in the gas blanket (usually nitrogen) one can determine the TCG concentration.

- Much higher accuracy can be achieved if *flame ionisation detectors* are used. Gaseous hydrocarbons are burned in a hydrogen flame and the change in electrical conductivity is measured. Prior to detection carbon oxides are hydrated to methane by applying nickel as a catalyst [6.79]. The content of hydrogen, oxygen and nitrogen can not be evaluated with flame ionisation detectors; thermal conductivity detectors have to be used for these gases.

- The third type of detectors operate on the *fuel cell* principle and consist of two platinum gas-permeable electrodes and a sulphuric acid electrolyte [6.68]. The energy sources for the fuel cell are, on the one hand oxygen, electrochemically reduced from ambient air, on the other hand hydrogen dissolved in the oil. An example of such a detector is given in figure 6.8. The current is directly proportional to the concentration of hydrogen in the oil.

A more detailed analysis involves the quantitative evaluation of the concentrations of different gases dissolved in the oil by *gas chromatography* [6.86]. In brief, the gas sample is given to a carrier gas stream to form the *mobile phase* of the chromatograph. Inert gases e.g. argon, helium or nitrogen are typically used as carrier gases. The mobile phase is then allowed to flow through a capillary column (*stationary phase* of the chromatograph), at controlled temperature. Several chemical and physical interaction processes between the mobile and stationary phase result in individual retention times for each component of the gas sample. Detectors are located at the

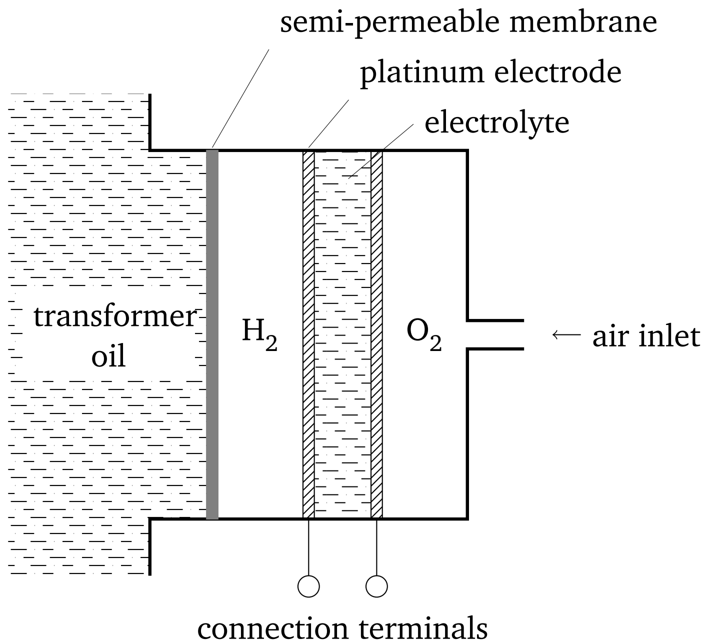

Figure 6.8: Fuel cell for on-line detection of hydrogen dissolved in the insulating oil (based on [6.55]).

outlet of the column and determine the amount and type of each component by considering the respective retention time. The thermal conductivity detectors and flame ionisation detectors described above are commonly used, although other types of detectors may also be applied. The output signal of the detectors is then passed to a computer system and, upon processing, the results are reported in a chromatogram. The various peaks in the chromatogram correspond to the different components of the gas sample.

Figure 6.9 illustrates the typical laboratory set-up for dissolved gas analysis. In the last decade many monitors have been introduced into the market for the purpose of on-line DGA, that is, directly at the equipment. In [6.87] a Cigré task force examined some of these monitors with regard to their applicability, accuracy and reliability, economics, as well as long-term stability. The results indicated that most available on-line monitors ensure a level of accuracy which satisfies IEC specifications (±15 %). Nevertheless, with regard to the cost associated with the use of such monitors, the task force explicitly recommends to consider not only the cost of acquisition, but also the cost of installation and operation.

The overall accuracy of fault gas analysis is indeed a very important aspect. For reliable identification of potential faults, accuracy better than ±10 % is recommended. Should the measuring error increase, diagnosis becomes more and more unreliable, and is meaningless if the error exceeds ±40 % [6.88]. Utilities are therefore encouraged to test and verify the accuracy of the laboratories they are cooperating with; for this purpose reference (pre-calibrated) oil samples are commercially available.

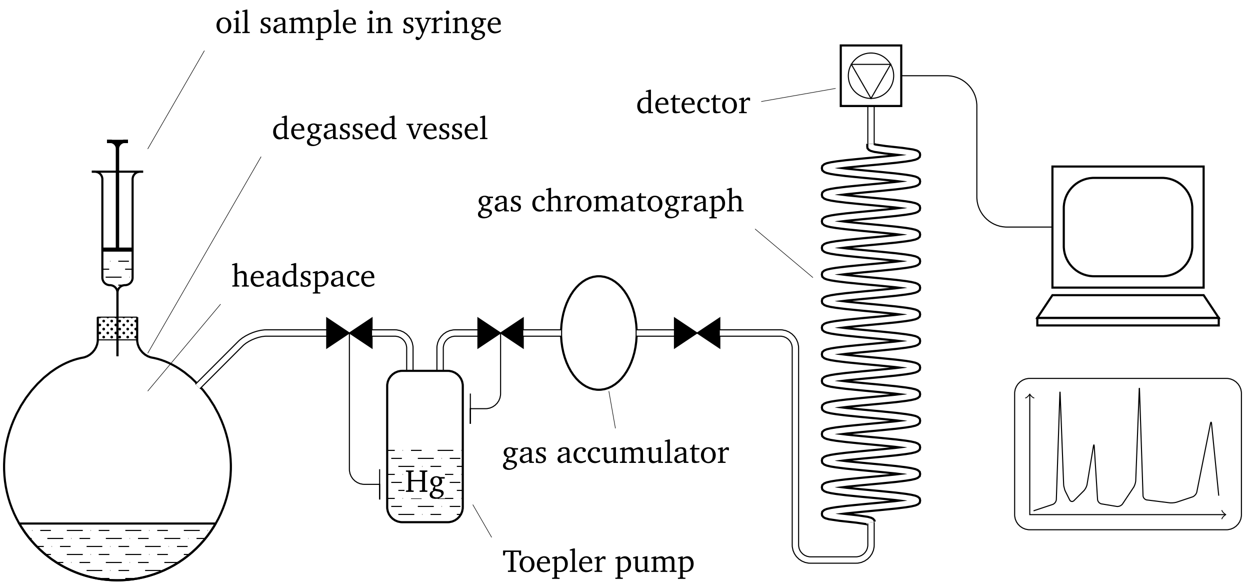

Figure 6.9.: Typical laboratory set-up for dissolved gas analysis with headspace gas extraction (based on [6.10]). The oil sample is injected into a previously degassed vessel. With the aid of a Toepler pump, dissolved gases are extracted from the oil under vacuum. The gas sample then enters a gas chromatograph. Due to the different retention times of the various components of the gas sample in the chromatograph's column, detectors located at its outlet can determine the amount and type of each component. The results are reported in a chromatogram.

6.2.3 Interpretation of measured gas concentrations

The interpretation of gases detected in the Buchholz relay or extracted from the oil must provide insight regarding the presence, type and severity of a potential internal fault in oil-filled power equipment. In section 6.2.1 we already addressed the dependence of gas released in case of a fault on the magnitude and type of the particular fault. We further noticed that normal oxidation of the oil as well as normal electrical and thermal stress will also lead to the generation of decomposition gases. The first objective of an interpretation scheme is, thus, to distinguish between normal and increased gassing in the oil.

In the early beginnings, analysis of fault gases in oil-filled equipment was a case-based issue: only selected units[35] were tested on their gas concentrations. In case the monitored gases increased markedly in concentration, the possibility of an internal fault had to be examined. Examples of such early investigations are given in [6.58, 6.60, 6.61].

Over the years, power utilities collected more and more data on fault gas analysis, on the basis of which systematic interpretation has been made possible. The main idea is to use statistical information on gas concentrations measured in the field in order to identify the equipment's "normal" gassing behaviour. Knowledge of such *norms* (also referred to as *typical gas concentrations*[36]), together with the measured gas concentrations of a particular device, provides evidence of potential incipient faults within the device.

Very few approaches, as for example the interpretation method developed by the California State University of Sacramento in cooperation with the Pacific Gas and Electric Company [6.89], provide fault diagnosis with respect to both presence and type of fault by means of direct comparison between the measured gas concentrations and some limit values, as shown in table 6.5. Most DGA interpretation schemes reported in the literature use the aforementioned norms to give evidence only of the possible *presence* of a fault; the *type* of the potential fault is identified in a further interpretation step.

The arguments in favour of a two-step approach are manifold. When using interpretation schemes based on thresholds, as in table 6.5, combinations of measured gas concentrations are possible which result in more than one fault diagnosis at the same time. Furthermore, the type of the equipment has been found to play a significant role with regard to its gassing behaviour, not only in case of an internal fault, but also during normal operation. But even when comparing the rate of gas generation for units of the same time, loading and ambient conditions have a significant effect. Keeping the above in mind, it is obvious that a comparison with the norms can only highlight measurements indicative of a possible fault; the type of the fault has to be investigated in more detail.

Since the broad introduction of DGA in the late 1960s to date, many surveys have been performed with the objective of evaluating typical concentrations of gases in oil-filled power equipment. Table 6.6 provides a review of such norms for power transformers reported in the literature. The values presently included in the most important standards on DGA, namely in IEC 60599 and IEEE C57.104, are given in the first two rows.

[35] Due to their high capital cost as well as their special importance for the power system, DGA has always focused mainly on large, high-voltage power transformers. For this reason, developments in DGA and its interpretation are closely linked to this particular type of equipment. In this chapter, all tables containing typical concentrations of gases dissolved in oil originate from investigations on power transformers.

[36] Traditionally, typical gas concentrations are defined as the 90-percentile of concentrations observed in the field.

Table 6.5.: Example of diagnosis by direct comparison of measured gas concentrations with limit values (in ppm by volume) [6.89]. Obviously, combinations leading to several fault diagnoses at the same time are possible, which is one of the many drawbacks of such interpretation methods.

Dissolved gas	Limit concentration	Diagnosis
hydrogen H_2	1,000	corona discharges, dielectric fault
methane CH_4	80	corona discharges
ethane C_2H_6	35	local overheating
ethylene C_2H_4	150	local overheating
acetylene C_2H_2	70	dielectric fault (arcing)
carbon monoxide CO	1,000	overload, paper decomposition
carbon dioxide CO_2	15,000	overload, paper decomposition

Obviously, the values obtained from the literature show significant variations. This is evidence of the existence of several factors influencing the typical gas concentrations in power transformers. Statistical investigations organised and conducted by Cigré have played a key role in understanding these influencing factors. It is thus not surprising that the results of the latest Cigré survey –published in technical brochure 296– have been adopted in the current IEC standard. The main factors influencing typical concentrations of gases dissolved in the oil of oil-filled equipment are:

- The *type of oil* determines the gassing behaviour of the equipment under normal stress. Traditionally, DGA focused on mineral oil-filled devices, but the introduction of other insulating liquids (silicone oils, synthetic hydrocarbons as well as natural and synthetic esters) has initiated new research in this area [6.70, 6.72, 6.90–6.92]. But even with regard to mineral oils, recent changes in refining processes have been found to influence the stray gassing behaviour [6.69].

- The *oil preservation system* (section 8.1.2) does not influence the generation of gaseous hydrocarbons, but is important with regard to the concentration of atmospheric gases (mainly nitrogen and oxygen) as well as of carbon oxides. In breathing units, the exchange of air between the conservator and the atmosphere as a result of changes in the operating temperature may result in fault gases escaping from the oil. This effect can be significant for units with pronounced loading cycles [6.93].

- The *hot spot temperature* is a significant factor for the gassing behaviour. Higher operating temperatures lead to increased generation of decomposition gases even if no fault is present. Moreover, the type of cooling applied[37] should also be taken into consideration, since it determines the temperature gradients within the equipment.

[37] Refer to section 8.1.1.

Table 6.6.: Review of typical concentrations of gases dissolved in the oil of large power transformers, from 1975 to date. All values are in parts per million by volume.

Year	Source	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
2008	IEEE C57.104[a] [6.68]	100	120	65	50	1	350	2,500
2006	Cigré & IEC 60599[b] [6.69]	50–150	30–130	20–90	60–280	2–20 / 60–280[c]	400–600	3,800–14,000
2006	LCIE[d]	50–600	170–240	940–1,100	240–430	13–290	530–890	4,600–8,700
2005	NTT [6.94]	150[e]	80	35	150	7	1,000	10,000
1999	IEC TC 14[f]	500	350	800	500	200	1,000	14,000
1989	Duval[g] [6.55]	200–250			500	20–200		
1987	Burec [6.66]	500	125	75	175	15	750	11,000
1977	Dörnenburg[h] [6.65]	200–250	100–200	100–200	150–300	15–35	500–1,000	6,000–11,000
1976	CSUS [6.89]	150	25	10	20	15	500	10,000
1975	Fallou[i] [6.95]	65	100	160	145		590	9,300
1974	Müller et al.[j] [6.71, 6.96]	50–100	50–100[k]	100–200	100–300	15–30	300–500	3,000–5,000

[a] The typical values reported in the table are maximal concentrations for classification in condition 1 (normal operation).

[b] In 2006 the joint Cigré task force D1.01/A2.11 published new data on typical values after the initial values in IEC 60599 (edition 2) had been criticised by the IEC TC 14 (transformers). The updated values provided by the task force have been accepted and are included in the current version of IEC 60599:2007 [6.67].

[c] Higher values are for power transformers with communicating on-load tap-changers (refer to chapter 8). The other values of this row apply to all transformers (with and without communicating tap-changer).

[d] Typical concentrations for shell-type power transformers published by LCIE in [6.69]. With the exception of ethane, higher concentrations are for transformers with communicating tap-changer. Values in this table have been rounded off.

[e] This value has been corrected by the author, since it is most probably a typing error in [6.94].

[f] In 1999, IEC TC 14 objected to the values included in the IEC 60599 document at that time and proposed drastically higher typical concentrations [6.69].

[g] Higher values correspond to transformers with communicating tap-changer.

[h] Lower values correspond to new transformers (service age beneath three years), whilst higher values refer to older transformers (service age above seven years).

[i] Results of a Cigré survey between 1973 and 1975 comprising 1280 transformers. Values have been rounded off.

[j] Lower values correspond to new transformers (less than five years of service), while higher values are for transformers with a service age between five and ten years.

[k] The maximal typical value has been revised in 1977 to 200 ppm by volume [6.71].

- The *type* of the equipment has also been found to play an important role. For example, instrument transformers demonstrate much lower typical gas concentrations than power transformers, while shell-type units generate more gases during operation than core-type units, possibly due to higher operating temperatures [6.69]. Especially for power transformers, the presence or not of communicating on-load tap-changers[38] must be taken into account when evaluating the typical gas concentrations.

- On the other hand, the *service age* of the equipment apparently has only little influence on typical gas concentrations [6.69], though it does influence the rate of increase in gas concentration, as will be shown later.

Section 6.2.1 made clear that the evolution of gases in oil-filled power apparatus is a very complex process. Measurements of dissolved gases exceeding the respective typical concentrations can therefore only be an *indication* that something could be wrong. In order to provide more evidence of a potential fault, further investigation is necessary. Generally speaking, detailed DGA interpretation methods found in the literature can be grouped in two classes: methods based on trend analysis and methods analysing the ratio of concentration of each gas to the other gases.

Methods based on *trend analysis* assess the condition of the internal insulation by examining the changes in gas concentration over the service time. In a way, this mode of action is similar to the principle applied by the Buchholz relay, where a sudden increase in free gases leads to tripping. The rate of increase in the concentration of a gas is calculated as:

$$r_n = \frac{c_{n,2} - c_{n,1}}{t} \tag{6.3}$$

where r_n is the rate of increase in the concentration of the n$^{\text{th}}$ gas, in ppm by volume per day, $c_{n,1}$ and $c_{n,2}$ are the levels of its concentration at the first and second measurements, respectively, in ppm by volume, and t is the time interval between the measurements, in days. In a similar way it is possible to calculate the rate of increase in the total concentration of combustible gases [6.68].

Recent investigations [6.69] have shown that the rate of increase in gas concentration is not constant, but largely depends on the service age of the equipment. Especially during the early years of operation, the total rate of increase is in general much higher. It seems that during this wear-in period some unstable chemical bonds in the paper or oil are broken, releasing thereby gases.

Interpretation on the basis of trend analysis is prescribed in the IEEE C57.104 standard, but also IEC 60599 recommends its application in section 8. Table 6.7 shows typical rates of increase in gas concentrations in power transformers, which have been evaluated by Cigré and have also been adopted in the current version of IEC 60599. An excess of 10 % or more over the values in table 6.7 is considered to be sufficient indication of an active fault.

Obviously, application of trend analysis by means of equation 6.3 requires at least two successive measurements of fault gases. A different approach, which can however be classified as an alternative form of trend analysis, is the method of *equilibrium analysis*. According to this method, the concentrations of gases dissolved in the oil are compared to the percentage concentrations of free gases sampled from the Buchholz relay or –in sealed units– from the gas blanket

[38] The term *communicating* describes whether the oil in the tap-changer's pre-selector is shared with the transformer's main tank.

Table 6.7.: Typical rates of increase in dissolved gas concentrations in ppm per year, as evaluated by Cigré for power transformers [6.69].

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
all transformers	35–132	10–120	5–90	32–146	0–4	260–1,060	1.7–10.0
communicating OLTC					21–37		×1,000

above the oil. Contrary to traditional trend analysis, the samples required for equilibrium analysis (free and dissolved gases) should be taken without any significant time lag. Assessment of the fault dynamics is based on the rate of gas diffusion from the oil into the headspace or the Buchholz relay. In order to identify equilibrium conditions, the method uses the ratio of the concentration in the gas phase to the equivalent concentration in the oil phase for each gas, as defined in equation 6.4 [6.22]:

$$q_n = \frac{c_{n,g} \cdot k_n(T)}{c_{n,o}} \tag{6.4}$$

where $c_{n,g}$ is the percentage concentration of the n$^{\text{th}}$ gas in the gas phase, in % by volume, $c_{n,o}$ is the concentration of the respective gas dissolved in the oil, in ppm by weight, and $k_i(T)$ is the temperature-dependent solubility factor of the nth gas in the oil, also known as *Ostwald solubility coefficient*. Values for the Ostwald coefficients of major gases dissolved in mineral oil at 20 °C and 50 °C are given in [6.67].

At equilibrium, the ratio of concentrations for decomposition gases is typically in the range $q_n \in [0.5; 2]$. On the other hand, breathing equipment feature rates of concentrations lower than 0.5 for atmospheric gases, due to the interaction between the oil and the atmosphere. No matter the oil preservation system, rates of concentrations exceeding factor two are indicative of disequilibrium and provide sufficient evidence of an abnormality.

Trend and equilibrium analysis assist in distinguishing between active faults and normal gassing from the oil, but provide only little information about the nature of the fault. We have already seen in section 6.2.1 that different fault types (low-energy discharges, disruptive discharges and overheating of the cellulose or of the oil) release varying amounts of energy and generate a distinct pattern of decomposition gases. By comparing the concentration of each gas to that of the other gases it should thus be possible to identify the type of a fault. In general, two possible DGA interpretation methods exist when examining the relation between gas concentrations.

The first method uses the concept of *"key gases"*, indicative for a particular type of fault. According to the discussion in section 6.2.1, low-energy discharges are related to the evolution of hydrogen and methane, whilst disruptive discharges (arcing) release mainly hydrogen and acetylene. On the other hand, thermal decomposition of the oil results in the generation of, in turn, ethane, ethylene and methane with increasing temperature. Experimental data on gassing from mineral oils under electrical and thermal stress have been published by Cigré in [6.95] and are presented in table E.8, appendix E.6.

With a view to this correlation between gases predominantly present in the oil and the type of the fault, attempts to identify *key gases* date back to the mid 1950s. In [6.59] Howe proposed the use of several chemical solutions on the basis of palladium chloride, silver nitrate and ammoniacal silver nitrate with the purpose of identifying hydrogen, acetylene and carbon monoxide, which he then related to oil degradation, disruptive discharges and to the degradation of cellulose, respectively.

The key gas method was further developed among others by Müller et al. [6.93, 6.96] and is presented in table 6.8. According to this table, the type of a potential internal fault may be identified by determining the primary (key) and secondary gases dissolved in an apparatus. DGA interpretation by means of the key gas method is adopted in IEEE C57.104 (compare table 6.9 below), but is not included in IEC 60599.

Interpretation of DGA by means of the key gas method is done by comparing the measured gas concentrations from a sample with known patterns, as those given in tables 6.8 and 6.9. Significant similarity to one of the gassing patterns provides evidence of the respective type of fault.

In order to assist in comparing measurements to gas concentration patterns, Duval proposed a graphical interpretation method, which can be regarded as a special form of the general key gas method. *Duval's triangle* was first introduced in 1974 [6.97] and has been revised several times since [6.55, 6.88, 6.98]. Due to its simplicity and high hit rate it quickly found broad acceptance and in recommended in the current edition of IEC 60599.

Table 6.8.: Key gases related to distinct fault types in mineral oil-filled power transformers, according to Müller et al. [6.93, 6.96].

Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
low-energy discharge	■	△	▽	▽	△
high-energy discharge	■	△	▽	△	■
disruptive discharge (arcing)	■	□	▽	□	■
overheating $< 300\,°C$	▽	△	■	△	▽
overheating $300\,°C$–$1{,}000\,°C$	▽	△	▽	■	▽
overheating $> 1{,}000\,°C$	△	□	▽	■	△

■ key gas for the respective fault type
□ secondary characteristic gas (high concentration)
△ secondary characteristic gas (low concentration)
▽ gas not typical for the respective fault type

Table 6.9.: Fault-specific percentage concentrations of dissolved gases in mineral oil-filled power transformers, according to IEEE C57.104 [6.68]. Values are given in % by volume and are related to the total concentration of combustible gases[39].

Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
partial discharge	85	13	1	1	–	–
disruptive discharge (arcing)	60	5	2	3	30	–
overheating, oil	2	16	19	63	–	–
overheating, paper	–	–	–	–	–	92

[39] IEEE uses the concept of combustible gases in order to differentiate from atmospheric gases. Since carbon dioxide is not a combustible gas, it is not considered in table 6.9.

Duval's triangle uses three gaseous hydrocarbons, namely methane, ethylene and acetylene in order to identify the possible type of a fault. The percentage concentration of each gas is evaluated and then plotted into a triangular coordinate system (figure 6.10). Each region of Duval's triangle is related to a distinct fault type.

One of the major advantages of DGA interpretation by means of Duval's triangle is that a diagnosis is always returned. Moreover, by graphically following changes over time for a particular piece of equipment, ongoing faults can be monitored closely. Recently, Duval's triangle has been extended to also cover transformers filled with non-mineral oils (silicone insulating oils as well as natural and synthetic esters) and on-load tap-changers [6.70, 6.99].

Interpretation of DGA with the key gas method described so far is based on the relation between the concentration of each individual gas to the *total gas concentration* in the equipment. A somehow different approach is implemented by interpretation methods based on *ratios of concentrations*: here, the concentration of two gases at a time are compared to each other, and a series of ratios are evaluated. Since the generation of decomposition gases is fault-specific, the type of a fault can be identified by the change in some of these ratios [6.22].

The first DGA interpretation scheme using ratios of gas concentrations was developed by *Rogers* for the UK Central Electric Generating Board (CEGB). At the time of its introduction in 1973, it comprised four ratios, namely methane to hydrogen, ethane to methane, ethylene to ethane, and acetylene to ethylene [6.100]. The initial interpretation scheme was revised in 1975 [6.101] and is provided in tabular form in appendix E.6 (table E.9).

In a second revision in 1978, the ratio of ethane to methane was deleted, since it has been found out that it only indicated a limited temperature range of decomposition, but did not assist in further identifying the fault [6.57]. In addition, the tables describing the method were rearranged in a more user-friendly form. The resulting interpretation scheme, shown in table E.10 of appendix E.6, was then adopted by IEC TC 10 for publication in the first edition of IEC 599[40].

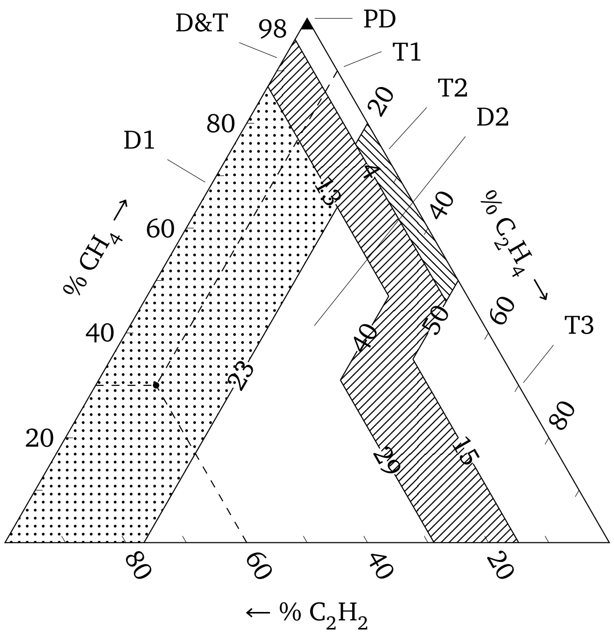

Figure 6.10: Duval's triangle for the interpretation of dissolved gas analysis of power transformers filled with mineral oil (based on [6.88]). The percentage concentration of dissolved methane, ethylene and acetylene is evaluated and plotted into the triangular coordinate system (here for the example: 30 % methane, 10 % ethylene, 60 % acetylene). The coding of the different regions is the same as in IEC 60599 (refer to table 6.12).

[40] The "guideline to the interpretation of dissolved free gases analysis" (IEC 599) was first published in 1978 and revised in 1999 to its second edition. Recently, in 2007, it was amended so as to adopt up-to-date typical gas concentrations observed in the field and published by Cigré. In the course of renumbering within IEC, the document is now coded as IEC 60599.

In the up-to-date edition of IEC 60599 a slightly modified interpretation scheme is used, as will be shown later. On the other hand, the current edition of IEEE C57.104 still uses the revised method by Rogers [6.68].

The second well-known DGA interpretation method using ratios of concentrations is the one proposed by *Dörnenburg* in 1974 [6.102], after some preliminary investigations dating back to 1967 [6.103]. It is still widely applied and is also recommended in the current IEEE C57.104. The interpretation scheme by Dörnenburg defines four ratios, slightly different from the ones proposed by Rogers. In particular, Dörnenburg's scheme used two primary ratios of concentrations (methane to hydrogen and acetylene to ethylene) as well as two secondary ones (ethane to acetylene and acetylene to methane). When determining the values of the above ratios, the concentration of each gas has to be compared with the limit values of table 6.11. A ratio is labelled as "significant" if at least one of the gas concentrations involved exceeds its respective limit value, further as "very significant" if this happens by a factor of two.

Table 6.10 shows the DGA interpretation scheme proposed by Dörnenburg. For a diagnosis to be considered as reliable, at least one primary ratio has to be very significant and one or more further ratios have to be at least significant. This stringent requirement is a drawback of Dörnenburg's method, and results in many situations where no reliable diagnosis is possible.

By far the most important interpretation method based on ratios of concentrations is the one defined in the current *IEC 60599*. It has evolved from the revised scheme by Rogers through several modifications and adaptations. Table 6.12 shows the interpretation method according to IEC 60599. Application of the interpretation scheme in table 6.12 requires that the concentration of at least one gas exceeds its typical value. For power transformers, typical concentrations recommended by IEC 60599 can be found in the second row of table 6.6. This requirement is one of the modifications compared to the method by Rogers.

Table 6.10.: Dörnenburg's method of DGA interpretation [6.102]. Reliable diagnosis requires one primary ratio being very significant and at least one further ratio being significant.

Fault type	primary ratios		secondary ratios	
	$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_6}{C_2H_2}$	$\frac{C_2H_2}{CH_4}$
low-energy discharge	< 0.1	–	> 0.4	< 0.3
high-energy discharge or arcing	0.1–1.0	> 0.7	< 0.4	> 0.3
overheating	> 1.0	< 0.7	> 0.4	< 0.3

Table 6.11.: Limit values of the concentration of gases dissolved in the oil, in ppm by volume [6.68, 6.102]. These values are used in Dörnenburg's interpretation method so as to identify significant ratios. The first row contains the limit values as proposed by Dörnenburg, whereas values in the second row are listed in IEEE C57.104.

Limit values in ppm by volume	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
according to Dörnenburg [6.102]	200	50	15	60	15
according to IEEE C57.104 [6.68]	100	120	65	50	1

Table 6.12.: DGA interpretation scheme according to IEC 60599 [6.67]. The method should only be applied if the concentration of at least one gas exceeds the respective typical value (for power transformers, typical gas concentrations are given in table 6.6).

ID	Fault type	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	partial discharge	not significant	$< 0.1^a$	< 0.2
D1	low-energy discharge	> 1.0	0.1–0.5	> 1.0
D2	high-energy discharge, arcing	0.6–2.5	0.1–1.0	> 2.0
T1	thermal fault $< 300\,°C$	not significant	> 1.0	< 1.0
T2	thermal fault $300\,°C$–$700\,°C$	< 0.1	> 1.0	1.0–4.0
T3	thermal fault $> 700\,°C$	< 0.2	> 1.0	> 4.0

[a] < 0.2 for partial discharges in instrument transformers, < 0.07 for partial discharges in bushings.

In addition to the three ratios in table 6.12 (acetylene to ethylene, methane to hydrogen and ethylene to ethane), other ratios are also considered in IEC 60599. The ratio of *carbon dioxide to carbon monoxide* (CO_2/CO) is characteristic for the involvement of cellulosic materials in the fault. Several investigations, e.g. in [6.104], have shown a good correlation between the amount of carbon oxides and the retention of the cellulose's tensile strength and degree of polymerisation, so that the total concentration of these gases is itself an important index for the condition of the solid insulation. It was also found out that pyrolysis of paper and pressboard releases carbon monoxide to a higher degree than carbon dioxide. A CO_2/CO ratio below factor three[41] is thus considered to provide evidence of a fault with potential involvement of paper e.g. conductor overheating. However, recent investigations [6.70] demonstrated that this is only valid for breathing equipment; sealed or positive-pressurised devices showed no significant correlation between the CO_2/CO ratio and faults with paper involvement. Another aspect which has to be considered with regard to breathing units is the interaction between the oil and the atmosphere which can result in the absorption of carbon dioxide from the ambient air [6.67]. For this reason, when determining the CO_2/CO ratio, IEC 60599 recommends to use only the difference from the last measurement rather than the absolute concentrations.

Another ratio discussed in IEC 60599 is the one of *oxygen to nitrogen* concentration (O_2/N_2). Since both gases are present in the atmosphere, they will diffuse into the oil of breathing units and saturate it. Taking into account the percentage concentrations in the atmosphere as well as their individual solubility coefficients, an O_2/N_2 ratio of approximately 0.5 is expected at equilibrium. A value lower than 0.3 is therefore indicative of an increased rate of oil oxidation, since it shows that oxygen is being strongly consumed. But also in sealed equipment, where nitrogen is typically used as gas blanket, the O_2/N_2 ratio can be used in order to identify potential leakages to the atmosphere (in this case oxygen would enter the system and increase the O_2/N_2 ratio).

The last ratio addressed in IEC 60599 is the one of *acetylene to hydrogen* concentration. Since acetylene is generated in large quantities during arcing, this ratio can be used in order to identify potential contamination of the transformer's oil in the main tank with oil from the tap-changer due to a leakage.

[41] Some researchers [6.66, 6.105] have proposed a limit value of 10 for the CO_2/CO ratio.

For the sake of completeness, a graphical interpretation method with close similarities to the aforementioned ratios of concentrations shall also be presented here. The *dissolved gas nomograph* was developed by Church for the US Bureau of Reclamation (Burec) and introduced in 1975 [6.66]. It combines the fault gas ratio concept with the typical gas concentrations in a graphical way (figure 6.11). The nomograph consists of vertical logarithmic scales representing the concentrations of the various gases. Measured gas concentrations are plotted into the nomograph and adjacent scales are connected by straight lines between the respective points. The slopes of these lines are the diagnostic criteria for determining the type of the fault [6.66]. A visual comparison of the slopes of the line segments with the keys provided is all that is needed to identify the fault type. Due to its simplicity and user-friendliness, the nomograph is widely accepted in practice, especially in the USA.

Summing up, it is obvious that numerous methods are available for the interpretation of dissolved gas analysis. The most relevant methods are those recommended in IEC 60599 and IEEE C57.104. In addition to the interpretation schemes, both standards also provide guidance to the systematic implementation of DGA in practice. The corresponding flowcharts can be found in appendix E.6. In the following two chapters the interpretation method defined in IEC 60599 will be used as reference.

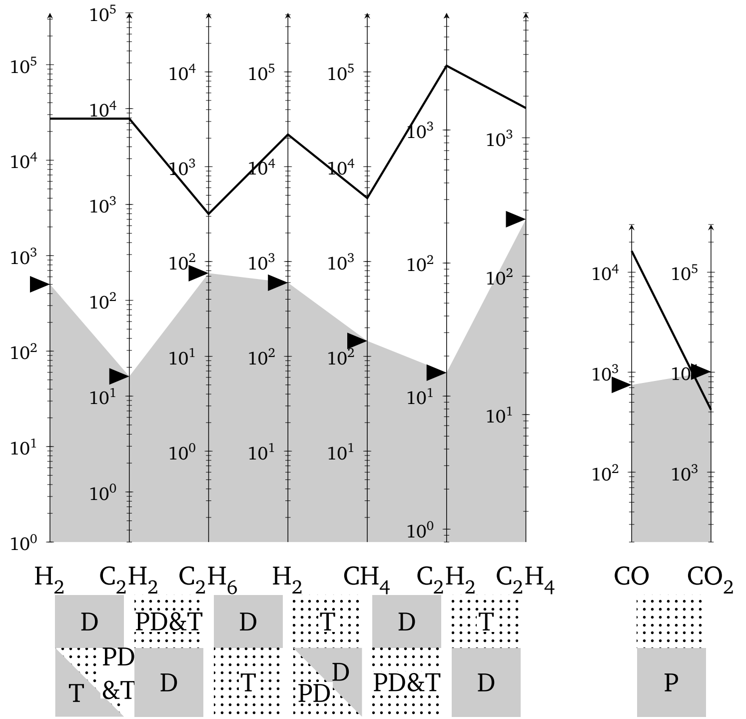

Figure 6.11.: Nomograph for the interpretation of dissolved gas analysis [6.66]. Measured gas concentrations are plotted in the vertical logarithmic scales and connected by straight lines. The slope of the line segments is a measure of the ratio of concentrations. Identification of the type of fault is done by comparing the slopes with the keys provided at the bottom of the figure (PD: partial discharges, T: thermal fault, D: dielectric fault, P: fault with paper involvement). Only line segments connecting points above the typical values (denoted by the shaded surface) are considered. The example plotted here indicates a dielectric fault with possible paper involvement.

7 Fuzzy DGA of instrument transformers

> It is often suggested that utilities only think about their populations of instrument transformers when they begin to explode. Whilst this is far from the truth, it is true to say that there is limited focus upon the long term asset management aspects of these devices despite the large populations which are in service.
>
> Cigré SC A3, 2009

For the last four decades, dissolved gas analysis (DGA) has been among the most common techniques for the purpose of condition assessment of oil-filled power equipment. Economic evaluation both in theory [7.1] as well as on the field has verified the positive influence of DGA on the cost of maintenance. DGA assists in identifying incipient faults of the internal insulation during service and reduces the risk of unplanned outages, although attempts to correlate individual DGA results with the probability of failure of the respective units [7.2, 7.3] are still lacking success. Still, there is a broad consensus between manufacturers of oil-filled power apparatus and electric power utilities regarding the role of DGA, especially for monitoring power transformers [7.4–7.6].

Chapter 6 gave an overview of dissolved gas analysis, covering all relevant topics: sampling of the oil, evaluation of the concentration of dissolved gases and, finally, interpretation of the results. It is the objective of this chapter to provide a practical example of DGA applied to a population of instrument transformers on the basis of IEC 60599. Contrary to power transformers, little has been published with regard to dissolved gases found in such equipment. The case study reported here will therefore also highlight the main differences between these two types of power equipment (instrument and power transformers) with respect to DGA.

Accordingly, the first part of this chapter reflects the state of the art of high-voltage instrument transformers, with special focus on inductive voltage transformers, since this is the type of equipment investigated in the case study. The following section briefly describes the data available from dissolved gas measurements on the field. It will be shown that typical gas concentrations in oil-filled instrument transformers are significantly lower than the respective values for power transformers which have been presented in chapter 6.

The case study provided here also demonstrates the main limitations of the diagnosis obtained by existing DGA interpretation schemes. *How sensitive is the diagnosis to potential measuring errors? Is the obtained diagnosis also reliable in the case of several, independent faults?* On a closer look, the information provided by the measurement of dissolved gases seems to lose in precision. This is the motivation for introducing fuzzy reasoning in order to enhance DGA interpretation.

The second part of this chapter is dedicated to the “fuzzification” of the IEC interpretation scheme. Following a brief literature review of fuzzy DGA interpretation techniques, section 7.4 provides the mathematical description of the developed fuzzy model on the basis of IEC 60599.

Again, the population of instrument transformers serves as a case study. Finally, a discussion of the results and some comments on the developed method are given in section 7.5.

7.1 Introduction to instrument transformer technology

IEC 60050 defines an instrument transformer (IT, also called *measurement transformer*) as "a transformer intended to transmit an information signal to measuring instruments, meters and protective or control devices". Accordingly, instrument transformers must fulfil two functions [7.7]: the *measuring* function comprehends the transformation of high currents and voltages into standardised measurements signals, which can be processed by the secondary equipment. Common values of rated secondary currents for current transformers are 1 A and 5 A. In the case of voltage transformers, rated secondary phase-to-phase voltage (rms) usually amounts 100 V, 110 V or 200 V. But also the power needed to activate the secondary circuit must be transmitted through the instrument transformer. This is especially important for older substations, featuring electromechanical protection relays with high power demand and high power loss due to long cable connections between the instrument transformers and the control room. The second duty assigned to instrument transformers is an *insulating* one: The transformed signal must be brought down from the high voltage in the primary circuit to virtually earth potential. Even in the case of a failure in the instrument transformer's internal insulation, provisions must be taken, so that secondary equipment will not be subject to high voltage.

The main application fields of instrument transformers in power system comprise metering and billing during normal operation as well as protection or *relaying* at fault conditions. For the purpose of metering and billing, the measuring *accuracy* is of great importance, whereas for fault protection purposes the *transient behaviour* of the transformers must be sufficient. With regard to accuracy, not only the magnitude of the transmitted secondary signal, but also its phase angle should be as exact an image of the primary signal as possible. According to IEC specifications, instrument transformers are grouped into five classes of accuracy, as shown in table 7.1. The label of each accuracy class corresponds to the maximum allowed magnitude transformation error (*ratio error*), i.e. accuracy class 0.1 specifies a maximum measuring error of $\pm 0.1\,\%$ with regard to the magnitude of the measured signal. For current transformers, the specified accuracy level has to be verified at primary currents amounting from 5 % to 120 % of the rated primary current, whilst voltage transformers must demostrate the specified accuracy within the range $80\,\% - 120\,\%$ of the rated primary voltage [7.7]. Relaying applications for protection purposes define lower requirements for accuracy (the measuring error has to be lower than $\pm 10\,\%$ at a primary current twenty times the rated steady-state primary current), however, the transient behaviour of inductive instrument transformers must ensure that the magnetic core will not be driven into saturation for a specified time interval of one second. This is important, since knowledge of both shape and magnitude of fault currents is essential for deciding for appropriate protective actions (fault identification and clearance).

The signals of interest in the power system are line currents as well as phase-to-phase and phase-to-ground voltages. Instrument transformers are therefore divided into current and voltage transformers, CTs and VTs respectively. Conventional current transformers operate on the basis of magnetic induction, whilst for voltage transformers both magnetic induction as well as capacitive coupling may be applied. In addition, a series of non-conventional instrument

Table 7.1.: Accuracy classification of instrument transformers according to IEC and IEEE [7.8–7.10]. The accuracy is defined by means of a maximum ratio error and a maximum phase displacement between the primary and secondary signals.

Application field	IEC specification	IEEE specification
calibration and precise tariff measurement of large amounts of electrical energy	0.1	0.3
precise tariff measurement	0.2	0.3
tariff measurement and precise metering	0.5	0.6
metering for the purpose of grid operation	1.0	1.0
fault protection and relaying	3.0	3.0

transformers (also referred to as *instrument transducers*[1]) have been developed since the 1970s with the purpose of improving transient performance, thus allowing for more reliable and faster fault clearance. Non-conventional instrument transformers are outside the scope of this section, however, a detailed discussion of such equipment can be found in [7.7, 7.11].

Nowadays, free-standing instrument transformers with rated primary voltage up to 245 kV are usually designed as combined units, intended to measure both current and voltage [7.12, 7.13]. The combined design offers several advantages: As only one apparatus has to be installed, only one foundation is needed, leading to significant savings in space. Furthermore, transportation and installation are more efficient, and the overall cost of acquisition is lower compared to two separate units. But also with regard to reliability are combined ITs superior as will be shown later [7.14].

Instrument transformers are installed in great numbers in the power system; therefore, power consumption is an important aspect and has to be kept as low as possible. In the past, electromechanical relays have been used for metering and protection applications. Typical burdens[2] ranged from 50 to 80 VA for current transformers and up to 200 VA for voltage transformers [7.7]. The introduction of electronic protection equipment with low energy consumption in the last decades has resulted in a decrease in rated burdens. In addition to the power consumption by the secondary circuit, power loss within the instrument transformer itself must also be considered. A high power loss is not only unfavourable for the overall energy efficiency of the power system, but also adversely affects the measuring performance of the transformer, since it alters the coupling between primary and secondary side.

The insulating system –both internal and external– of instrument transformers is determined by three main criteria: dielectric, thermal and environmental requirements [7.16]. *Dielectric requirements* are based on the rated insulation level[3], which is typically linked to the intended service voltage e.g. according to IEC specifications. However, specific applications may call for higher insulation levels, for example if an instrument transformer is integrated within a gas-

[1] IEC 60050 defines a transducer with electrical output as “a device intended to transform, with a specified accuracy and according to a given law, the measurand, or a quantity already transformed therefrom, into an electrical quantity.”

[2] The *burden* of an instrument transformer is the impedance of the secondary circuit, expressed as the apparent power absorbed by the secondary circuit at a specified power factor, usually 0.8 lagging [7.7, 7.15].

[3] The *rated insulation level* of a power apparatus reflects both the short duration power frequency withstand voltage as well as the rated lightning and switching impulse withstand voltage.

Table 7.2.: Insulating systems of common instrument transformers.

Internal	External	Voltage level	Typical application
oil & paper	porcelain	72.5 kV – 765 kV	outdoor and GIS
SF_6 gas	composite	72.5 kV – 765 kV	outdoor
cast resin	cast resin	< 72.5 kV	indoor, outdoor and GIS

insulated switchgear. With respect to the external insulation, the rated lightning and switching impulse withstand voltage determine the arcing clearance of the instrument transformer and, thus, its height. The *thermal requirements* are particularly important for current transformers with an oil-impregnated paper insulating system [7.7], due to the thermal limitations posed by the cellulose. IEEE C57.13 specifies three thermal classes for instrument transformers (maximum acceptable temperature rise of 55 °C, 65 °C and 80 °C, respectively), which have to be verified by temperature rise tests. *Environmental requirements* depend largely on the intended location of the device. Outdoor applications might pose a challenge regarding pollution, contamination, or exposure to extreme temperatures and moisture, whilst such considerations are redundant in indoor applications. Especially pollution and contamination are important factors that determine the necessary creepage distance of the external insulation. Finally, *mechanical requirements* have an influence on the choice of the external insulation: general mechanical and potential seismic stress as well as stress resulting from the internal service pressure[4] of instrument transformers determine the wall thickness of post insulators and the design of the flanges [7.7].

The internal insulating system of instrument transformers may be designed on the basis of:

- *oil-impregnated paper*: Traditionally, instrument transformers designed with a rated primary voltage of 72.5 kV and above use mineral insulating oils and dielectric paper as insulating materials. The paper is applied in the form of strips by winding machines, or in the form of sheets wound by hand. After winding, the paper is dried and impregnated according to the process described in section 6.1.3. Throughout the winding process, it is important to provide sufficient overlap of the individual strips or sheets, so that no continuous oil channels are formed perpendicular to the layers, since interfacial effects along the latter would lead to partial discharges and degrade the dielectric strength of the insulating system [7.7].

- *SF_6 gas*: Contrary to oil-impregnated paper insulating systems, application of SF_6 gas to high-voltage instrument transformers is rather new (field experience covers ninety and twenty years, respectively [7.12]). In inductive SF_6-insulated transformers, insulation of the windings is provided by dry-type dielectrics e.g. paper and organic or synthetic films. Usually, pure SF_6 with a service pressure in the range of one to five bar [7.17] is applied, though extreme climatic conditions (ambient temperatures reaching −40 °C) may call for mixtures of SF_6 with nitrogen. Electrode surface quality and the absence of particles within the internal insulating systems must be controlled, since they influence the dielectric behaviour of SF_6-insulated instrument transformers.

4 The internal service pressure is the gas pressure applied to the post insulator in the case of SF_6-insulated instrument transformers, or the hydrostatic pressure in the case of oil-immersed devices.

- *cast resin*: Cast resin serves both as internal and external insulating medium at the same time. As a result, resin-insulated instrument transformers feature good thermal characteristics (heat dissipation within the insulation) and high mechanical strength. Moreover, their operation is virtually maintenance-free. However, the dielectric strength of cast resin is moderate, and the voltage gradient at service voltage should not exceed 30 kV/cm [7.7]. For this reason, the rated primary voltage of resin-insulated instrument transformers is limited up to 72.5 kV.

For the external insulation of free-standing instrument transformers, two design principles are widely used. *Porcelain* insulators are common for oil-immersed units, but may also be applied to devices with internal insulation on SF_6 basis. However, in the latter case, a tube made of glass fibre reinforced epoxy resin must be fitted within the insulator, since porcelain can only withstand internal service pressures up to two bar absolute [7.7]. Due to limitations related to manufacturing (casting), hollow porcelain insulators are usually no longer than approximately 1.5 – 2.0 meters, depending on their proportions i.e. inner/outer radius and wall thickness. For high-voltage applications, higher arcing distances might be necessary[5]. In this case two or more parts must be connected by ceramic jointing or by applying epoxy glue. When porcelain is used as external insulating material, metal flanges are fitted at the ends of the insulator. In the past, the flanges have been clamped, however nowadays, cementing is the preferred method.

The introduction of SF_6 as internal insulating medium has been accompanied by the development of *composite insulators* for the external insulation, although such insulators may also be applied to paper-insulated ITs as well. A composite insulator consists of a tube made of glass fibre reinforced resin equipped with vulcanised silicone rubber weather sheds which are moulded on the outer surface of the tube. This design offers high mechanical strength, and can withstand internal service pressures of several bar. Even in case of a disruptive mechanical failure (explosion), risk exposure with composite insulators is low compared to porcelain insulators, where sharp-edged fragments hurtle through the air. In addition, the silicone coating exhibits hydrophobic (water-repellent) behaviour, which is advantageous against pollution.

Table 7.2 gives an overview of common insulating systems for instrument transformers. Generally speaking, oil-paper-insulated units hold the majority in high-voltage applications. A survey conducted between 1985 and 1995 by Cigré [7.7] came to the conclusion that approximately 96 % of all installed instrument transformers with rated primary voltage over 72.5 kV are oil-immersed, the rest being equally shared between resin-insulated and SF_6-insulated units (refer to table F.1 in appendix F.1). A more recent survey within austrian utilities [7.18] showed similar results (84.6 % oil-porcelain, 6.4 % oil-composite and 7.8 % SF_6-composite).

In the following paragraphs we shall focus on oil-immersed inductive voltage transformers, since this type of equipment will be investigated in the case study presented here.

7.1.1 Oil-immersed inductive voltage transformer

Unlike current transformers, which are connected in series with the phase conductor, voltage transformers are connected in parallel (between phase and earth or directly between phases) and operate –from a systems point of view– virtually in open-circuit, exhibiting a very high impedance. With regard to the two basic functions mentioned in section 7.1 (measuring and

5 For example, a 420 kV current transformer by Ritz has an arcing distance of 3765 mm [7.13].

insulating), in *inductive voltage transformers* (also called magnetic voltage transformers, MVTs) these are both fulfilled by the primary (high-voltage) winding.

The layout of MVTs depends mainly on the rated primary voltage. In the range up to 245 kV, the *dead-tank design* is state of the art (figure 7.1(a)): The magnetic core of a dead-tank voltage transformer is located at the base of the device and is connected to earth potential. Directly adjacent to the core is the secondary (low-voltage) winding, lagged by the high-voltage winding. The latter is of the trapezoidal multi-layer type [7.7], providing excellent characteristics regarding voltage gradients both during normal operation as well as in the case of high-frequency surges on the primary side. In addition, earthed screens are inserted between the windings in order to prevent penetration of transient overvoltages from the primary into the secondary circuit.

Dead-tank MVTs feature internal bushings connecting the primary winding (located at the base of the device) to the high-voltage terminal (figure 7.1). Similar to paper-oil-insulated high-voltage bushings, electric field stress grading is applied for this purpose: Screens of metal foil or carbonised paper are inserted at regular intervals in the paper insulation, and the so-formed series capacitances define the distribution of the electric field within the bushing. The ends of the intermediate screens deserve closer attention, as localised high electric field stress could initiate partial discharges. Appropriate solutions comprise the use of toroidal grading rings, connected at the ends of the screens, or the use of a large number of screens at low potential difference between them (few thousands Volt) [7.7].

The *open-core design* with disc windings has also been traditionally applied to inductive voltage transformers (figure 7.1(b)). However, compared to dead-tank MVTs, voltage transformer of the open-core type have several drawbacks. For instance, the electric field distribution within disc windings in case of transient overvoltages is very steep, with the first turns subjected to ex-

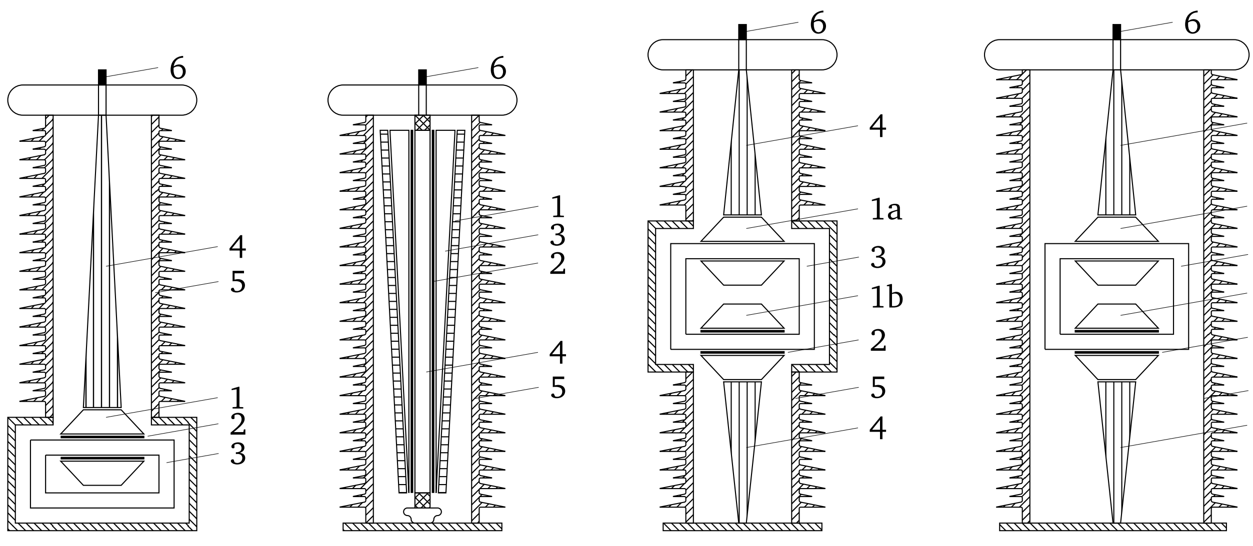

Figure 7.1.: Basic layout of inductive voltage transformers (based on [7.19]): (a) dead-tank design, (b) open-core design with disc windings, (c) cascade-type transformer with live tank, and (d) cascade-type transformer with active part enclosed in the post insulator. Legend: 1) primary winding, 2) secondary winding, 3) magnetic core, 4) bushing, 5) post insulator, 6) high-voltage (primary) terminal.

tremely high electric stress. Also, the layout of open-core transformers calls for higher amounts of insulating oil [7.12]. Consequently, the open-core design is not applied any more to new MVTs.

The dead-tank design cannot be applied when the rated primary voltage exceeds 420 kV, due to the limited insulating capability between the high-voltage terminal of the primary winding and the earthed core. The solution is to have the magnetic core at some intermediate potential; this principle is applied to *cascade-type* MVTs. In the 420 kV voltage level[6] one cascade is used: the primary winding is subdivided into two parts, distributed over two limbs of the core and connected in series (figure 7.2). The core itself is directly connected to the intermediate node and its potential is half the potential of the high-voltage terminal. The lower part of the primary winding is surrounded by the secondary (low-voltage) winding. In order to reduce the effect of stray flux from the primary winding's upper part –which adversely influences the primary-secondary coupling factor– compensation windings are introduced (figure 7.2). They are installed immediately under the two parts of the primary winding and connected in series, so that the stray flux of the upper sub-winding is re-introduced into the secondary winding.

At even higher voltage, two cascades can be stacked and connected in series: The double cascade will have four wound limbs in total and the two cores will then have potentials of 75 % and 25 % respectively of phase-to-earth voltage. Using the same principle some MVTs have been produced with three or more cascade units [7.7].

The active part (magnetic core and windings) can be mounted inside the insulator or enclosed in an intermediate metal tank, whose potential amounts half the service line-to-earth voltage (*live-tank design*). Live-tank cascade-type MVTs (figure 7.1(c)) use slender insulators, and less amount of insulating oil is required. This design is nowadays state of the art. On the other hand, cascade-type MVTs with enclosed active part (figure 7.1(d)) have the advantage that no additional flanges and gaskets are required, which has a positive influence on oil tightness and overall reliability, as will be shown later in section 7.1.2.

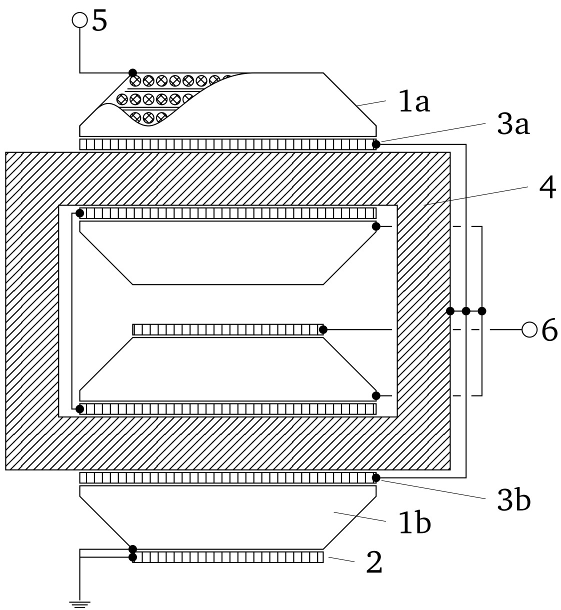

Figure 7.2: Schematic winding layout in a cascade-type MVT. The primary (high-voltage) winding is subdivided into two parts (1a and 1b), connected in series and distributed over two limbs of the core. The magnetic core (4) is at half the service potential. Compensation windings (3a and 3b), connected in series mitigate the negative effect of stray flux from the upper primary sub-winding, and ensure a good primary-secondary coupling factor. Other symbols: (2) secondary winding, (5) high-voltage terminal, (6) secondary terminal.

[6] Recently, some manufacturers have also introduced dead-tank MVTs with rated primary voltage 420 kV e.g. [7.20].

The typical material used for the magnetic core of inductive voltage transformers is electrically graded silicon iron. It has high saturation level (approximately 1.96 T [7.16]) and exhibits low power loss. The rather wide ankle region[7] is not much of an issue, since the line-to-earth voltage during service usually remains within the range of 90 % to 110 % of its nominal value. In order to increase the accuracy of MVTs at fault-to-ground conditions, a combination of silicon iron with nickel iron is also possible[8].

Magnetic saturation usually does not pose a risk to the operation of inductive voltage transformers. Contrary to current transformers, where line overcurrents (both transient and steady-state) flowing through the primary winding may well saturate the core, voltage transformers are connected in parallel; only the magnetising current flows therefore though their primary winding. Consequently, cut cores[9] are not required. However, also voltage transformers may saturate under certain conditions. The most relevant phenomenon is *ferroresonance*, and involves the resonant behaviour of the MVT's non-linear inductance with some series capacitance in the power systems e.g. with the grading capacitors of open line circuit breakers [7.21–7.24].

In oil-paper-insulated instrument transformers, changes in ambient or operating temperature result in variations of the internal pressure, unless the oil is allowed to expand. The applicable *oil preservation systems* are, in general, similar to those used for large power transformers (refer to section 8.1.2):

- Until the 1960s, oil-immersed instrument transformers were manufactured as breathing units, equipped with air-drying breathers (figure 7.3(a)) [7.25]. A known problem was the slow diffusion of moisture through the breather into the internal insulating system due to the absence of pronounced loading cycles, especially in the case of voltage transformers.

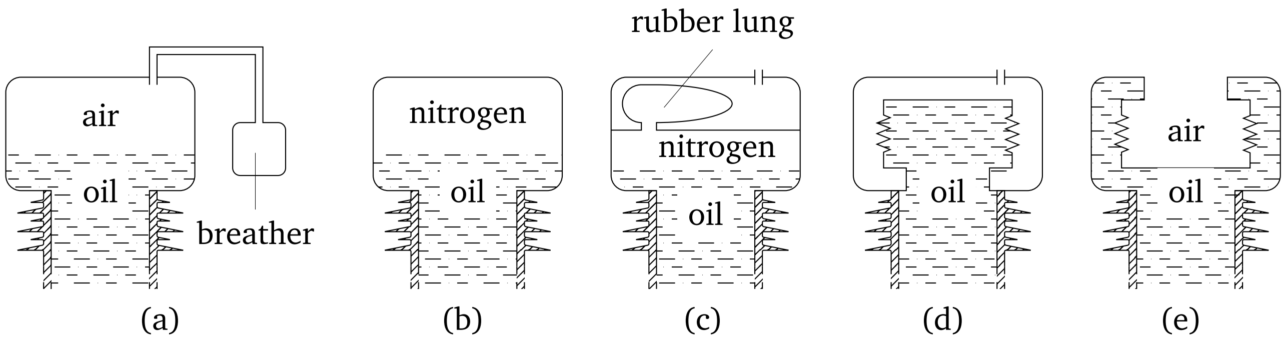

Figure 7.3.: Oil preservation systems for oil-immersed instrument transformers: (a) breathing unit, (b) sealed with nitrogen cushion in the headspace (pressurised), (c) sealed with nitrogen cushion and rubber lung, (d) hermetically sealed with positive-type metallic bellows, and (e) hermetically sealed with negative-type metallic bellows.

[7] The *ankle region* of a ferromagnetic material describes its behaviour at low flux density. A wide ankle region is related to significant spread of the magnetic permeability at low flux, which has a negative influence on the accuracy of the transformation from the primary to the secondary side.

[8] Nickel iron has a much narrower ankle region, but its saturation level is rather low (approximately at 0.76 T [7.16]).

[9] *Cut cores* (sometimes also called *gapped* cores) are magnetic cores with an intermediate air gap. The air gap increases significantly the core's reluctance, but also its saturation level. The resulting magnetising characteristic curve is more linear and can thus be used for measuring fault currents.

- This lead to the introduction of *sealed systems*. A nitrogen cushion was introduced in the headspace above the oil and the transformer was either hermetically sealed or was equipped with a rubber lung in contact with the surrounding air (figures 7.3(b) and (c), respectively). The latter design allowed for the expansion of the insulating oil, thus keeping the internal pressure almost constant. One major disadvantage of this approach is the low partial discharge inception voltage when the oil is saturated with nitrogen.

- Nowadays, the preferred method for the purpose of oil preservation is to use metallic bellow made of stainless steel. These bellows may be either of the positive type, with the expanding oil inside and the surrounding medium (atmospheric air) outside, or of the negative type, with the insulating oil outside (figures 7.3(d) and (e)). Due to the easier installation of oil level indicators, positive bellows are state of the art (figure 7.4).

A recent survey, conducted among Austrian utilities in 2009 [7.18], showed that more than 76 % of all installed oil-immersed instrument transformers in the high-voltage level (rated voltage 123 kV upwards) are equipped with metallic bellows for oil preservation purposes. Another 23, 5 % use a nitrogen cushion in the headspace, and only 0.3 % were identified as breathing units.

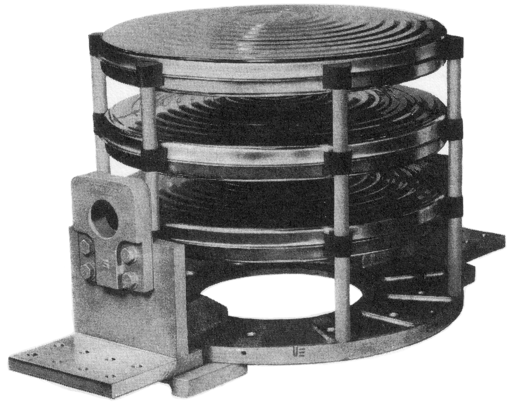

Figure 7.4: Oil preservation system comprising three positive-type metallic bellows [7.17]. The bellows are made of stainless steel and are welded along their periphery. The corrugated form allows for the expansion of 10 litres per bellow. The bellows are installed on the top of the instrument transformer, protected from ambient influences by a metallic hood.

7.1.2 Reliability of instrument transformers

Instrument transformers are the most common equipment in high-voltage power systems and the number of units in service worldwide amounts a few millions [7.19]. In addition, instrument transformers provide the signals needed by the control and protection systems. The combination of these two aspects –high piece number and importance for the protection system– underlines the major impact such equipment may have on the overall reliability of a power grid.

Fortunately, the reliability of instrument transformers is rather high, compared with other types of substation equipment. Yet the desire of power utilities for transformers with exceptionally high availability and long lifetime at low maintenance intensity could not be fully satisfied, even after the introduction of the hermetically-sealed design [7.26]. This section gives a brief overview of standard requirements for instrument transformers, a review of published failure statistics, as well as a list of applicable monitoring techniques.

The International Electrotechnical Commission defines standard requirements for instrument transformers in the IEC 60044 series[10]. Type tests listed in IEC 60044 include, among others:

- *short-circuit withstand capability* tests: during service, instrument transformers may be subject to short-circuit currents[11], which will significantly stress the windings. It must be therefore ensured that the transformer will be able to withstand a potential short-circuit current. The applied test practice may either implement a post-set short-circuit (the transformer is first energised and the secondary circuit is the shorted) or a pre-set short-circuit [7.27].
- *temperature-rise* tests: with regard to temperature rise, three classes of instrument transformers are defined [7.10]. During temperature-rise tests the hottest spot temperature of the unit is measured and compared to its ratings.
- *lightning impulse* withstand tests, both chopped wave and full wave: lightning impulses are a severe stress to the internal insulation of inductive instrument transformers. Acceptability criteria are usually established by means of gas-in-oil levels [7.7].
- *power-frequency withstand* tests (at rated primary voltage below 300 kV) or *switching impulse withstand* tests (at rated primary voltage above 300 kV), both under wet conditions. These tests question primarily the external insulation of the equipment.

The desire for higher levels of reliability has motivated utilities to establish statistics of instrument transformer failures, both in national and international level. The objective of such failure statistics is to provide insight in the most common failure modes so that appropriate prevention and/or mitigation actions can be taken. However, collecting and documenting information about failures of instrument transformers is no easy task: In spite of the large number of units in service, failure occurrence is rather seldom (the rate of failures is less than 0.05 % of incidents per year, compare table 7.3). In addition, failures are often catastrophic, leading to explosion of the porcelain post insulator and leaving little evidence of the primary cause of failure [7.28]. Last but not least, the fact that on-line monitoring is not state of the art for instrument transformers requires higher documentation efforts, as (usually hand-written) reports e.g. from visual inspections have to be digitised and stored.

On international level, the most detailed failure statistics have been established by Cigré in the course of two broad surveys[12]: The first survey, conducted from 1970 to 1987 by working group 23.07 included approximately 136 thousand units; results have been published in [7.19]. In this first survey, incidents have been categorised into major and minor failures. A *major failure* is defined as a “sudden explosive event, directly leading to outage of the equipment” [7.7]. The consequence of a major failure for the equipment is usually so severe that the affected unit has to be permanently removed from service. According to the above definition, major failures cannot be detected in advance. On the other hand, *minor failures* are “non-violent, but sudden events leading to urgent system outage within a defined time interval, usually within an hour”. Contrary to major failures, minor failures are detected in advance, however, on-line monitoring

[10] Part 1 refers to current transformers, while part 2 deals with inductive voltage transformers [7.8, 7.9].

[11] The short-circuit can occur in the secondary circuit of the transformer or –in the case of current transformers– at some distant location in the primary circuit.

[12] A third survey, including all types of substation equipment, is currently in process by working group A3.06. The technical brochure with the results is expected to be published in the fall of 2011.

Table 7.3.: Overview of the second Cigré enquiry on instrument transformers: relative failure rates [7.7]. The failure rates (in % per year) are derived by dividing the number of reported incidents by the number of instrument transformers and the time horizon of the survey (ten years).

Type of instrument transformer	Major failures	Minor failures	Defects
current transformers	0.040	0.019	0.098
inductive voltage transformers	0.044	0.020	0.216
capacitive voltage transformers	0.026	0.066	0.182
combined instrument transformers	0.023	0.042	0.277
all instrument transformers[a]	0.022	0.042	0.276

[a] Values reported in this row originate from all paper-oil-insulated transformers, including current transformers, inductive and capacitive voltage transformers as well as combined transformers.

systems are required for this purpose. Monitoring techniques, both on-line and off-line, will be discussed later in this section.

The main limitation of the first survey by Cigré derives from the fact that most outages of instrument transformers are not due to minor or major failures, but rather due to smaller defects, identified during periodic inspections. Cigré study committee A3 defines a *defect* as a "non-urgent (planned) outage of a unit with the purpose of repair or replacement". For this reason, a second survey has been conducted upon completion of the first one [7.7]. The second survey covered the time interval from 1985 to 1995 and included a total of approximately 131 thousand high-voltage instrument transformers (rated primary voltage greater than 60 kV). The surveyed transformers have been grouped by type (current transformers, inductive and capacitive voltage transformers, or combined transformers) and by their internal insulating system (oil-impregnated paper, SF_6 gas, or resin insulation) as presented in section 7.1. Incidents have been categorised as major failures, minor failures, and defects. An overview of the respective rates of occurrence is given in table 7.3.

Obviously, the rate of occurrence of defects is significantly higher than the respective rates for minor and major failures (roughly by factor 5–10). This is in direct relation to the detectability of the different events: defects are detected during planned visual inspections or in the course of maintenance actions, while minor faults can only be identified by on-line monitoring (which however is not widely used) or as a result of tripping of the protection system. The latter is also the only detection possibility in the case of major faults. In table 7.4 the responses of utilities participating in the second Cigré survey with regard to the detection of incidents is summarised; the experience in the field is in accordance with the above reasoning.

Table 7.5 shows the assumed primary cause of the various incidents. Almost half of all faults and defects have been assigned to the original design of the equipment. In particular, major failures occur mainly due to poor electrical design, presumably leading to partial discharge inception. Excessive dielectric stress e.g. by lightning impulses is also a quite common cause for major failures. On the other hand, poor manufacturing and general tightness problems in the original design are the most pronounced causes for minor faults and defects of instrument transformers. Oil leaks account for more than 40 % of all defects in service and therefore deserve further consideration.

Table 7.4.: Detection of failures and defects of instrument transformers. The presented values describe the number of incidents identified by means of each detection method divided by the total number of incidents and have been reported by utilities participating in the second Cigré survey [7.7]. In addition, the entry for planned visual inspections and maintenance has been broken down in accordance with [7.26].

Detection method	Incidents detected
planned visual inspection and maintenance	63.30 %
– dissolved gas analysis or measurement of dissolved hydrogen	25.32 %
– visual inspections	21.52 %
– measurement of partial discharges	5.06 %
– other	11.40 %
tripping of protection system	13.30 %
alarm from on-line monitoring systems	10.90 %
failures of similar equipment	3.90 %
other	8.60 %

Table 7.5.: Primary cause of failures and defects of instrument transformers according to [7.7].

Primary cause of failure	Major failures	Minor Failures	Defects
design fault	42.5 %	43.9 %	65.5 %
– electrical	40.0 %	15.9 %	12.2 %
– mechanical	2.0 %	10.5 %	11.1 %
– material	0.2 %	2.5 %	7.5 %
– oil leaks	0.0 %	15.0 %	35.2 %
inadequate manufacturing	13.3 %	11.1 %	13.8 %
– general quality	4.3 %	1,4 %	1.3 %
– moisture ingress	3.3 %	0.5 %	1.8 %
– oil leaks	5.7 %	8.9 %	6.3 %
– gas leaks	0.0 %	0.0 %	0.8 %
– corrosion	0.0 %	0.3 %	3.6 %
ageing	9.6 %	12.3 %	2.8 %
lightning	12.0 %	2.4 %	0.3 %
misapplication	5.7 %	14.7 %	4.0 %
inadequate maintenance	0.4 %	0.7 %	1.0 %
unknown	17.0 %	14.7 %	12.6 %

The phenomenon identified as the main cause of leaks in paper-oil-insulated transformers is *crevice corrosion*[13] (also called *gas corrosion*). Figure 7.5 shows the progress of crevice corrosion in the region of the flange. The concentration of an electrolyte e.g. water in the narrow, but deep crevice between the adjacent flanges gives rise to corrosion, which can progress and attack the o-ring's slot, undermining it. In this case, tightness is no more granted and the insulating oil leaks out. Although tightness is nowadays identified as a key reliability issue [7.7], type and routine tests for sealing integrity and durability are not uniformly described in the standards. Endurance tests performed by some manufacturers mainly focus on the metallic expansion bellows.

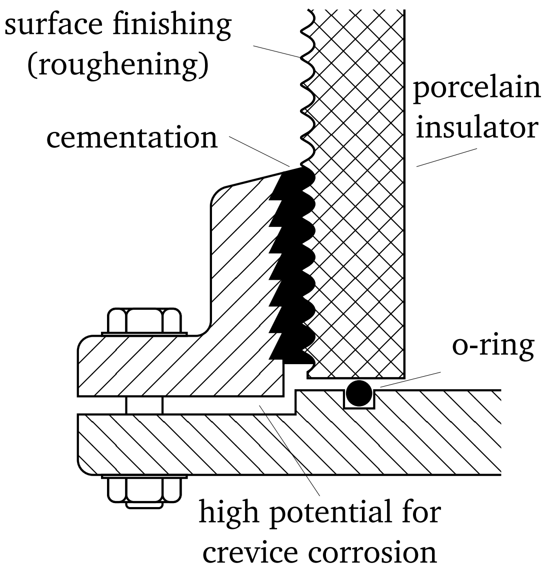

Figure 7.5: Crevice corrosion of flanges (based on [7.14]). The narrow and deep crevice in the region of the flange increases the potential for corrosion, since the concentration in the crevice may be significantly different from the surrounding environment. In order to prevent corrosion, the gap has to be wide enough to allow for sufficient ventilation ($\geq 1\,\mathrm{mm}$) and must be filled with weather-resistant silicon grease. Application of durable wax, covering the complete flange, is another possibility, occasionally used in medium-voltage equipment.

A design issue especially related with pressurised instrument transformers (refer to figures 7.3(b) and 7.3(c)) is the documented leakage of nitrogen through the porous cask cover. This effect may also lead to moisture ingress into the internal insulating system. It is for this reason that the reliability performance of pressurised systems is rather low [7.30].

Monitoring the condition of instrument transformers can assist in preventing minor and major failures, thus enhancing reliability. In addition, by detecting defects at an early stage, the cost of repair can be kept low. Generally speaking, instrument transformers are monitored by means of periodic inspections and preventive maintenance actions (health checks). Common monitoring techniques for paper-oil-insulated transformers include [7.7, 7.18, 7.26]:

- *visual inspections*: instrument transformers should be checked in frequent time intervals, for example once a month, with regard to potential oil leaks, contamination of the external insulation, condition of expansion bellows, potential corrosion of exposed metallic surfaces as well as integrity of earthing connections.
- *oil level indicators* and/or *bellow position indicators*: abnormal variations of the oil level or of the position of the expansion bellows without any significant change in the operating and ambient conditions are usually evidence of oil leaks.

[13] DIN EN ISO 8044 defines *crevice corrosion* as "localised corrosion associated with, and taking place in, or immediately around, a narrow aperture or clearance formed between the metal surface and another surface (metallic or non-metallic) [7.29].

- *measurement of the insulation resistance*: significant changes in the insulation resistance can result from the ingress of moisture into the internal insulating systems of from contamination of the external insulation. Alternatively to the insulation resistance, the leakage current can be measured.

- *dissolved gas analysis*: DGA of instrument transformers is a powerful tool for condition assessment and will be discussed in detail in section 7.3. In [7.26], a time interval between successive measurements of five years or less is recommended. In case longer time intervals are implemented, intermediate measurement of the oil's hydrogen content are advisable.

- *thermovision*: sources of excessive heat, for example due to poor connections in the primary terminals can by detected by means of thermovision cameras.

- tan δ *measurements*: for new paper-oil-insulated instrument transformers, the dissipation factor is in the range between 0.2 % and 0.4 % at ambient temperature [7.7]. An increase of the dissipation factor is usually evidence of excess moisture or other contamination products in the internal insulating system. Typical variations of the dissipation factor do not exceed 0.05 % [7.7].

According to the second Cigré survey, the first two monitoring techniques are applied by the majority of utilities. On the other hand, dissolved gas analysis, thermovision analysis, and measurement of the dissipation factor are usually applied to transformers which have been previously found to have a minor fault or a defect. It should also be noted that most utilities apply a combination of the aforementioned techniques for monitoring purposes. Furthermore, the comparison of measurements obtained from a unit with older measurements (*fingerprints method*) or between measurements obtained from different units of the same type is also a widely-accepted practice in order to identify potential abnormal performance.

On-line monitoring of instrument transformers is not very common: the main reason is the rather unfavourable cost/benefit relation of on-line monitoring systems, especially in view of the extremely low rate of major failures. Consequently, on-line monitoring is only applied to transformers of particular importance for the power system. Currently, common on-line monitoring techniques for paper-oil-insulated instrument transformers include relative tan δ measurement, on-line dissolved gas analysis, on-line measurement of partial discharges as well as continuous monitoring of the oil pressure [7.28].

7.2 Overview of data available for investigation

The case study presented in this chapter is based on a research project which has been conducted in cooperation with a large German transmission system operator [7.31]. Proprietary information is therefore treated confidentially; however, general remarks and comments are given throughout the case study. The scope of the project was the investigation of dissolved gas analysis of paper-oil-insulated instrument transformers, in particular with respect to following questions:

- Is it possible to identify any significant dependence of the concentration of dissolved gases on the service age of the equipment?

- Do instrument transformers, for which oil leaks have been detected, demonstrate any specific pattern of dissolved gas concentrations? Or, the other way round, is a correction of measurements obtained from such equipment necessary prior to its interpretation?

- Do the results of DGA applied to a test sample of transformers correspond with the actual faults and defects detected within the sample?

- Does the implementation of fuzzy logic principles for the purpose of DGA interpretation lead to more reliable fault diagnosis?

- Does the implementation of alternative limit values for the gas concentrations (differing from values stated in the respective standards) during DGA interpretation lead to more reliable fault diagnosis?

This section provides background information on the data in the test sample. The sample comprises 130 high-voltage inductive voltage transformers with rated primary voltage 420 kV. All transformers in the sample are of the same type and have been manufactured by a single facility, although five different production batches have been documented. Table 7.6 gives an overview of the identified batches, along with the installation years of the respective units. Grouping of the sample by production batch is essential in order to be able to assess any potential dependence of the dissolved gas content.

Table 7.6.: Identified production batches in the test sample.

Batch	Installation years	Number of units
A	1990 to 1995	4
B	1983	27
C	1985 to 1998	31
D	1986	1
E	1982 to 1993	59

The age profile of the test sample is depicted in figure 7.6. The service experience associated with the available sample amounts 2939 field-years. Diving this figure by the size of the sample (130 units) yields an average service age of approximately 22.6 years.

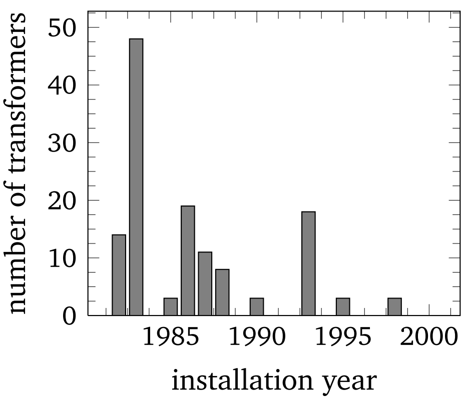

Figure 7.6: Age profile of instrument transformers in the test sample. The average service age at the time of the analysis (2009) was 22.6 years.

The transformers are of the live-tank cascade type (refer to figure 7.1(c) in section 7.1.1). Internal insulation is provided by oil-impregnated[14] paper, while porcelain post insulators are used for external insulation. For the purpose of oil preservation and oil expansion, positive-type metallic bellows are applied [7.32]. The ratings of the instrument transformers are summarised in table F.2 [7.13, 7.31].

A total of 145 measurements of dissolved gases are provided for the test sample; in other words, only a single measurement per unit is available for the majority of the transformers. Almost all measurements have been conducted in 2008 and 2009 in course of a broader condition assessment program. In addition, some gas content measurements date back to 1984 (almost immediately after installation) and are related to units with minor defects (e.g. limited oil leaks). Three different test laboratories have been assigned with the analysis of the oil sample; a preliminary statistical analysis did not identify any significant correlation between dissolved gas levels and test laboratory.

Statistical data on the occurrence of failures and defects has also been provided for the test sample. Only a single failure event is documented in the failure statistics with one transformer having a catastrophic failure. Although the particular unit is not included in the test sample, the respective transformers of the other two phases (included in the sample) have been also taken out of service. As will be shown in the next section, measurements of dissolved gases obtained from these transformers indicate the presence of an internal fault. Dividing the number of failed transformers in the sample (two) by the total field-years yields a failure rate of 0.068 % per year, which is in good agreement with the results of the second Cigré survey (table 7.3).

The number of documented defects is significantly higher: a total of 14 defects have been identified and are summarised in table 7.7. Most defects are associated with tightness problems leading to oil leaks, with two transformers being affected repeatedly. The fact that most oil leaks

Table 7.7.: Overview of detected faults and defects in the test sample.

Type of event	Transformer ID	Service age	Remarks
failure	292977	1	catastrophic failure of
	292984	1	adjacent transformer
oil leak	291016	3 & 3	oil sampling valve, connection to bellows
	291246	14 & 22	oil sampling valve
	291247	1	no further description
	291272	1	no further description
	291584	1	no further description
partial discharge	108060	24	loose strands, signs of tracking along
	108062	24	the insulator's inner surface
overheating	295857	17	compensation winding not
	295859	17	properly connected
	296408	17	
under investigation	106698	21	
	106713	21	

[14] All transformers are filled with the non-inhibited mineral insulating oil Shell Diala G ®(appendix E.5).

have been observed during the first service years implies that their primary cause is poor design and/or insufficient manufacturing. Again, this observation is in agreement with the second Cigré survey (table 7.5).

Incipient dielectric faults have been detected in two transformers during internal visual inspection. In particular, loose strands and signs of tracking on the inner surface of the porcelain insulator have been identified. These transformers drew the attention of the maintenance personnel during a partial discharge measurement. Another three transformers were found faulty with signs of overheating, presumably caused by not properly connected compensation windings leading to the formation of eddy currents within the live tank. Finally, two further units have been taken out of service and are suspected of having some internal defect, though investigation was –at the time of the analysis– still in progress.

The rate of defects within the sample amounts 0.47 % per field-year and is approximately two times higher than the value reported in the second Cigré survey [7.7]. In the next section, the performance of dissolved gas analysis with respect to the detection of internal faults and defects will be examined.

7.3 DGA according to IEC 60599

This section describes the application of dissolved gas analysis to the test sample of instrument transformers. DGA interpretation is performed on the basis of IEC 60599 (table 6.12). For the purpose of analysis, a fully-automated, computer-aided interpretation tool has been developed in Microsoft® Excel®.

Nowadays, many network operators commission independent test laboratories to analyse oil samples taken from oil-filled power equipment and interpret the measured gas content of the oil. In order to further assist users in keeping track of DGA results, many test laboratories offer software solutions for systematic filing and evaluation of dissolved gas measurements[15]. The data is stored in the server of the laboratory and can be viewed by the user via secure internet connection. Nevertheless, such software solutions are not yet widely accepted by the users: data confidentiality and liability of the interpretation results are important issues that must be considered first. For this reason, stand-alone applications, located in-house at the owner and user of the equipment, are more appropriate.

In the described research project such a stand-alone computer application has been developed. The application is designed within Microsoft® Excel® and uses several Visual Basic® routines (macro) to incorporate the interpretation rules. The program is structured according to the DGA interpretation scheme in IEC 60599 (figure E.5 in appendix E.6), although the rate of change in gas concentration has not been considered since only one measurement was available for most transformers in the sample. With regard to the typical gas concentrations used for preliminary filtering, the user can choose among five different sets of values, as will be shown in section 7.3.3. Finally, the software tool facilitates systematic export and filing of the interpretation results for future reference. The following paragraphs give answers to the questions stated in the beginning of section 7.2.

[15] Examples of such software solutions for the purpose of DGA can be found under http://www.satcs.co.za/html/software.html and http://www.nttworldwide.com/dgasoftware.htm.

7.3.1 Correlation between gas concentration and service age

During service, instrument transformers are subject to dielectric and thermal stress. Normal[16] ageing processes within the internal oil-impregnated insulating system could therefore result in evolution of decomposition gases. In hermetically sealed equipment –as with the test sample provided– these gases would remain in the insulating system, mainly in the oil. The first question to investigate is, thus, whether normal ageing leads to a rise in the concentration of decomposition gases in the oil.

The procedure for statistical analysis is as follows: First, all measurements corresponding to faulty or potentially faulty equipment have to be excluded. This is important, since measurements obtained from units with failed internal insulation will show significantly higher gas content, no matter the service age. Accordingly, measurements obtained from the units listed in table 7.7 have been excluded, leaving 129 data entries for further analysis. For each measured decomposition gas[17] the remaining entries have been plotted against the service age of the equipment at the time of measurement. The service age can be determined by considering the date of oil sampling and the date of installation of the respective device.

No correlation between service age and concentration levels could be identified for any decomposition gas. It is therefore reasonable to argue that *normal operation of hermetically sealed inductive voltage transformers is not related to thermal or electrochemical decomposition of the oil or paper insulation,* at least up to a service age of 30 years.

Further analysis focused on the question of any potential dependence of the measured dissolved gas content on the particular production batch. The analysis showed that devices belonging to batch E (table 7.6) demonstrated significantly higher dissolved gas levels (approximately by a factor of 2.8), although for most devices the measured concentrations were still in the range of typical values as proposed in IEC 60599. This finding backs up the requirement that dissolved gas analysis (in particular with respect to typical levels of gas concentrations) must always be fitted to the equipment under investigation. However, keeping the rather small size of the test sample in mind, no further data partitioning was possible or reasonable.

7.3.2 Influence of oil leaks on DGA

In a further step the question of any potential influence of oil leaks on the measured dissolved gas content has been investigated. In case such an influence exists, measurements obtained from devices with known oil leaks would have to be corrected prior to their interpretation.

In the case of an oil leak, atmospheric gases i.e. nitrogen, oxygen and –to a lesser extent– carbon oxides could diffuse into the oil and result in higher measured gas concentrations. The rate of diffusion is determined by the size of the oil-atmosphere interface at the location of leak, by the gas concentration of dissolved gases in the oil (partial pressure) and by the rate of oil circulation[18] within the instrument transformer. In addition to the penetration of atmospheric gases into the internal insulating system, oil leaks could also allow for moisture ingress; excess

[16] Normal ageing is assumed unless a fault or defect of the internal insulation is present.

[17] Measurements of following gases were included in the test sample: nitrogen, oxygen, carbon monoxide, carbon dioxide, methane, ethane, ethylene, acetylene, propane (C_3H_8) and propylene (C_3H_6). The latter two gases, however, have not been further considered for the interpretation of DGA.

[18] Oil circulation is based on the thermosyphon effect and largely depends on the temperature gradient inside the transformer.

moisture could then drive hydrolytic decomposition to the paper, leading to the formation of decomposition gases.

For the purpose of statistical analysis, three data sub-sets were established: the first sub-set includes measurements of dissolved gas concentrations obtained from devices with known oil leaks (table 7.7). Remarkably, all leaky instrument transformers were of the production batch E. Since oil leaks are easy to detect e.g. during visual inspection, it has been assumed that all other transformers did not have any tightness problems. They were included in the second data sub-set, together with the corresponding measurements of dissolved gas content. However, the presence of faults in the internal insulation would lead to higher measured levels of decomposition gases and eventually falsify the result of the analysis. A third data sub-set was therefore extracted from the second one by excluding all measurements corresponding to faulty or potentially faulty equipment. For all relevant atmospheric gases (nitrogen, oxygen and carbon oxides) the minimum, mean and maximum value as well as the 75-percentile of the respective concentration in the oil has been evaluated in each data sub-set. Similar investigations were also done on the basis of the ratios of oxygen to nitrogen and carbon dioxide to carbon monoxide concentrations.

The mean gas concentration in transformers with known oil leaks has been found to be higher than in the second and third sub-set (approximately by a factor of 1.5 to 2). However, this finding could not be confirmed for the maximum values. Consequently, and because of the extremely small size of the first data sub-set (only five measurements), the assumption that oil leaks result in higher concentrations of atmospheric gases in the oil could not be definitely confirmed.

A possible explanation is that measurements of dissolved gas levels have been performed predominantly in 2008 and 2009, long time after the actual occurrence of the oil leaks. Keeping in mind the early service age of the equipment at the time of leak occurrence as well as the presumably short time interval between leak detection and its removal, the amount of atmospheric gases diffusing into the internal insulating system must have been rather low.

7.3.3 Typical values of gas concentration for instrument transformers

The first step for DGA interpretation according to IEC 60599 is the comparison of actual measurements of dissolved gas concentrations with some reference values. As long as the measured concentrations do not exceed these *typical values*, no fault is assumed. Typical gas concentrations are not universal, but always specific to the particular type of equipment; for example, in table 6.6 typical values obtained from the literature for large power transformers have been shown.

IEC 60599 recommends the use of a custom percentile for the determination of typical gas concentrations from a sample of measurements. Usually the 90-percentile is used; in other words typical values are chosen in a way that 90 % of all measured concentrations do not exceed them. The arbitrary choice of the base percentage should reflect the expected rate of failure and defect occurrence [7.33]. In case no typical gas concentrations have been determined for a particular type of equipment, giudeline values are available in appendix A of IEC 60599 and may be used instead.

In this research project dissolved gas analysis is based on five different sets of reference gas concentrations. The first three sets have been extracted from the literature and are listed in table 7.8. In addition, two further sets have been evaluated directly from sample of available

Table 7.8.: Overview of reference gas concentrations used in the case study. The first set comprises typical values for voltage transformers (all types of oil preservation systems) as extracted from [7.33]. The second set refers only to hermetically sealed instrument transformers (both voltage and current transformers). The last set is recommended for use by the manufacturer of the particular transformers under investigation [7.34]. It is based on the findings of Cigré working group 23.07, published in an Èlectra article [7.35].

Reference set	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
A	70–1,000	11–120	7–130	20–30	4–16	250–1,100	800–4,000
B	300	30	50	10	2	300	900
C	120	20	40	10	5		

dissolved gas measurements. Contrary to sections 7.3.1 and 7.3.2, when evaluating typical gas concentrations measurements obtained from faulty or potentially faulty equipment must be also considered. The 90-percentile and 95-percentile have been determined in this way.

This information is proprietary and therefore cannot be published here. However, it must be noted that values corresponding to the 90-percentile have been found to be significantly lower than those proposed by the IEC or the manufacturer and listed in table 7.8. This observation is in agreement with arguments brought up recently by several users of paper-oil-insulated instrument transformers, especially in Austria. During a workshop in Graz, network operators recommended the use of lower values as typical gas concentrations in sealed equipment and prompted manufacturers to adapt the documentation of their products accordingly [7.18].

7.3.4 Fault detection by means of DGA

In chapter 6 we have already introduced the interpretation scheme for dissolved gas analysis according to IEC 60599. The scheme described in table 6.12 classifies faults into six different categories: partial discharges, dielectric faults of low and high energy, and thermal faults of varying energy density. In addition to this *detailed* interpretation scheme, the standard also provides a *simplified* scheme for fault classification [7.33]. The simplified scheme does not facilitate the ratio of ethylene to ethane concentration and only differentiates between three main fault categories: partial discharges, dielectric faults, and thermal faults. Table 7.9 illustrates the simplified IEC interpretation scheme.

Obviously, the simplified interpretation scheme always returns a diagnosis, provided at least one measured gas concentration is higher than the respective typical value. On the other hand, the detailed scheme may fail to provide a diagnosis in some certain cases (e.g. for the combination $C_2H_2/C_2H_4 = 0.5$, $CH_4/H_2 = 0.5$, $C_2H_4/C_2H_6 = 0.5$, compare table 6.12).

Both simplified and detailed interpretation schemes have been implemented in the developed software tool. In conjunction with the five sets of typical gas concentrations presented in section 7.3.3, a total of ten different interpretation formats have thus been established[19].

[19] The upper values have been used in the first reference set (first row in table 7.8).

Table 7.9.: Simplified DGA interpretation scheme according to IEC 60599 [7.33]. As with the detailed scheme, further analysis should only be applied if the concentration of at least one gas exceeds the respective typical value.

ID	Fault type	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$
PD	partial discharge	not significant	< 0.2
D	discharge	> 0.2	not significant
T	thermal fault	< 0.2	not significant

Table 7.10 gives an overview of the performance of the different interpretation formats with respect to fault detection[20]. Correct classification is provided in the cases of positive diagnosis for faulty equipment or negative diagnosis for fault-free equipment (positive diagnosis means that an internal fault is assumed). The lower the assumed values of typical gas concentrations, the more devices will be classified as potentially faulty. A balance must thus be found between identifying as many defective pieces of equipment as possible and misclassifying as few healthy units as possible.

Table 7.7 has been used as reference when labelling the equipment as "faulty" or "fault-free". Obviously, not all defects listed there are actual faults and must therefore be identified as such by dissolved gas analysis. This fact is highlighted in table 7.11: none of the five transformers with registered oil leaks has been identified as potentially faulty. This is not surprising: in section 7.3.2 we have already noted that the correlation between oil leaks and dissolved gas levels is rather weak. The detection performance, as described in table 7.10 for faulty equipment, must therefore be revised to exclude transformers with oil leaks. In this case the hit rate of the tested interpretation formats varies between 89 % (reference set A) and 100 %.

But also the detection performance with regard to "fault-free" equipment should be put into perspective. The fact that no defect is known (i.e. has already been registered) for a device does not necessarily mean that the particular device is indeed fault-free.

Table 7.10.: Detection of faults in the test sample by means of the detailed DGA interpretation scheme (table 6.12) for the five different value sets of typical gas concentrations (table 7.8). Number in parentheses denote cases where typical values have been exceeded, the presence of a fault is thus assumed, although the interpretation scheme could not identify the type of fault.

Equipment status	Diagnosis	Ref. A	Ref. B	Ref. C	90-percentile	95-percentile
faulty equipment	positive	5(3)	5(4)	5(4)	5(4)	5(4)
	negative	6	5	5	5	5
fault-free equipment	positive	1	6(2)	5(3)	10(6)	1(1)
	negative	115	108	108	100	114

[20] In table 7.10 only the results of the detailed interpretation schemes are depicted. The respective results of the simplified schemes are similar, with the exception that a diagnosis is always provided (cases where a fault is assumed, but the type of fault could not be assessed by the detailed scheme are given in parentheses in table 7.10).

Table 7.11.: Fault detection for faulty or defective transformers. Fault type classification by the detailed or simplified interpretation schemes (last two columns) is identical no matter the used set of typical gas concentration levels. Fault type coding is in accordance with IEC 60599, "n.i." stands for detected but unidentified faults.

Defect	Transformer ID	Ref. A	Ref. B	Ref. C	90 %	95 %	Detailed	Simplified
failure	292977		✓	✓	✓	✓	n.i.	PD/D
	292984	✓	✓	✓	✓	✓	n.i.	PD/D
oil leak	291016						–	–
	291246						–	–
	291247						–	–
	291272						–	–
	291584						–	–
partial discharge	108060	✓	✓	✓	✓	✓	n.i.	D
	108062	✓	✓	✓	✓	✓	D2	PD/D
overheating	295857	✓	✓	✓	✓	✓	T2	T
	295859	✓	✓	✓	✓	✓	T2	T
	296408	✓	✓	✓	✓	✓	T2	T
under investigation	106698	✓	✓	✓	✓	✓	n.i.	T
	106713	✓	✓	✓	✓	✓	T3	T

Following remarks sum up the presented application of DGA to the test sample of instrument transformers on the basis of IEC 60599:

1. The higher the assumed typical gas concentration levels, the fewer devices are identified as faulty.

2. Use of the 90-percentile results in a high number of positive diagnoses. Keeping the low failure rate of instrument transformers in mind, it seems reasonable to call for the use of a higher percentile instead (e.g. the 95-percentile).

3. The hit rate of all interpretation formats is very high. Dissolved gas analysis is thus an efficient tool for fault detection in instrument transformers.

4. In some cases the detailed interpretation scheme failed to assess the type of the fault.

5. On the other hand, the simplified scheme always provides fault type classification. However, the assessment of the type of fault was not always unambiguous; in some cases more than one fault types were proposed.

In conclusion, dissolved gas analysis assists the user in identifying potential faults and assessing the type of fault. However, one important question still remains unanswered: *How reliable is the fault identification obtained?* This aspect –among others– will be discussed in the next section.

7.4 Application of fuzzy logic to DGA

A closer look at the layout of known DGA interpretation schemes reveals their major shortcoming: they are all *boolean classifiers* (true/false classification) and cannot properly treat uncertainties e.g. due to measuring inaccuracy. This limitation will be demonstrated by a simple example.

Example 7.1 *Let us consider the case of following measurement of dissolved gas concentrations: 282 ppm H_2, 5 ppm CH_4, 7 ppm C_2H_6, 1 ppm C_2H_4. According to table 6.12, the first rule of the IEC interpretation scheme (partial discharge faults) is:*

if ratio $\frac{CH_4}{H_2}$ is lower than 0.2 *and* ratio $\frac{C_2H_4}{C_2H_6}$ is lower than 0.2 *then* fault type is partial discharge

Obviously the above measurement will be classified as indicative of a potential partial discharge fault. However, how would the diagnostic finding change if the concentration of a single gas was slightly different, e.g. if ethylene concentration was two instead one part per million? In this case the ratio of ethylene to ethane concentration would be higher than 0.2; as a result, classification as partial discharge would not hold any more. ■

In dissolved gas analysis uncertainty originates from measuring errors when determining the concentration of gases in the oil. In spite of the high accuracy of modern gas chromatographs the effect of measuring errors can be significant to DGA interpretation, especially in case of low gas concentrations, as illustrated by the example above. In general, IEC specified a maximum measuring error of $\pm 15\,\%$ for gas chromatographs. However, this specification applies only when the measured gas concentration is significantly higher (by a factor of ten) than the detection limit. According to IEC 60567 the detection limit for measurements conducted in the field amounts 5 ppm for hydrogen and 1 ppm for hydrocarbonic compounds [7.36].

Care must be therefore taken during DGA interpretation with regard to measuring errors. In IEC 60599 this issue is addressed in section 6.2: in the range above ten times the theoretical detection limit, a measuring error up to $\pm 5\,\%$ is assumed for a single measurement of gas concentration. With decreasing gas content the measuring error increases, and at five times the detection limit a maximum error of ± 20 ppm is expected [7.33]. The uncertainty related with ratios of concentrations is even higher, since ratios involve two measured concentrations (and the associated measuring errors). In order to account for measuring errors in DGA, IEC 60599 therefore recommends to evaluate and interprete all possible combinations by varying the measured gas concentrations accordingly. However, this procedure is hardly ever applied due to its complexity[21].

In summary, the motivation for introducing fuzzy reasoning to dissolved gas analysis originates from the need for proper consideration of measuring uncertainties. Instead of generating multiple combinations from a single measurement and then using a boolean classifier for interpretation, a robust fuzzy classifier can be used. The advantage of a fuzzy classifier for DGA

[21] By considering the measuring error associated with each gas concentration and varying the measuring results accordingly, a *range of values* can be determined for each ratio of concentrations. The lower limit is obtained by assuming the lowest concentration value for the nominator of the ratio and the highest concentration value for the denominator – vice versa for the upper limit of the range. Keeping in mind the layout of the DGA interpration scheme (three types of relations: “lower than ...”, “higher than ...”, “between ...”) up to 3^3 combinations have to be considered for the interpretation of a single dissolved gas measurement.

interpretation is –besides its simplicity– the fact that a *confidence factor* can be provided for the proposed diagnostic finding. The confidence factor is a measure of how reliable the finding is. For decisions regarding maintenance or replacement of power equipment this information is as important as the finding itself.

Furthermore, an alleged advantage of fuzzy DGA is related to the case of more than one faults being active within an oil-filled device at the same time. In such a case, evolution of decomposition gases occurs in superposition of several electrochemical and thermal decomposition processes. Most DGA interpretation schemes, on the other hand, have been developed under the assumption of a single fault (for example, refer to Halstead's thermodynamic model in section 6.2.3). It is therefore reasonable to question their reliability in case of multiple faults. Whether the application of fuzzy logic to DGA can help overcome thus limitation, as proposed in the literature [7.37–7.40], or not will be examined in the case study of section 7.5.

At this point a brief literature review on fuzzy logic application to dissolved gas analysis shall be provided. In the section to follow, the structure of the developed fuzzy model will be described.

In 1993, Lin et al. published a paper entitled "An expert system for transformer fault diagnosis using dissolved gas analysis" [7.41]. To the knowledge of the author, this has been the first published research work on fuzzy dissolved gas analysis. *Automation* of DGA interpretation was the primary target; Lin et al. applied fuzzy reasoning to the revised interpretation scheme by Rogers (table E.10) for this purpose. In a case study, they analysed 101 transformers of the Taiwan Power Company in order to test the accuracy of the developed method. Unfortunately they did not provide any comparison to the reference interpretation scheme (i.e. without application of fuzzy logic).

Such a *comparative analysis* can be found for example in [7.37, 7.38, 7.42]. In [7.37] Ma et al. used fuzzy reasoning to extend the IEC interpretation scheme. A case study, comprising twenty power transformers, proved the superior diagnostic performance of fuzzy DGA interpretation. Similar findings have been reported by Hooshmand and Banejad in [7.38]. In their investigation, they included –in addition to the IEC interpretation scheme– the method by Rogers. In [7.42] Muhamad et al. applied fuzzy reasoning to a series of DGA interpretation methods. In a case study, they compared the diagnostic consistency[22] of each method with and without the extension by fuzzy logic. Apart from the DGA nomograph and the key gas method, the diagnostic consistency of all other interpretation methods was improved when using fuzzy reasoning.

The *practical implementation* of fuzzy DGA is also a common topic of published work. For instance, Falqueto and Telles used the freeware Xfuzzy 3.0[23] to develop a fuzzy DGA interpretation tool on the basis of the key gas method and the revised interpretation method by Rogers [7.44]. By means of appropriate interfaces, they managed to integrate the fuzzy DGA interpretation tool into the general control system of the Itaipu power plant. Again other published papers describe the development of fuzzy DGA interpretation tools within MATLAB® or by means of C^{++} programming [7.40, 7.45].

Despite the positive feedback from research work on fuzzy dissolved gas analysis, manufacturers and users still hesitate to introduce fuzzy DGA in a wide scale and only rarely address the topic, as in [7.5]. The existence of internationally accepted standards (IEC 60599 and

22 Muhamad et al. define *consistency* as the percentage ratio of correctly identified faulty equipment [7.42].

23 Xfuzzy 3.0 is a development environment for fuzzy-inference-based systems, distributed as freeware by the Seville Institute of Microelectronics [7.43]. The environment is programmed in Java™, so it can be executed on any platform with JRE® (Java Runtime Environment) installed.

IEEE C57.104) is presumably the main reason for this negative attitude. Nevertheless, change in the research field is initiated by the recent (re)introduction of non-mineral insulating oils, especially of natural esters. The aforementioned standards only apply to mineral insulating oils; ester liquids feature different gassing behaviour due to their differing chemical composition. As a result, a fundamental restructuring of dissolved gas analysis and its interpretation is necessary for ester-filled equipment. It appears that fuzzy DGA also benefits from this new challenge: for example, in its recent technical brochure on DGA of non-mineral oils [7.46], Cigré also discusses possible improvements in DGA by implementing fuzzy logic principles. In addition, research groups both in the University of Manchester [7.42, 7.47–7.50] as well as in the University of Stuttgart [7.51–7.53] link research work on DGA of synthetic and natural esters with the application of artificial intelligence, especially of fuzzy logic.

7.4.1 Implementation of fuzzy DGA

For the purpose of fuzzy dissolved gas analysis, the software tool described in section 7.3 has been extended accordingly. Since Microsoft® Excel® is not designed to cope with fuzzy rules, a set of custom-defined routines have been programmed in Visual Basic®. Their task is to facilitate evaluation of membership functions and subsequent computation of fuzzy rules. The DGA interpretation scheme according to IEC 60599 is entered into the software in tabular form, similar to table 6.12 in chapter 6. On the other hand, typical gas concentrations can be either entered directly by the user, for example in accordance with table 7.8, or may be computed automatically from the sample of dissolved gas measurements.

In a first step, for each measurement the actual gas level is compared to its corresponding typical value. Contrary to standard DGA, where the result of this comparison is either true (typical value is exceeded) or false (typical value is not exceeded), in fuzzy DGA a degree of belief is rather returned. The degree of belief is thus a measure of the total *confidence factor* of the diagnostic finding provided during the second step of fuzzy DGA interpretation.

From a mathematical point of view, comparison with typical values resembles a "greater than ..." inequality. Accordingly, two fuzzy sets are defined: the first set $A_{c>\tilde{c}} = \{(c, \mu_{c>\tilde{c}})\}$ accounts for the case when measured gas concentrations c exceed the respective typical value $\tilde{c}$, whereas its complement $A_{c\leq\tilde{c}} = \bar{A}_{c>\tilde{c}}$ considers the opposite case. For the purpose of modelling fuzzy set $A_{c>\tilde{c}}$ the increasing limited ramp function of equation 7.1 is used:

$$\mu_{c>\tilde{c}}(c) = \begin{cases} 0 & , c \leq c_a \\ \frac{c-c_a}{c_b-c_a} & , c_a \leq c \leq c_b \\ 1 & , c \geq c_b \end{cases} \tag{7.1}$$

The piecewise definition of the above membership function allows for explicit definition of the core and support[24] of fuzzy set $A_{c>\tilde{c}}$ and was thus preferred to e.g. an increasing sigmoid function (section 2.2.1), where the membership values zero and one are only reached asymptotically.

[24] The core and support of the fuzzy set according to equation 7.1 are $\{c|\mu_{c>\tilde{c}}(c) = 1\} = \{c|c > c_b\}$ and $\{c|\mu_{c>\tilde{c}}(c) > 0\} = \{c|c > c_a\}$ respectively.

Keeping the extension theorem in mind, the transition point[25] of the membership function has to be equal to the assumed typical gas concentration. By varying the distance of parameters c_a and c_b to the typical gas concentration $\tilde{c}$, the range of fuzzy transition can be adjusted: the wider the interval $[c_a, c_b]$, the smoother will the fuzzy transition be. In conclusion, the expression in equation 7.2 is used to define parameters c_a and c_b, with δ being a measure of the fuzzy transition range.

$$c_{a,b} = \tilde{c} \cdot (1 \pm \delta) \tag{7.2}$$

The second step involves the interpretation of ratios of gas concentrations with the purpose of determining the type of fault. In general, the IEC interpretation scheme makes use of three types of relations:

- "higher than ...": similar to the first interpretation step, a fuzzy set $A_{r>\tilde{r}}$ is defined for this type of relations, with r being the actual value of the considered ratio of concentrations and $\tilde{r}$ being the reference value. The membership function of equation 7.1 is used for the description of fuzzy set $A_{r>\tilde{r}}$. Again, the transition point of the implemented membership function must be set at $\tilde{r}$.
- "lower than ...": decreasing membership functions describe fuzzy sets $A_{r\leq\tilde{r}}$ corresponding to this type of relations. In particular, the complementary function of $\mu_{c>\tilde{c}}$ is used (equation 7.3). The parameters of the membership function r_a and r_b are determined as $r_{a,b} = \tilde{r} \cdot (1 \pm \delta)$.

$$\mu_{r>r_t}(r) = \begin{cases} 1 & , r \leq r_a \\ \frac{r_b - r}{r_b - r_a} & , r_a \leq r \leq r_b \\ 0 & , r \geq r_b \end{cases} \tag{7.3}$$

- "between ...": contrary to the relations described above, fuzzy sets of the "between ..." type of relations feature a limited core, which is determined by the lower and upper reference value for the ratio of concentrations, $\tilde{r}_l$ and $\tilde{r}_u$ respectively. In this case, a piecewise-defined membership function can not be used, since increasing the degree of fuzzification could lead to intersection of the lower and upper fuzzy transition range. Instead, the superposition of two limited ramp membership functions is used in order to describe the fuzzy set $A_{\tilde{r}_l\leq r\leq\tilde{r}_u}$ (equation 7.4). Parameters r_{a_k} and r_{b_k} are determined as $r_{a_1,b_1} = \tilde{r}_l \cdot (1 \pm \delta)$ and $r_{a_2,b_2} = \tilde{r}_u \cdot (1 \pm \delta)$.

$$\mu_{\tilde{r}_l\leq r\leq\tilde{r}_u}(r) = \mu_1(r) - \mu_2(r) \tag{7.4}$$

$$\text{with } \mu_k(r) = \begin{cases} 0 & , r \leq r_{a_k} \\ \frac{r - r_{a_k}}{r_{b_k} - r_{a_k}} & , r_{a_k} \leq r \leq r_{b_k} \qquad k = 1, 2 \\ 1 & , r \geq r_{b_k} \end{cases}$$

[25] The *transition point* of a membership function is given for $\mu(x) = 1/2$. For the function in equation 7.1, the transition point is at $1/2(c_a + c_b)$.

1 evaluate degree of membership $\mu_{c_i>\tilde{c}_i}(c_i)$ to fuzzy set $A_{c_i>\tilde{c}_i}$ for each dissolved gas according to equation 7.1

↓

2 determine overall confidence factor of diagnosis:

$$\alpha_d(\underline{c}) = \perp \left\{ \mu_{c_1>\tilde{c}_1}(c_1), \mu_{c_2>\tilde{c}_2}(c_2), \ldots, \mu_{c_n>\tilde{c}_n}(c_n) \right\} \tag{7.5}$$

↓

3 evaluate fuzzy rules

$$\mu_{res,j}(\underline{r}, d_j) = \perp \left\{ \mu_j(d_j), \top \left\{ \mu_{j,1}(r_1), \mu_{j,2}(r_2), \mu_{j,3}(r_3) \right\} \right\} \tag{7.6}$$

↓

4 scale confidence factors of individual diagnoses:

$$D_j = \alpha_d(\underline{c}) \frac{\mu_{res,j}(\underline{r}, d_j)}{\sum_j \mu_{res,j}(\underline{r}, d_j)} \qquad \text{if } \sum_j \mu_{res,j}(\underline{r}, d_j) \geq 1 \tag{7.7a}$$

$$D_j = \alpha_d(\underline{c}) \cdot \mu_{res,j}(\underline{r}, d_j) \qquad \text{else} \tag{7.7b}$$

Figure 7.7.: General flowchart for fuzzy DGA interpretation.

Figure 7.7 summarises the general procedure for the interpretation of a single measurement of dissolved gas levels: first, the question whether the measured concentration exceeds typical levels is answered. For this purpose the degree of membership to fuzzy set $A_{c>\tilde{c}}$ is evaluated for all relevant gases (hydrogen, methane, ethane, ethylene and acetylene). Their union yields the overall confidence factor for the diagnosis. In the developed fuzzy DGA interpretation tool, equation 7.5 uses the maximum operator as T-conorm.

In a next step, the IEC interpretation rules are evaluated (six for the detailed scheme, three for the simplified one). Singleton membership functions are used for the rules' outputs:

$$\mu_j(d_j) = \begin{cases} 1 & \text{if } d_j = 1 \\ 0 & \text{else} \end{cases}$$

The fuzzy output of equation 7.6 is thus a measure of the confidence factor associated with the particular rule. Due to individual evaluation of equation 7.6 for each interpretation rule, the sum of the so-obtained confidence factors will usually not match the overall confidence factor determined in step 2 (figure 7.7). In a final step, the confidence factors of the diagnostic findings must therefore be scaled according to equation 7.7. During scaling, one has to distinguish between two cases:

- The DGA interpretation scheme provides sufficient evidence of one or more fault types. This case is characterised by $\sum_j \mu_{res,j}(\underline{r}, d_j) \geq 1$ and calls for scaling down the individual confidence factor of each diagnosis.
- In the opposite case, weak indication of any particular type of fault is given; the interpretation scheme partially fails to identify the type of fault. Scaling is then performed according to equation 7.7b. Furthermore, an additional class ("undefined type of fault") has to be defined with following measure assigned to it:

$$D_{\text{undefined}} = \alpha_d(\underline{c}) \cdot \left(1 - \sum_j \mu_{res,j}(\underline{r}, d_j) \right)$$

7.5 Results and discussion

The sample of instrument transformers introduced in section 7.2 has been used as a case study in order to investigate the performance of the developed fuzzy DGA interpretation tool. This section provides an extract of the results obtained, along with key conclusions.

The main difference between fuzzy and standard (non-fuzzy) DGA interpretation is in the existence or not of a fuzzy transition range. A central question is thus: *How does the implemented transition range influences the diagnostic result of fuzzy DGA*? In section 7.4.1, the fuzzy interpretation scheme has been defined parametrically: by means of a single parameter δ the fuzzy transition range of a membership function can be directly adjusted[26]. In the case study three levels of fuzzification have been examined, as shown in table 7.12. The higher the level of fuzzification, the higher is the uncertainty associated with the available measurements of dissolved gases. In table 7.12 the high uncertainty associated with acetylene concentration as well as with the ratio of acetylene to ethylene concentration is justified by the very low levels of acetylene usually measured in the field.

By combining three levels of fuzzification with two general schemes for DGA interpretation (detailed or simplified) and with five sets of typical gas concentrations (section 7.3.3) a total of thirty different formats have been established. In general, the various formats showed similar behaviour, especially with regard to the influence of the level of fuzzification on the diagnostic findings. For this reason, only the results of the detailed interpretation scheme with typical gas concentrations obtained from the 95-percentile of the available measurements will be discussed here.

Figures 7.8 and 7.9 show the diagnostic findings for fuzzification level 1 and 3, respectively. On the right-hand side are the results of standard DGA (compare also table 7.11), on the left hand side the results of fuzzy DGA. Appendix F.3 further shows the results obtained from the simplified interpretation scheme as well as from the detailed scheme for fuzzification level 2.

As expected, the confidence factor for diagnosis provided by standard DGA interpretation is either zero or one. On the other hand, for fuzzy DGA more than one types of fault may be identified for a single device; the corresponding confidence factor may take any value between zero and one.

The results of the case study on fuzzy DGA can be summarised as follows:

1. Increasing the level of fuzzification results in more devices being labelled as potentially faulty. For example, in figure 7.8 (fuzzification level 1) 16 units are highlighted, whereas figure 7.9 (fuzzification level 3) counts 27 units. With increasing level of fuzzification the transition range of membership functions is enlarged. As a result, more measurements are identified as "above typical levels". However, the corresponding degree of membership to fuzzy set $A_{c>\tilde{c}}$ is still low. By defining a minimum total confidence factor $\alpha_d(\underline{c})$ for further consideration (e.g. greater than 25 %) such measurements can be filtered off.

2. In case more than one types of fault have been proposed by the fuzzy DGA interpretation tool, they usually belonged to the same group (i.e. dielectric or thermal faults). This seems reasonable, since similar faults initiate –more or less– the same decomposition processes.

[26] Accordingly, the standard DGA interpretation scheme can be obtained by setting δ equal to zero for all membership functions.

Table 7.12.: Levels of fuzzification considered in the case study. Values in the table correspond to parameter δ of each membership function, which determines the width of the fuzzy transition range.

Fuzzification level	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
1	5 %	5 %	5 %	5 %	20 %	40 %	10 %	10 %
2	10 %	10 %	10 %	10 %	40 %	60 %	20 %	20 %
3	20 %	20 %	20 %	20 %	60 %	80 %	40 %	40 %

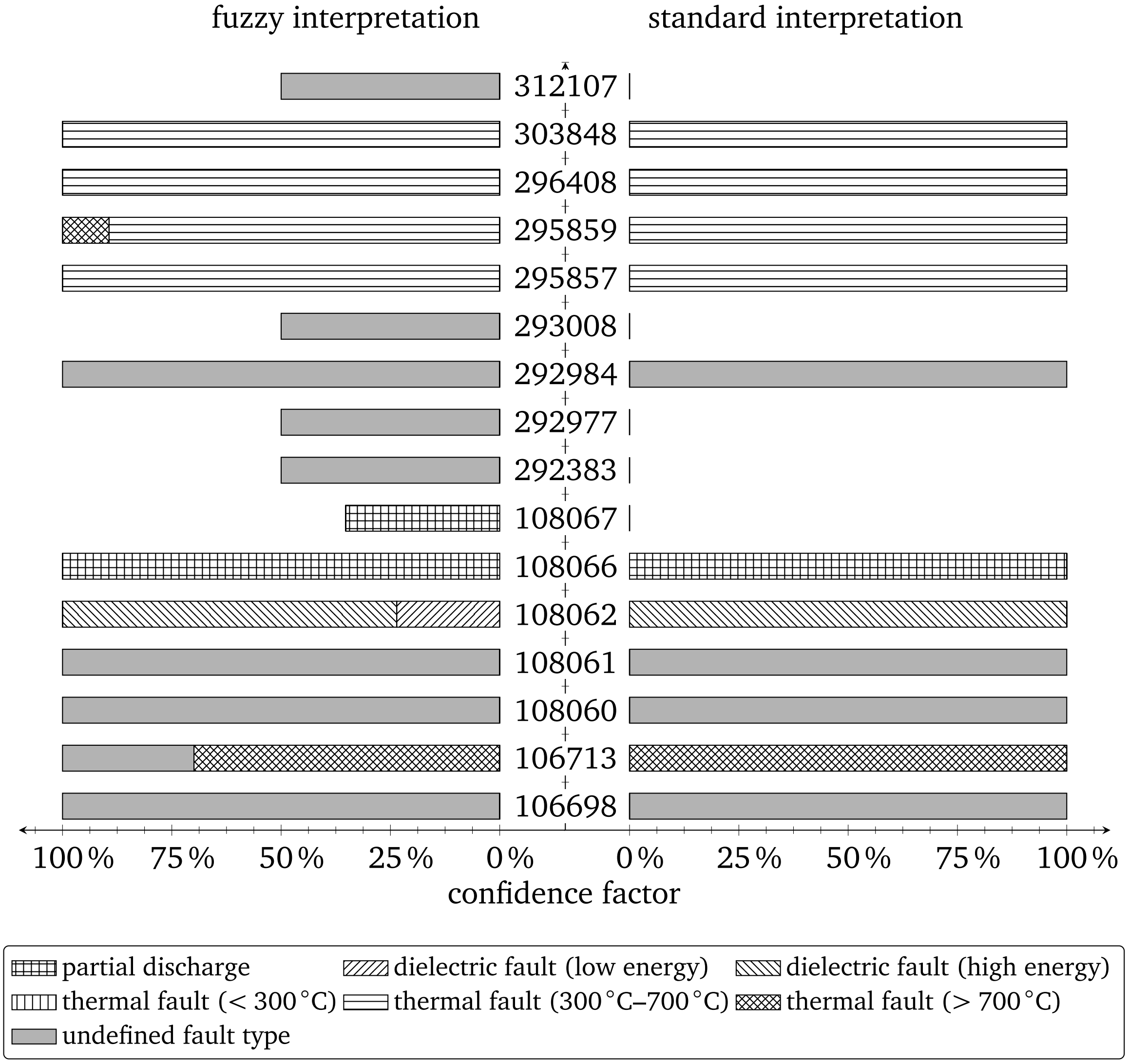

Figure 7.8.: Diagnostic findings of the detailed fuzzy interpretation scheme for fuzzification level 1 (typical gas concentrations obtained from the 95-percentile). Values in the y axis correspond to the ID code of equipment.

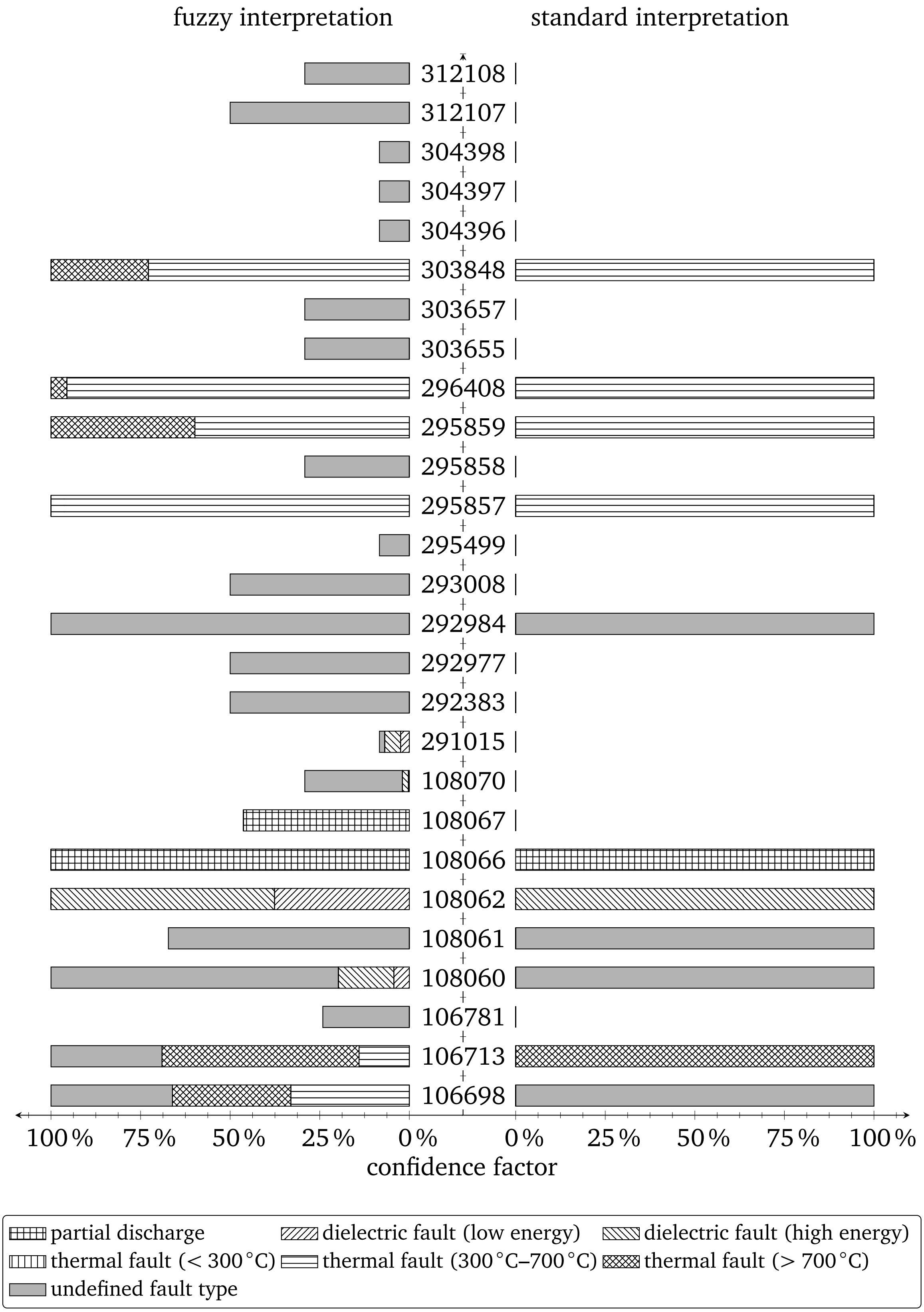

Figure 7.9.: Diagnostic findings of the detailed fuzzy interpretation scheme for fuzzification level 3 (typical gas concentrations obtained from the 95-percentile).

3. Fuzzy dissolved gas analysis identifies more suspect devices than standard DGA. According to figures 7.8 and 7.9 five additional units are definitely detected (total confidence factor higher than 25 %). In one case, precise classification of the type of fault is provided as well (unit 108067 – partial discharge).

4. All devices detected by standard dissolved gas analysis have also been identified by fuzzy DGA, although the confidence factor might be differing (for example, consider unit 108061 in figure 7.9). This is normal, since fuzzy DGA is an extension of standard dissolved gas analysis.

5. Extension of the detailed interpretation scheme by fuzzy reasoning cannot prevent from cases where the type of fault remains unidentified. Only in one case (unit 106698 in figure 7.9) did fuzzification assist in providing fault type classification.

In this chapter, the practical performance of the developed fuzzy DGA interpretation scheme has been tested on the basis of a case study. The main conclusion is that:

> *The extension of existing interpretation schemes by fuzzy reasoning provides effective means for enhancing the applicability, accuracy and overall performance of dissolved gas analysis and is therefore recommended.*

8 Parameter adaptation for DGA of power transformers

Much learning does not teach understanding.

Heraclitus of Ephesus, 535 – 475 B.C.

In the previous chapter we have seen how fuzzy logic can be successfully applied to extend the standard DGA interpretation scheme according to IEC 60599 so as to identify multiple faults as well as to provide a degree of belief for the proposed diagnosis. In addition, typical key gas concentrations for the test sample of instrument transformers have been adjusted to the available measurement data. Generally speaking, this approach works well when sufficient knowledge is incorporated in the DGA interpretation scheme, but it does not fully exploit available information from the examined sample.

The case study presented in this chapter goes one step further and deals with the question: *Provided both dissolved gas measurements and fault classification are provided independently for a given sample, would it be possible to adapt the threshold values in table 6.12 for appropriate DGA interpretation*? In other words, the task is no more to interpret available dissolved gas measurements and obtain the corresponding fault classification (as in case study 3), but to find the correct interpretation scheme so as to bring dissolved gas measurements and respective fault classification together. Obviously, fault classification in this case must be provided by means other than DGA, for example by partial discharge measurements or visual inspections.

Generally speaking, the question stated above is one of mathematical modelling: the objective is to find an appropriate mapping function from the input set (dissolved gas measurements) to the output set (fault classification). It would be possible to design a model from scratch, making no assumptions or use of a priori information about the mapping function itself (*black box* approach). Usually, techniques from the field of artificial intelligence, especially neural networks, are applied to black box problems. On the other hand, we could partially use a priori information during modelling (*white box* approach[1]). For example, we could search for an interpretation rule for partial discharges which has the same structure as in IEC 60599 (*if* ratio 2 is lower than … *and* ratio 3 is lower than … *then* fault type is partial discharge), but other threshold values.

In the case study presented in this chapter the latter approach is taken. In particular, the DGA interpretation scheme in table 6.12 is retained in structure, and adapted threshold values are estimated for a given sample of power transformers. The main advantage of the white box approach is that learned values can be easily compared with the ones in IEC 60599. Parameter estimation is performed by means of learning fuzzy models as introduced in section 2.4.1.

[1] Depending on the extend to which a priori information is used during mathematical modelling, the term *grey box* is sometimes used as a combination of black box and white box modelling.

This chapter is structured as follows: first, a short introduction on power transformers is given, with special attention on aspects relevant to dissolved gas analysis. Section 8.2 is dedicated to the developed learning fuzzy models for DGA interpretation. A brief literature review of research activities on adaptive artificial intelligence models applied to power transformers for DGA purposes is also presented. In section 8.3 the reader will find an overview of the power transformer sample used in the case study, followed by the most important results and comments.

8.1 Introduction to power transformer technology

A *power transformer* is defined by IEC 60050 as "a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power". The most important IEC standards on power transformers are included in the IEC 60076 series. Other power transformer relevant IEC standards as well as IEEE standards may be found in [8.1], chapter 17. Depending on their location in the power system, high-voltage power transformers are usually grouped into one of the following three categories.

Generator step-up transformers are used to connect generators to the transmission grid. They feature a very high voltage ratio, with typical values for the rated voltage on the primary[2] (low-voltage) side lying between 10.5 kV for generators of low rated power up to 27 kV for larger units [8.2]. On the other hand, the rated voltage of the secondary (high-voltage) winding can vary between 110 kV and 800 kV, with higher values for larger units [8.1]. The rated power of generator transformers usually amounts several hundreds MVA and may well exceed 1 GVA. Generator step-up transformers are usually connected in YNd so as to account for lower winding currents on the low-voltage side. Moreover, the YNd-connection allows for solid earthing of the high-voltage neutral which offers significant advantages regarding insulation coordination.

Grid (or *system intertie* [8.1]) transformers connect transmission systems with different voltages together with the purposed of exchanging both active and reactive power between the systems. For the example of the German transmission grid, where three voltage levels are used, system intertie transformers will have a voltage ratio of 380 kV/220 kV, 380 kV/110 kV or 220 kV/110 kV. The power rating of grid transformers is quite high and may vary between several hundreds MVA and two GVA. In order to facilitate lower weight, lower physical dimensions as well as lower manufacturing costs, grid transformers are typically auto-connected[3]. Figure 8.1 shows the equivalent circuit of an auto-connected three-phase transformer with tappings located in the phase of the low-voltage side. Although changing tappings in grid transformers does not significantly influence the voltage on either side (transmission systems are well-meshed and the voltage is controlled by the generators), it will influence the exchange of reactive power flow between the systems [8.1]. Auto-connected grid transformers are typically used in transmission systems with directly earthed system neutral. In this case, they

[2] The terms *primary* and *secondary* for the classification of windings describe the (active) power flow direction during normal operation. Power is received from the primary-side system and transmitted to the secondary-side system. Contrary to the classification into high and low-voltage windings, the distinction between primary and secondary winding is, thus, always dependent on the respective location of the transformer in the power system.

[3] A transformer is called *auto-connected* if at least two of its windings have a common part.

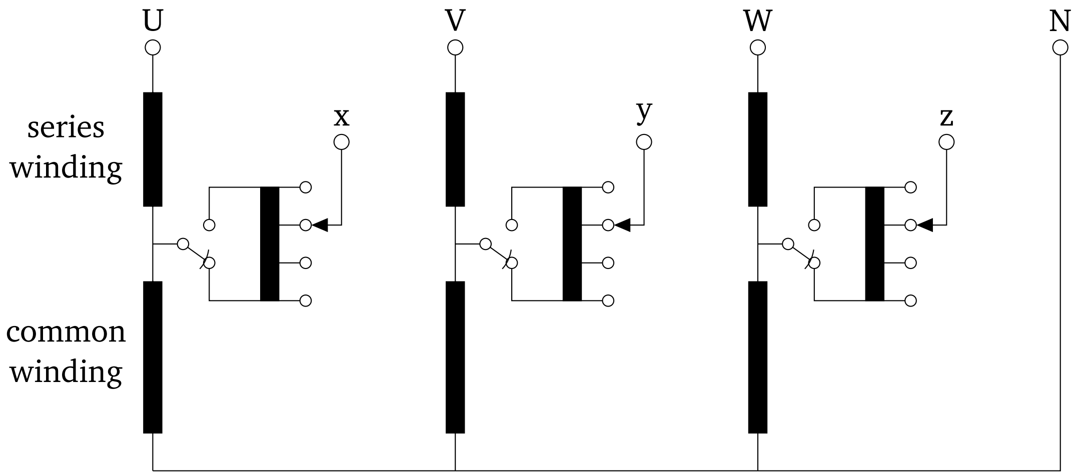

Figure 8.1.: Equivalent circuit of an auto connected three-phase transformer with tappings located in the phase of the low-voltage side. The *common* (lower) winding is connected to the neutral with its turns being common for both high and low-voltage side. On the other hand, the *series* (upper) winding is connected between the common winding and the high-voltage terminal. Power transmission between high and low-voltage side is partially inductive, partially galvanic.

are connected as YNyd, featuring a d-connected tertiary winding to provide low zero sequence impedance.

Step-down transformers connect the transmission system with the distribution system. The primary (high-voltage) winding has typically a rated voltage of 110 kV, while the rated voltage of the secondary winding may vary between 10 kV and 20 kV. Power ratings are in the range 12.5 MVA to 63 MVA [8.2], sometimes going up to the power rating of the transmission line. In Germany, step-down transformers connecting the transmission system with the distribution system are connected in Y(N)d, since the system neutral in distribution grids is insulated from earth. They are normally equipped with on-load tap-changers[4] so as to facilitate automatic voltage regulation on the low-voltage side.

All high-voltage power transformers are oil-immersed[5], and most of them use mineral oil as insulating fluid (in the past, PCBs have been partially employed in applications where a higher flash point of the insulating fluid was asked for; for such applications, use of synthetic and natural esters is being discussed lately – refer to section 6.1.2 for more information). Dissolved gas analysis is thus well-applicable for condition assessment of such transformers.

[4] *On-load tap-changers* (OLTC) are installed in power transformers with automatic voltage regulation. Their task is to change the transformer's voltage ratio without disconnecting the load. For this purpose, tappings must be provided on the primary or secondary winding. The most common design of on-load tap-changers consists of a *no-load tap selector* and a *diverter switch*. In principle, during a tap change the tap selector pre-selects the new tapping to be used (*make before break* principle), and the diverter switch then commutates to the selected tap. During commutation, the current flow has to be interrupted/diverted, which is associated with significant arcing activity. For this reason, the diverter is usually located in a different oil compartment than the main transformer tank and uses a separate oil conservator. In modern on-load tap-changers, the diverter switch consists of vacuum interrupters in order to avoid oil degradation and reduce maintenance needs.

[5] In this chapter, the term oil is equivalent to all insulating fluids used in high-voltage power transformers, including e.g. natural and synthetic esters, other synthetic oils etc.

When applying DGA to high-voltage power transformers, the degree of utilisation has to be taken into account: A highly utilised transformer will tend to generate more low-energy fault gases –especially hydrogen– over the same operation time period. Usually generator step-up transformers will belong to this group. On the other hand, the degree of utilisation of system intertie and step-down transformers will be much lower due to redundancies in the transmission grid.

High voltage power transformers are usually *three-phase* transformers of the core or shell type[6], although transformer banks consisting of three single-phase transformers are also used in case of extremely high power requirements, transportation limitations, redundancy requirements or other special reasons. Low-voltage windings are located adjacent to the core and are usually of the helical type. On the other hand, disc windings are used for the high-voltage side; they are located concentrically around the low-voltage windings. Pressboard barriers provide insulation between the windings and between low-voltage windings and core. The core itself is nowadays made of thin sheets (typical lamination thickness is from 0.18 mm to 0.30 mm) of cold-rolled, grain-oriented silicon steel alloy, which are insulated from each other in order to minimise eddy current losses [8.1]. Figure 8.2 shows a 500 MVA three-phase core-type power transformer during assembly.

In the following sections, several aspects of high-voltage power transformers with relevance to DGA shall be discussed.

8.1.1 Thermal considerations

Power loss in transformers is usually divided in two groups [8.3]: *no-load* losses occur in the magnetic circuit of the transformer (iron core), thus also called *iron* losses. Their main causes are magnetic hysteresis[7] and eddy currents induced into the core. On the other hand, *full-load* losses or simply *load* losses occur mainly in the windings due to resistive heating when current flows through the winding conductors. Since copper is the most usual conductor material used in transformers, full-load losses are also called *copper* losses. Depending on the loading of the transformer, no-load or full-load losses may be dominant.

In spite of the very high efficiency of power transformers (typically higher than 98 % − 99 %), heat generated due to power loss may still be significant. For example, a power transformer with rated power 400 MVA will experience losses in the range of 1.6 MVA during operation [8.3]. Such an amount of excess heat must be actively transfered outside the transformer to the surrounding medium.

Cooling of oil-immersed power transformers is discussed in IEC 60076-2 and IEC 60076-6. According to these standards, cooling system classification is performed by examining following aspects:

[6] The terms *core* and *shell* type transformer are nowadays deprecated by the IEC. Older definitions in IEC 60050 described core type transformers as "transformers in which the magnetic circuit takes the form of columns "(legs or limbs), whereas shell type transformers are "transformer where the packets of laminations forming the core and yokes surround the windings and enclose generally the major parts of them". Generally speaking, the distinction between the two types is based on whether the magnetic circuit has unwound magnetic return paths (shell type) or not (core type).

[7] *Magnetic hysteresis* describes the "resistance" of magnetic dipoles to a change in the applied magnetic field; for materials demonstrating magnetic hysteresis, energy is needed to re-orient magnetic dipoles in a magnetic field, leading to power loss proportional to the applied field frequency.

Figure 8.2.: Assembly of a 500 MVA three-phase power transformer. The transformer is of the core type (three limbs) and facilitates on-load tap-changers for voltage regulation (far right part). Its rated voltage on the high-voltage side is 380 kV (courtesy by Siemens, 2007).

- *insulating oil type*: IEC 60076-2 distinguishes between insulating oils with flash point below 300 °C (mineral oils and synthetic esters), above 300 °C (silicone oils, natural esters, previously also PCBs) or unknown flash point. Decisions on the type of applicable insulating oils are based on assessing the hazard of fire and usually depend on the location of the transformer: for example, in the vicinity of residential areas a higher flash point might be a requirement.
- *insulating oil circulation*: Depending on the amount of heat generation inside the transformers due to power loss, circulation of the insulating oil can be either *natural* on the basis of the thermosyphon effect[8] or *forced* by means of external oil pumps. If furthermore, the insulating oil is intentionally diverted into the cooling ducts, one speaks of *directed* circulation.
- *surrounding medium type*: Usually air is the surrounding medium of power transformers, therefore heat due to power loss is transferred directly to it. However, in some occasions transformers are built-in (e.g. in deep underground caverns of hydro power stations) and the surrounding air available could be insufficient for cooling. In these cases, oil to water heat exchangers are used.
- *surrounding medium circulation*: Natural circulation of surrounding air due to convective cooling is sufficient for cooling smaller transformers with rated power up to 40 MVA. However, for larger generation step-up or system intertie transformers, air circulation forced by fans is applied. In case water is used as secondary cooling medium, circulation is always forced by water pumps.

IEC 60076-2 provides a table for classification of cooling systems applied to power transformers. An abstract is given in table 8.1. According to this classification, a mineral oil-filled transformer with natural oil circulation and equipped with fans for air circulation is labelled as ONAF.

Table 8.1.: Classification of cooling systems for power transformers (abstract from IEC 60076-2). Different coding has been previously used in the USA, e.g. a ONAF transformer was previously labelled as FA [8.4].

		Code Letter	Description
Internal	First letter (medium)	O	Liquid with flash point $\leq 300\,^\circ\mathrm{C}$
		K	Liquid with flash point $> 300\,^\circ\mathrm{C}$
		L	Liquid with no measurable flash point
	Second letter (mechanism)	N	Natural convection (thermosyphon)
		F	Forced circulation
		D	Directed forced circulation
External	Third letter (medium)	A	Air
		W	Water
	Fourth letter (mechanism)	N	Natural convection
		F	Forced circulation

8 The term *thermosyphon* describes a phenomenon where liquid is circulating in a loop due to heating. Heating causes expansion of the liquid, thus reducing its density; under the influence of gravity, cooler, denser liquid then moves downwards to the heat source, and, by doing so, displaces already heated liquid –a circular movement occurs.

In spite of the active transportation of excess heat generated in core and windings to the surrounding medium by the cooling system, the temperature distribution in the transformer is not uniform: at the bottom part, where cool oil is returning form the heat exchanger, the temperature is low. In its movement upwards, the oil is then heated by the core and mainly by the windings and reaches its highest temperature at the top of the tank. A similar temperature distribution is also apparent inside the winding itself: the conductor, being the heat source, features the highest temperature, with temperature falling over the layers of the winding. The aforementioned effects result in a *hotspot*[9] region at the central upper part of the winding.

This is true no matter the type of the cooling system, however, the temperature distribution inside the transformer does vary for the different types. In particular, the directed, forced oil circulation will result in a more uniform distribution [8.3]. This, in turn, allows for better utilisation of the transformer without increasing hotspot temperature to an unacceptable level. Since the temperature distribution in the transformer might have an influence on the generation rate of fault gases, it is recommended to take the cooling system into consideration for dissolved gas analysis.

8.1.2 Oil preservation systems

The transformer's temperature varies in service mainly due to power loss, causing expansion and contraction of the oil inside the transformer. The change in volume can be quite significant (up to 8 % assuming a constant pressure level [8.5]) resulting in high pressure variations unless the oil is allowed to expand. However, if oil expansion was to take place in a natural way, an interface between the warm transformer oil in the upper part of the tank and atmospheric air would be required. Such a natural interface would lead to diffusion of oxygen and water from the atmoshpere into the oil, significantly reducing its insulating properties and accelerating ageing of the transformer's internal insulating system (the influence of water and oxygen on ageing of the oil-impregnated paper insulating system is described in detail in section 6.1.3). It is therefore the task of *oil preservation systems* to isolate the transformer's internal insulation from the atmosphere while, at the same time, appreciating the need for pressure compensation. Oil preservation systems can be grouped into one of the following three categories: conservator systems, positive-pressure systems and sealed-tank systems.

Conservator (or *breathing*) systems: In order to allow for oil expansion, an oil conservator can be installed. Conservators are usually cylindrical metal drums located in top or near the transformer at higher level. They are connected via pipe with the transformer's main tank and partially filled with insulating oil in a way that the main tank is always completely filled with oil, no matter the operating temperature. Contrary to the oil in the main tank, oil in the conservator remains rather cool (heat exchange through the pipe connection is limited) and the diffusion rate of oxygen into the oil is low [8.5]. The conservator-side pipe lead should be installed somewhat higher than base level to allow for potential impurities resulting from the reaction of oil in the conservator with oxygen and water to deposit at the conservator's bottom and not be transported into the main tank [8.5].

In the early years, small power transformers were built as *free breathing* units: at higher operating temperatures, oil displaced air from the conservator; atmospheric air was then sucked in

[9] The hotspot temperature is widely recognised as a significant parameter when assessing a transformer'S ageing status.

directly when the temperature dropped and oil contracted again. The result was high absorption of water depending on the atmospheric humidity level. This problem is resolved by the introduction of *breathers*: a breather is a filtering and drying system which removes particles and humidity from the atmospheric air before allowing it to flow into the conservator. In the past, *calcium chloride* ($CaCl_2$) was used as drying agent [8.6], nowadays *silica gel*[10] is usually used. In the case of very humid climates or large and important power transformers, a *refrigeration breather* can also be used. Here, incoming air is dried by freezing [8.1].

Breathing oil conservation systems may also be equipped with *rubber air bags* (bladders) in the conservator. The interior of the bag is connected to atmosphere so it can breathe in when the oil contracts and breathe out when the oil expands. A further modification is the use of *membranes* or *diaphragms* located horizontally at the surface of the oil in the conservator. Again, expansion and contraction of the oil occurs with no direct contact between oil and atmospheric air. Finally, it is also possible to introduce an intermediate pressure compensation system into the conservator which used nitrogen and oil as decoupling interface, as shown in figure 8.3 [8.5, 8.7]. Unfortunately, the overall size of the conservator has to be tripled for this purpose.

Positive-pressure (or *quasi-breathing*) systems use inert gas to fill the space above the insulating oil (either in the main tank itself or in the conservator provided one is installed). Usually a nitrogen "cushion" is used for this purpose. When the oil volume increases due to an increase in temperature, nitrogen is vented to the atmosphere through a vent valve –the transformer is breathing out. Contrary to the conservator system describes above, however, no atmospheric air is sucked in during breathing in when the temperature falls again. Instead, nitrogen is provided from a cylinder of compressed gas via a pressure-reducing feed-in valve [8.1]. By adjusting the settings of the feed-in and vent valve it is possible to minimise nitrogen consumption. Since the feed-in valve will always have a higher release pressure, a positive gas pressure is always maintained inside the transformer, justifying the name of this type of oil preservation systems.

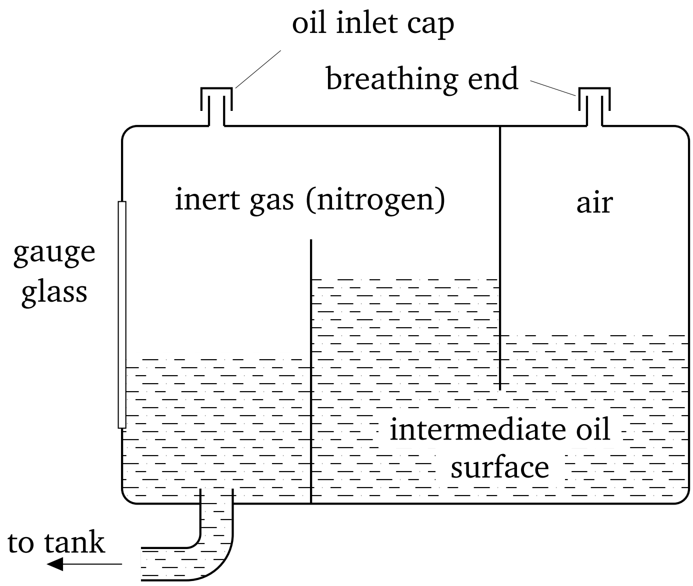

Figure 8.3: Conservator consisting of three compartments with intermediate nitrogen/oil interface (based on [8.5]). Expansion and contraction of the insulating oil occurs without direct contact with the atmospheric air. This type of oil preservation systems are also known as *gas-oil seal* systems (refer to the discussion in [8.7]). Note the pipe lead, located higher than base level to allow for the deposition of sludge in the conservator.

[10] Silica gel is impregnated with colour indicators so as to visualise its saturation level with water. A new, environmental friendly organic colour indicator (colour is changing form originally orange to colourless when the gel gets almost half saturated with water) is now substituting the widely used cobalt chloride (colour change from blue to pink) [8.1]. As soon as the level of saturation reaches 15 % per weight, the gel should be replaced; the wet silica gel may be reactivated by drying it in an oven.

Sealed-tank systems feature no connection –direct or indirect– between the oil and the atmosphere. As the name implies, the tank is sealed and completely occupied by the oil and potentially a nitrogen cushion above it (other inert gases may also be used). Since the volume remains constant, changes in temperature inevitably lead to pressure variations [8.7]. Sometimes corrugated wall tanks are therefore applied so as to partially take up these pressure variations. Sealed-tank systems have been successfully used with distribution transformers for many years [8.8] and the overall service experience is good. However, it was not till recently that high-voltage power transformers could also be designed with a hermetically sealed tank [8.3, 8.9, 8.10]. The main problem is that, for the latter transformers, the tank cannot take up the oil expansion due to the substantially larger changes in oil volume. Instead, a special expansion radiator has to be installed. Nowadays, all major transformer manufacturers offer sealed-tank solutions for large, high-voltage power transformers.

Figure 8.4 schematically shows the layout of the common oil preservation systems. If a conservator is installed, a Buchholz relay[11] may be used for protection purposes.

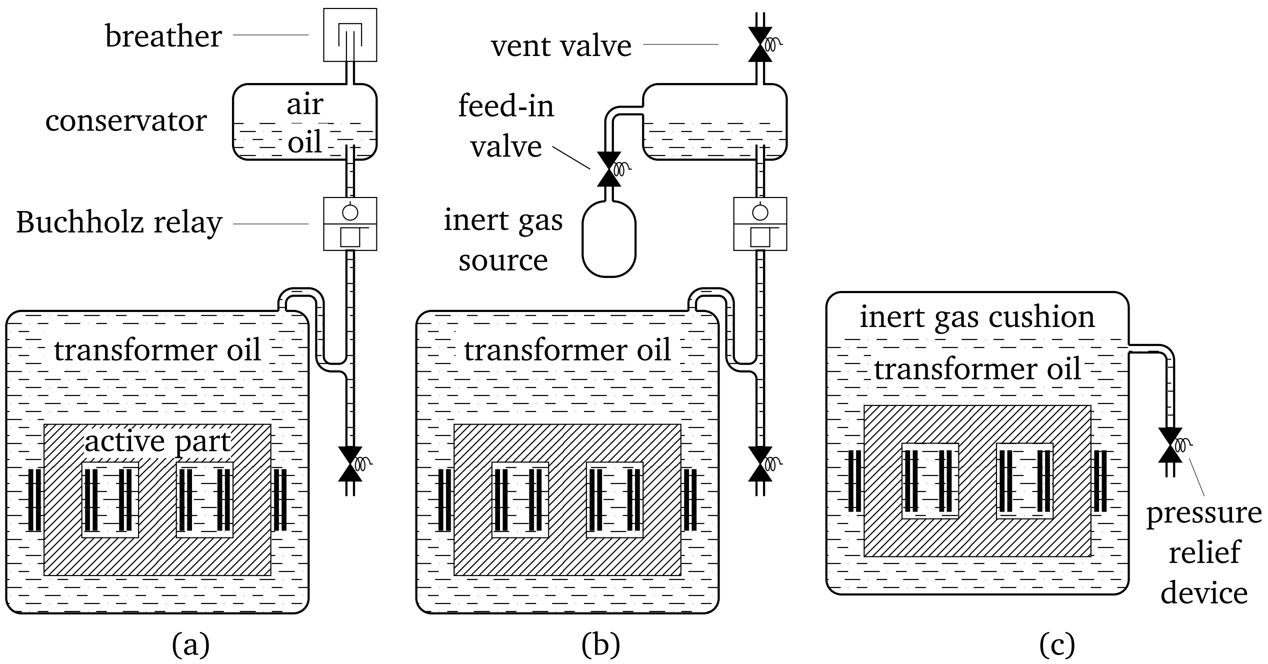

Figure 8.4.: Schematic layout of oil preservation systems (based on [8.4]): (a) conventional oil preservation system with conservator and breather,(b) positive-pressure oil preservation system,(c) sealed-tank oil preservation system.Positive-pressure systems may or may not include a conservator, in the first case application of a Buchholz relay is possible. No matter the preservation system, pressure relief devices are always installed at the main tank in order to limit the tank overpressure in case of an internal fault. The U-bend pipe connection between tank and conservator in figures (a) and (b) acts as thermal seal.

[11] The Buchholz relay is installed in the piping between the transformer's main tank and the conservator. Its purpose is to detect sudden and incipient faults that may occur in the transformer by measuring the generation of fault gases.

A survey conducted by Cigré [8.11] showed that there are substantial differences between Europe and the USA regarding the preferable oil preservation system for power transformers: for example, in Germany only 5 % of all units in service are pressurised or facilitate a diaphragm, whilst in the USA almost all installed units use this kind of oil preservation systems.

The type of the applied conservation system will have some influence on the concentrations of dissolved gases in the oil. This is particularly true for atmospheric gases like nitrogen, oxygen and –to some extent– carbon dioxide. This fact has to be taken into consideration during DGA interpretation. In IEC 60599, sections 5.4 and 5.5, the CO_2/CO and O_2/N_2 ratios are discussed. The first ratio serves as an indicator for potential involvement of the paper insulation in a fault. A value in the range lower than three is such an indication [12]. Obviously, breathing systems allow atmospheric carbon dioxide to enter into the oil; therefore, the value of the CO_2/CO ratio has to be corrected in these cases. The second ratio (O_2/N_2) is sometimes used as an indicator for ongoing oxidation processes inside the oil-impregnated paper insulating system. For hermetically sealed or positive-pressure transformers, oxygen is consumed over time due to oxidation and the value of this ratio decreases. On the other hand, breathing systems do not prohibit oxygen diffusion into the oil. As a result, the value of the O_2/N_2 ratio will drop slower in breathing transformers than in sealed-tank or positive-pressure transformers for the same oxidation rate of the internal insulation. The increased oxygen concentration in breathing systems will also lead to a somehow higher generation of hydrocarbonic fault gases, although this influence is rather negligible.

Last but not least, the *gas bubbling* tendency of a power transformer is also largely influenced by the type of the applied oil preservation principle. Extensive research was performed in the late 1950s regarding this phenomenon [8.13–8.16], which will be briefly described here.It is relevant for positive-pressure or sealed-tank systems where an overlying gas (usually nitrogen) cushion is in contact with the transformer oil. The solubility of nitrogen in the oil depends mainly on pressure [13] and temperature: the higher the pressure and/or temperature, the higher will the solubility be [8.13]. For example, at normal operating condition, a nitrogen-cushion transformer may have up to 14 % by volume nitrogen dissolved in the oil [8.14]. However, when the loading is decreased, pressure and temperature will fall, and so will also nitrogen solubility. Because of the low surface-to-oil ratio, nitrogen gas dissolved in the oil will move only slowly towards the overlying gas space; the oil will be supersaturated with nitrogen gas until an equilibrium is reached again. In the presence of mechanical agitation (e.g. by the cooling pump) the supersaturated oil will tend to bubble out, thus reducing the dielectric strength of the transformer's internal insulation. This phenomenon does not occur with conservator-type oil preservation systems where gas pressure is maintained at a constant level.

[12] The requirement $CO_2/CO < 3$ as an indication of potential paper involvement in a fault is proposed by IEC 60599. This value has, however, been criticised by some researchers [8.12]: for DGA of forced-cooled, conservator-type transformers with air diaphragms in the conservator, they proposed a much higher threshold value of 10.

[13] *Henry's law* shows a linear relationship between the amount of gas that dissolves into a liquid and the partial pressure of the gas above the liquid. It is generally valid in cases where relatively large pressures and high concentrations are avoided.

8.2 Learning fuzzy models for DGA interpretation

In the beginning of this chapter we already described the problem of adjusting the DGA interpretation scheme to a sample of dissolved gas measurements and their corresponding diagnosis as one of mathematical modelling. Models found in the literature for this purpose follow either a black box or a white box approach. Before introducing the learning fuzzy models proposed in this thesis, a brief literature review on adaptive DGA interpretation shall be given. The reader is encouraged to refer to [8.17] for a more detailed review.

In an inspiring though short paper [8.18] published in 1993, Dukarm discusses the possibilities offered by *artificial intelligence* (AI) techniques, in particular by fuzzy logic and neural networks, for DGA optimisation. It is not so much the fuzzy DGA method he proposes (his model is a straightforward application of the key gas and the Roger's ratio methods, with nothing "adaptive" at it; besides, Lin et al. had already proposed an expert system for DGA interpretation based on fuzzy logic in [8.19] – refer to section 7.4), but the idea of applying *artificial neural networks* (ANN[14]) which opens new horizons. In [8.18], he uses feed-forward neural networks with one hidden layer and trains them by backpropagation. Furthermore, the possibility of using *self-organising maps* (SOM[15]) is also briefly discussed.

Since then, artificial neural networks have often been applied to DGA interpretation. One of the first such applications is described in [8.20], where Vanegas et al. used the standard Denkyoken and IEC interpretation methods to initialise their three-layer neural network. After initialisation, the network was trained by backpropagation on the basis of 26 samples. Zhang et al. also used ANNs for DGA interpretation in [8.21], though a different, two-step approach was chosen there. In particular, one neural network was dedicated to major failure detection whereas a second, independent network assessed the cellulose condition.

A self-organising map was implemented for DGA interpretation by Thang et al. in [8.22]. Learning was performed in a supervised way on the basis of more than 700 historical dissolved gas records. The main characteristic of the proposed method is that it does not depend upon DGA interpretation schemes for its development –only measured gas data is needed.

A behaviour similar to that of a self-organising map can be achieved by *learning vector quantisation* (LVQ[16]). Yang et al. introduced LVQ networks for DGA interpretation in [8.23], using the IEC gas ratios as input. For any given input, the three ratios C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 were first fuzzified, and then passed to several LVQ networks. The resulting *fuzzy LVQ network* is equivalent to a fuzzy inference system where the consequence of each rule –evaluated by one LVQ network each– is trained.

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14 An *artificial neural network* is a mathematical model emulating the structure of biological neural networks. It comprises many neurons, connected to each other by weighted branches. When an input is applied to the network, a computational information signal travels through the branches and activates the neurons, producing an output at the end of the network. The output is a function of the input and the layout of the network (in particular of the activation functions of the neurons and of the branch weights). By means of appropriate training of the network, any input-output relationship can be approximated.

15 *Self-organising maps* are a special form of artificial neural networks introduced by the Finish professor Teuvo Kohonen in 1982. Their main difference to traditional neural networks is that, during training, branch weights are not adapted separately, but within a specific region ("neighbourhood"), that is, more than one neuron are "displaced" simultaneously in the network. As implied by their name, self-organising maps are trained without supervision and will tend to take the "shape" of the required pattern.

16 *Learning vector quantisation* networks are the precursors of self-organising maps. Contrary to the latter, only the neuron nearest to any given input is "displaced" during training.

Vector quantisation is also applied in [8.24], where Tang et al. use a least-square *support vector machine* (SVM[17]) for DGA interpretation. For training purposes, 167 data sets comprising five key gas ratios are used, which are then sampled by means of a bootstrap technique so as to ensure equal number of training data sets for all fault classifiers. The training results of the proposed least-square SVM are also compared with those obtained for a standard neural network, a LVQ network as well as for a standard SVM.

In order to overcome the limitations imposed by binary classification as with support vector machines, some researchers have proposed *fuzzy clustering* methods for DGA interpretation. Generally speaking, classification with fuzzy clusters results from a set of membership functions in the input space, specific to each class. Instead of crisp vectors (as with e.g. LVQ networks) *ranges* and corresponding *membership functions* are trained during learning. Wang et al. have proposed the use of artificial neural networks in order to train the membership functions of the input variables. In [8.25], they describe a fuzzy inference system where each fault class is modelled by one rule and the corresponding membership functions in the rule's premise are neural networks. Instead of traditional backpropagation, they rely on *evolutionary programming* (EP) and Levenberg-Marquandt optimisation for training the neural networks.

An interesting approach for fuzzy clustering using a fuzzy equivalence matrix is introduced by Zhang et al. in [8.26]. Here, unsuprevised learning is applied to the clusters for training purposes. A further advantage of the proposed method is that, by modifying the level for the implemented fuzzy cut-sets, it is possible to choose the classification depth (i.e. how many clusters should be used) in an easy way.

A group of researchers from Taiwan, Huang et al., have combined a standard fuzzy inference system with *evolutionary programming* for training purposes. In [8.27], they considered the Roger's ratio, Döernenburg's and IEC methods and constructed the initial framework of their system accordingly. During training, they used evolutionary programming to adapt the membership functions of the input variables as well as the rules' implications. Since the problem of training the implication of the rules is one of integer optimisation (each sample is assigned to one of the following fault classes: no fault, partial discharged, dielectric or thermal fault), in a later publication [8.28], they applied in parallel EP to train the membership functions and genetic programming to train the rules' implications. In general, their method can be regarded as the first learning fuzzy model applied to DGA interpretation.

Recently, Fischer et al. proposed a further learning fuzzy model for this purpose [8.29–8.31]. In a first step, they used artificial neural networks and trained them on the basis of dissolved gas data published by IEC TC 10 [8.32]. The trained networks then provided the implication parts for a Sugeno-type fuzzy inference system.

A similar method for mapping a neural network into a Sugeno-type, rule-based fuzzy inference system is provided by Castro and Miranda in [8.33]. Their work demonstrates that it is theoretically possible to transform a neural network into an equivalent fuzzy system. The knowledge gained during training the neural network can then be described in a more natural way within the rules of the fuzzy system.

Finally, several researchers have proposed methods for *merging* different interpretation schemes so as to obtain a more reliable classification result. The combination of artificial neural networks, trained according to dissolved gas data, with a knowledge-driven fuzzy inference system is described in [8.34–8.36]. The objective is to used the ANN in case it can

[17] A *support vector machine* is a binary, non-linear classifier, defined by a set of support vectors. Through training, a hyperplane is constructed in the input space, so that any given sample will be assigned to exactly one class.

ensure reliable classification and to rely on the accumulated service experience from traditional DGA interpretation otherwise. A similar approach is taken in [8.37], though standard DGA interpretation schemes are modelled by neural networks rather than fuzzy inference systems there.

Merging can also be performed on the basis of the *Dempster-Schafer theory*[18] (or *theory of evidence*). Such an approach is proposed by Tomsovic et al. in [8.38]. They first use fuzzy cut-sets to transform the output membership functions from different fuzzy interpretation schemes into crisp sets, and then combine these sets according to Dempster's rule of combination.

In summary, the literature review brings us to following conclusions:

1. Artificial neural networks are suitable for learning patterns in dissolved gas data. Their training procedures are well-developed; however, the knowledge gained from learning is captured inside the networks and cannot be expressed in natural language. The same is also true for learning vector quantisation networks and support vector machines.
2. Self-organising maps and fuzzy-clustering algorithms are similar to neural networks in this respect, but have the advantage that learning can be done in an unsupervised way.
3. On the other hand, fuzzy inference systems can be "read" by the user by observing their rule base. So far, learning fuzzy models proposed for DGA interpretation [8.27, 8.29] mainly train the implication part of the rules. In the case of [8.27], the size of the rule base is not a priori fixed; it rather changes during training.
4. Several techniques have been proposed for merging several interpretation schemes together. The objective is to obtain a more reliable interpretation result.

Returning to the question formulated at the beginning of this chapter (adaptation of the thresholds in the IEC interpretation scheme by training the input membership functions of its fuzzy equivalent scheme without changing its general layout), it is obvious that none of the aforementioned methods can be applied. The main advantage of such an approach is that the adapted thresholds determined by training can be directly compared with their corresponding values in the original IEC interpretation scheme. For this reason, learning fuzzy models on basis of the IEC scheme will be introduced in the following sections; each fault class (partial discharges, dielectric and thermal fault) is modelled by its own classifier.

8.2.1 Learning fuzzy model for partial discharges

IEC 60599 defines following interpretation rule for fault classification as partial discharge (compare table 6.12):

if ratio 2 is lower than 0.1 *and* ratio 3 is lower than 0.2 *then* fault type is partial discharge

The fuzzy system used for learning is constructed according to section 2.4.1. As already discussed there, the negation of the interpretation rule above is also necessary. In order to correctly model the "lower than ..." relations, decreasing sigmoid membership functions are applied (equations 8.1). The complete fuzzy model is graphically shown in figure 8.5.

[18] The *Dempster-Schafer theory* is a generalisation of the traditional, Bayesian probability theory. It states that the *degree of plausibility* of a given hypothesis can be higher than its *degree of belief*. In Bayesian probability theory, both are assumed to be equal and are combined to the *degree of probability*.

$$\mu_{r_2}(r_2) = \frac{e^{-a_2(r_2-c_2)}}{1+e^{-a_2(r_2-c_2)}} \tag{8.1a}$$

$$\mu_{r_3}(r_3) = \frac{e^{-a_3(r_3-c_3)}}{1+e^{-a_3(r_3-c_3)}} \tag{8.1b}$$

Similar to equation 2.51 in section 2.4.1, we obtain following (crisp) output y^{ν}_{res} for the fuzzy model, given an input vector of key gas ratios $(r^{\nu}_1\ r^{\nu}_2\ r^{\nu}_3)$:

$$y^{\nu}_{res} = \top_{ag}\left\{\mu_{r_2}\left(\underline{p}_{r_2}, r^{\nu}_2\right), \mu_{r_3}\left(\underline{p}_{r_3}, r^{\nu}_3\right)\right\} \tag{8.2}$$

where $\underline{p}_{r_2}$ and $\underline{p}_{r_3}$ are the parameters of the respective membership functions. If we implement the product operator for the aggregation of the premise $\top_{ag}$, we finally obtain the partial derivatives of the mean square approximation error ϵ with respect to each parameter (compare equation 2.52 in section 2.4.1):

$$\frac{\partial\epsilon}{\partial a_2} = \frac{1}{s}\sum_{\nu=1}^{s}\left(y^{\nu}_{res} - \tilde{y}^{\nu}\right)\cdot\mu_{r_3}(\tilde{r}^{\nu}_3)\cdot\frac{\partial\mu_{r_2}(\tilde{r}^{\nu}_2)}{\partial a_2} \tag{8.3a}$$

$$\frac{\partial\epsilon}{\partial c_2} = \frac{1}{s}\sum_{\nu=1}^{s}\left(y^{\nu}_{res} - \tilde{y}^{\nu}\right)\cdot\mu_{r_3}(\tilde{r}^{\nu}_3)\cdot\frac{\partial\mu_{r_2}(\tilde{r}^{\nu}_2)}{\partial c_2} \tag{8.3b}$$

$$\frac{\partial\epsilon}{\partial a_3} = \frac{1}{s}\sum_{\nu=1}^{s}\left(y^{\nu}_{res} - \tilde{y}^{\nu}\right)\cdot\mu_{r_2}(\tilde{r}^{\nu}_2)\cdot\frac{\partial\mu_{r_3}(\tilde{r}^{\nu}_3)}{\partial a_3} \tag{8.3c}$$

$$\frac{\partial\epsilon}{\partial c_3} = \frac{1}{s}\sum_{\nu=1}^{s}\left(y^{\nu}_{res} - \tilde{y}^{\nu}\right)\cdot\mu_{r_2}(\tilde{r}^{\nu}_2)\cdot\frac{\partial\mu_{r_3}(\tilde{r}^{\nu}_3)}{\partial c_3} \tag{8.3d}$$

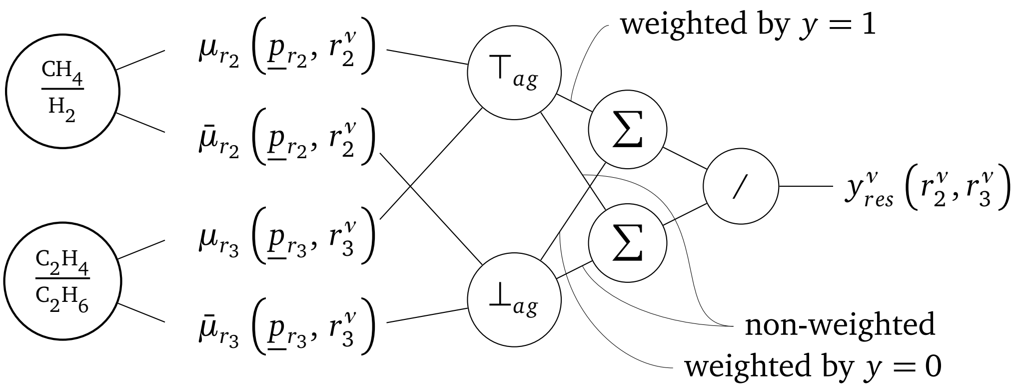

Figure 8.5.: Fuzzy interpretation scheme for classification of partial discharge faults. Membership functions μ_{r_2} and μ_{r_3} are both of the "lower than" type, modelled by monotonically decreasing sigmoid functions (equation 8.1). The first rule features a product T-norm and implies an output value of $y = 1$ (classification as a fault), its negation implies $y = 0$ (compare section 2.4.1). The final two layers implement the centre-of-area defuzzification.

with $y^{\nu}_{res} = \mu_{r_2}(\underline{p}_{r_2}, \tilde{r}^{\nu}_2) \cdot \mu_{r_3}(\underline{p}_{r_3}, \tilde{r}^{\nu}_3)$. The partial derivatives of the decreasing sigmoid function may be found in appendix G.1. Equations 8.3 are applied to the resilient backpropagation algorithm (RPROP) described in figure 2.4 (section 2.4.1).

In order to check the performance of the learning algorithm following procedure has been adopted: First, reference input vectors $(\tilde{r}^{\nu}_1\, \tilde{r}^{\nu}_2\, \tilde{r}^{\nu}_3)$ with $\tilde{r}^{\nu}_i \in [0;\, 1]$, $i = 1, 2, 3$ were randomly generated. The input vectors were then handled according to the interpretation rule in IEC 60599 and a reference output $\tilde{y}^{\nu}$ was assigned to each input vector. The resulting dataset of $s = 1000$ reference input-output data pairs served as input for the learning algorithm.

In addition to the standard RPROP algorithm described in section 2.4.1, several modifications have also been investigated. These modifications include:

- application of the original superSAB algorithm[19] (without any residual term as in RPROP),
- use of the approximation error with respect to each individual training data pair $\epsilon^{\nu} = \left(y^{\nu}_{res} - \tilde{y}^{\nu}\right)^2$ as performance measure (similar to "on-line" learning, as opposed to "off-line" learning, where the mean square approximation error $\epsilon = \sum_{\nu=1}^{s} \epsilon^{\nu}$ over the whole dataset is rather used),
- pre-defining some parameters of the membership functions, in particular the shape parameters a, and estimating only the scale parameters c.

Comparative results are given in appendix G.2. In summary, the standard RPROP algorithm as presented in section 2.4.1 (off-line learning, all model parameters to be estimated) demonstrated significantly better performance and will by used throughout this chapter. When tested under the aforementioned controlled conditions, it needed only 130 iterations and a computation time of 1.9 seconds to reach an approximation accuracy of $\epsilon < 10^{-9}$. The resulting estimates for the scale parameters (c_2 and c_3 in equations 8.1) featured a deviation of less than ±6 % from their reference values in IEC 60599.

8.2.2 Learning fuzzy model for dielectric faults

With respect to dielectric faults, IEC 60599 provides two interpretation rules for fault classification depending on the energy dissipated (fault types D1 and D2 in table 6.12). However, in the case study provided in this chapter, no distinction between low and high energy faults has been made (refer to section 8.3). Consequently, the two interpretation rules have to be merged as:

if ratio 1 is higher than 1 *and* ratio 2 is between 0.1 and 0.5 *and* ratio 3 is higher than 1
or if ratio 1 is between 0.6 and 2.5 *and* ratio 2 is between 0.1 and 1 *and* ratio 3 is higher than 2
then fault type is dielectric

Increasing sigmoid functions are used to model the "higher than ..." relations, while generalised bell-shaped functions account for the "between ..." relations (compare section 2.2.1). In particular, the implemented membership functions are shown in equation 8.4: the left-hand side functions (with index 1) account for the first part of the above rule's premise (low energy

[19] For a detailed description of the superSAB backpropagation algorithm refer to [8.39] and [8.40]

fault, D1) while the right-hand side functions (index 2) account for the second part (high energy faults, D2).

$$\mu_{r_{1,1}}(r_1) = \frac{1}{1+e^{-a_{1,1}(r_1-c_{1,1})}} \qquad \mu_{r_{1,2}}(r_1) = \frac{1}{1+\left|\frac{r_1-c_{1,2}}{a_{1,2}}\right|^{2b_{1,2}}} \tag{8.4a}$$

$$\mu_{r_{2,1}}(r_2) = \frac{1}{1+\left|\frac{r_2-c_{2,1}}{a_{2,1}}\right|^{2b_{2,1}}} \qquad \mu_{r_{2,2}}(r_2) = \frac{1}{1+\left|\frac{r_2-c_{2,2}}{a_{2,2}}\right|^{2b_{2,2}}} \tag{8.4b}$$

$$\mu_{r_{3,1}}(r_3) = \frac{1}{1+e^{-a_{3,1}(r_3-c_{3,1})}} \qquad \mu_{r_{3,2}}(r_3) = \frac{1}{1+e^{-a_{3,2}(r_3-c_{3,2})}} \tag{8.4c}$$

Figure 8.6 graphically shows the complete fuzzy model for dielectric fault interpretation. Note that the negation of the above rule is also implemented. The output y^{ν}_{res} is the interpretation result for a given input vector of key gas ratios $(r^{\nu}_1\, r^{\nu}_2\, r^{\nu}_3)$. A value of $y^{\nu}_{res} = 1$ doubtless identifies the measurement input as dielectric fault, as indicated by equation 8.5.

$$\begin{aligned} y^{\nu}_{res} = \bot_{ac} \Big\{ &\top_{ag}\left[\mu_{r_{1,1}}\left(\underline{p}_{r_{1,1}}, r^{\nu}_1\right), \mu_{r_{2,1}}\left(\underline{p}_{r_{2,1}}, r^{\nu}_2\right), \mu_{r_{3,1}}\left(\underline{p}_{r_{3,1}}, r^{\nu}_3\right)\right], \\ &\top_{ag}\left[\mu_{r_{1,2}}\left(\underline{p}_{r_{1,2}}, r^{\nu}_1\right), \mu_{r_{2,2}}\left(\underline{p}_{r_{2,2}}, r^{\nu}_2\right), \mu_{r_{3,2}}\left(\underline{p}_{r_{3,2}}, r^{\nu}_3\right)\right]\Big\} \end{aligned} \tag{8.5}$$

Aggregation within both parts of the rule's premise is performed individually by applying a product T-norm (denoted by $\top_{ag}$ in figure 8.6). Accordingly, their negations make use of the probabilistic sum operator. Finally, both parts of the premise are merged by applying a maximum-type accumulation operator $\bot_{ac}$. Due to the applied maximum T-conorm, the resulting partial derivatives with respect to the model parameters have a slightly different form than in section 8.2.1. In particular, for each input dataset $\{(\tilde{r}^{\nu}_1\, \tilde{r}^{\nu}_2\, \tilde{r}^{\nu}_3), \tilde{y}^{\nu}_{res}\}$ only the part of the premise whose aggregation result is higher is trained. Equations G.7 and G.8 in appendix G.3.1 show the partial derivatives of the mean square approximation error ϵ used for learning of the first and second part in the premise, respectively.

A procedure similar to the one already described in section 8.2.1 has been adopted so as to check the performance of the learning algorithm: in total, $s = 10000$ reference input vectors $(\tilde{r}^{\nu}_1\, \tilde{r}^{\nu}_2\, \tilde{r}^{\nu}_3)$ with $\tilde{r}^{\nu}_i \in [0; 4]$, $i = 1, 2, 3$ were randomly generated. Each input vector was interpreted according to IEC 60599 providing a corresponding dielectric fault assessment $\tilde{y}^{\nu} \in \{0; 1\}$ as reference output, where a value of one (zero) indicates presence (absence) of a dielectric fault.

The partially overlapping membership functions in the rule's premise (e.g. ratio 1 higher than 1 in the first part and between 0.6 and 2.5 in the second) were initially expected to cause difficulties during learning. In particular, if both parts of the premise had to be trained simultaneously, it was expected that learning would result to one and the same membership function per input, consisting of the union of the respective membership functions (e.g. for the first ratio this would mean higher than 0.6). However, due to the fact that only the part of the premise with the highest aggregation result was trained at a time, the learning algorithm performed well and identified distinct membership function for each part. Only 57 iterations and a computation time of 40.8 seconds were needed to achieve an approximation accuracy of $\epsilon < 10^{-2}$. The resulting estimates for the scale parameters in equation 8.4 showed a deviation from their reference values in IEC 60599 which varied between $\pm 1.5\,\%$ and $\pm 6\,\%$.

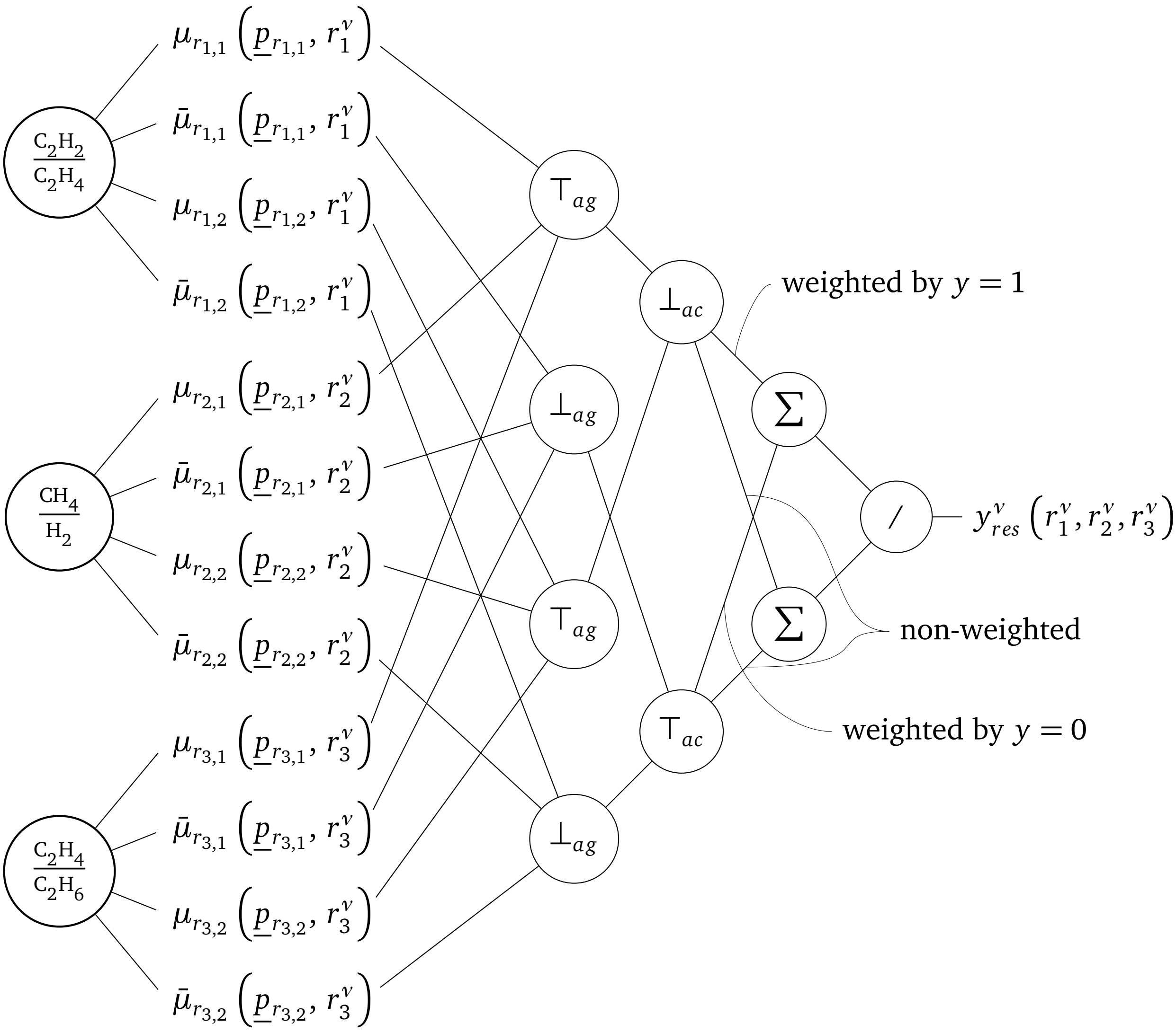

Figure 8.6.: Fuzzy interpretation scheme for classification of dielectric faults. The far left layer comprises the key gas ratios as crisp values, which are then fuzzified in the next layer. Membership functions $\mu_{r_{1,1}}$, $\mu_{r_{3,1}}$ and $\mu_{r_{3,2}}$ are of the "higher than" type (increasing sigmoid functions), while $\mu_{r_{1,2}}$, $\mu_{r_{2,1}}$ and $\mu_{r_{2,2}}$ are of the "between" type (bell-shaped). In total, two rules and their negations are used for fault classification (reflecting fault types D1 and D2 as in IEC 60599). The rules are merged using the T-conorm $\bot_{ac}$.

8.2.3 Learning fuzzy model for thermal faults

IEC 60599 provides three rules for thermal fault classification depending on the temperature reached at the fault location, as given in the last three rows of table 6.12. These rules have to be merged, since no distinction between low and high energy faults has been made during fault classification in section 8.3. The accumulated rule to be used for learning is thus:

if ratio 2 is higher than 1 *and* ratio 3 is lower than 1
or if ratio 1 is lower than 0.1 *and* ratio 2 is higher than 1 *and* ratio 3 is between 1 and 4
or if ratio 1 is lower than 0.2 *and* ratio 2 is higher than 1 *and* ratio 3 is higher than 4
then fault type is thermal

The above expression contains relations of the "lower than ...", "higher than ..." and "between ..." type. Respectively, decreasing and increasing sigmoid functions as well as generalised bell-shaped functions were applied (refer to appendix G.1). The resulting membership functions are shown in equation 8.6.

Again, the second index of the membership functions implies the respective part in the rule's premise, i.e. equation 8.6d refers to the first part, equations 8.6a and 8.6e to the second and equations 8.6b and 8.6f to the third part. Finally, the membership function for the second key gas ratio $\mu_{r_2}(r_2)$ is the same for all parts in the premise, since the one and same threshold value is provided for all three rules in the IEC 60599 interpretation scheme.

Special care must also be taken with the scale parameters in equations 8.6d and 8.6f ($c_{3,1}$ and $c_{3,3}$ respectively). For key gas ratio 3, the interpretation scheme in table 6.12 uses common threshold values in the three rules. The same approach has been adopted also in the fuzzy interpretation scheme, with the scale parameters $c_{3,1}$ and $c_{3,3}$ being substituted as: $c_{3,1} = c_{3,2} - a_{3,2}$ and $c_{3,3} = c_{3,2} + a_{3,2}$.

$$\mu_{r_{1,2}}(r_1) = \frac{e^{-a_{1,2}(r_1 - c_{1,2})}}{1 + e^{-a_{1,2}(r_1 - c_{1,2})}} \quad (8.6a)$$

$$\mu_{r_{1,3}}(r_1) = \frac{e^{-a_{1,3}(r_1 - c_{1,3})}}{1 + e^{-a_{1,3}(r_1 - c_{1,3})}} \quad (8.6b)$$

$$\mu_{r_2}(r_2) = \frac{1}{1 + e^{-a_2(r_2 - c_2)}} \quad (8.6c)$$

$$\mu_{r_{3,1}}(r_3) = \frac{e^{-a_{3,1}(r_3 - c_{3,1})}}{1 + e^{-a_{3,1}(r_3 - c_{3,1})}} \quad (8.6d)$$

$$\mu_{r_{3,2}}(r_3) = \frac{1}{1 + \left| \frac{r_3 - c_{3,2}}{a_{3,2}} \right|^{2b_{3,2}}} \quad (8.6e)$$

$$\mu_{r_{3,3}}(r_3) = \frac{1}{1 + e^{-a_{3,3}(r_3 - c_{3,3})}} \quad (8.6f)$$

The complete fuzzy model for thermal fault interpretation is shown in figure 8.7. Each pair of aggregation operators $\top_{ag}$ and $\perp_{ag}$ stands for one of the three rules and its negation: the first rule (T < 300° C) is at the top part of the figure, while the last one (T > 700° C) is at the bottom part. For a given input vector of key gas ratios $(r_1^v \; r_2^v \; r_3^v)$ the output of the model y_{res} is calculated as:

$$\begin{aligned} y_{res}^v = \perp_{ac} \Big\{ & \top_{ag} \left[\mu_{r_{1,1}}\left(\underline{p}_{r_{1,1}}, r_1^v\right), \mu_{r_2}\left(\underline{p}_{r_2}, r_2^v\right), \mu_{r_{3,1}}\left(\underline{p}_{r_{3,1}}, r_3^v\right) \right], \\ & \top_{ag} \left[\mu_{r_{1,2}}\left(\underline{p}_{r_{1,2}}, r_1^v\right), \mu_{r_2}\left(\underline{p}_{r_2}, r_2^v\right), \mu_{r_{3,2}}\left(\underline{p}_{r_{3,2}}, r_3^v\right) \right], \\ & \top_{ag} \left[\mu_{r_{1,3}}\left(\underline{p}_{r_{1,3}}, r_1^v\right), \mu_{r_2}\left(\underline{p}_{r_2}, r_2^v\right), \mu_{r_{3,3}}\left(\underline{p}_{r_{3,3}}, r_3^v\right) \right] \Big\} \end{aligned} \quad (8.7)$$

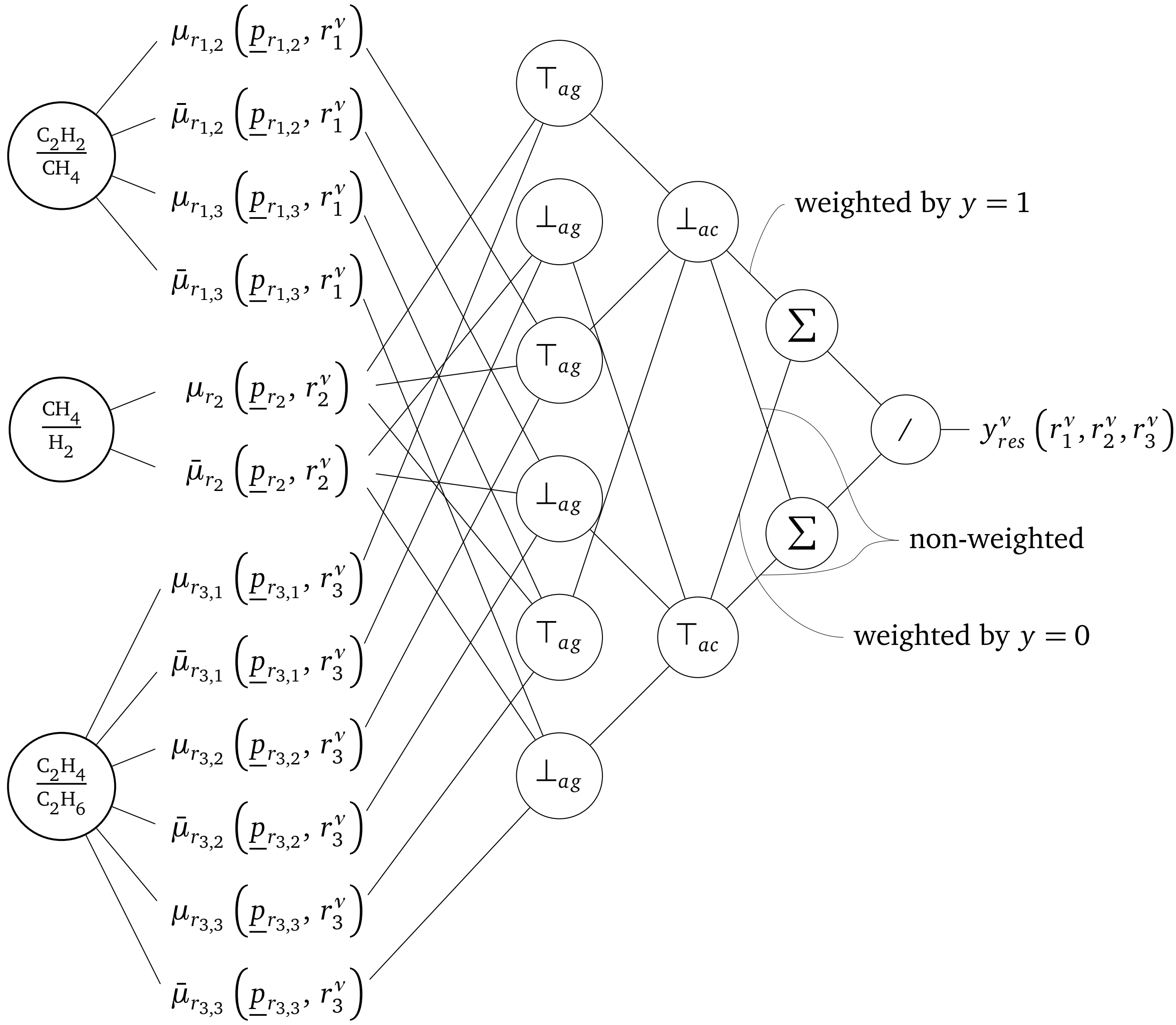

Figure 8.7.: Fuzzy interpretation scheme for thermal fault classification. In total, three classification rules (thermal faults with T $<$ 300° C, 300° C $<$ T $<$ 700° C and T $>$ 700° C, respectively, as in IEC 60599) and their negations are implemented. Each rule is modelled by an aggregation T-norm $\top_{ag}$, its negation by the corresponding T-conorm $\perp_{ag}$. The rules are finally accumulated using the $\perp_{ac}$ operator and defuzzified in the last two layers to the right.

In particular, product T-norms and probabilistic sum T-conorms have been used for aggregation of each part of the rule's premise, similarly to the fuzzy learning models for partial discharges and dielectric faults. Also, a maximum-type accumulation operator $\perp_{ac}$ is applied so as to merge the aggregation results of all parts. Accordingly, during learning only the part of the premise whose aggregation results is highest is trained. The partial derivatives of the mean square approximation error ϵ used with the RPROP learning algorithm are given in appendix G.3.2.

The learning algorithm was tested under the same procedure as in sections 8.2.1 and 8.2.2: 10000 randomly generated reference input vectors and their (thermal) fault classification according to IEC 60599 $\{(\tilde{r}_1^\nu\ \tilde{r}_2^\nu\ \tilde{r}_3^\nu),\ y_{res}^\nu\}$ formed the training database.

The algorithm performed well and reached an approximation accuracy of $\epsilon < 10^{-3}$ in only 121 iterations with a total computational time of 77.4 seconds. The resulting estimates for the scale parameters in equation 8.4showed a deviation of less than $\pm 2\,\%$ from their reference values in IEC 60599.

8.2.4 General comments on learning fuzzy models for DGA interpretation

At this point, some general remarks on the fuzzy interpretation models presented in the previous sections shall be outlined. Due to the fact that fault classification in section 8.3 does not distinguish between high and low energy faults, the fuzzy models for dielectric and thermal faults used merged interpretation rules. With respect to the performance of the learning algorithm, following has been experienced:

- In general, a high approximation accuracy could be reached with low computational cost. Computation time largely depends on the size of the learning database (number of reference input-output datasets), whereas the number of iteration the algorithm needs to converge depends mainly on the layout of the fuzzy model (i.e. number of rules and membership functions).
- The scale parameters obtained after training were very close to the values in IEC 60599 used for learning. Deviations were within acceptable levels of up to $\pm 6\,\%$.
- On the other hand, learning resulted in very high values for the shape parameters (i.e. the resulting membership function were very steep). The reason is that, during learning, the reference output for each dataset has been evaluated by interpreting the (randomly generated) input ratios according to IEC 60599, which itself is of binary nature. As a result, higher approximation accuracy is reached for steeper membership functions. In case real measurements (showing some fuzziness) are used as learning input, this trend might not be that pronounced. Anyway, shape parameters are rather irrelevant for the present case study, since the adapted threshold values for DGA interpretation are solely defined by the scale parameters.
- Especially for the dielectric fault interpretation model in section 8.2.2, it turned out that, by using a maximum-type operator for rule merging, potential problems of overlapping membership functions can be overcome.
- The learning algorithm extracts information from both positive and negative fault classification of the reference datasets (i.e. presence or absence of fault). In the extreme case

of having input datasets with solely positive (negative) diagnosis, the membership functions will tend to have a very large (narrow) support, so as to include (exclude) all inputs. Typically, significantly more input data with a negative diagnosis (no fault) will be available. In order to avoid falsification of the results, appropriate adaptation of the objective function in equation 2.44 will be necessary in this case. A practical approach could be to partition the learning database into positive and negative fault classification, calculate the approximation error for each partition separately and then use their average value in the objective function. This approach was used during learning in sections 8.2.1 to 8.2.3 with the adapted mean square approximation error calculated as in equation 8.8. The first term accounts for all datasets with positive fault classification (with s_1 being their respective number), while the second term comprises all datasets with negative fault classification.

$$\epsilon = \frac{1}{2s_1} \sum_{\nu:\tilde{y}^\nu=1} \left(y_{res}\left(\underline{p}_1, \underline{p}_2, \ldots, \underline{p}_n, \underline{\tilde{x}}^\nu\right) - \tilde{y}^\nu \right)^2 + \frac{1}{2s_2} \sum_{\nu:\tilde{y}^\nu=0} \left(y_{res}\left(\underline{p}_1, \underline{p}_2, \ldots, \underline{p}_n, \underline{\tilde{x}}^\nu\right) - \tilde{y}^\nu \right)^2 \quad (8.8)$$

Summing up, the learning fuzzy models presented in the previous sections are both accurate and reliable. They can therefore be applied to estimate adapted threshold values for DGA interpretation in accordance with the general structure provided in IEC 60599 for measurements obtained in the field. This will be shown in the section 8.4 for the case study of power transformers introduced in the next section.

8.3 Overview of data available for investigation

The case study presented here is based on information from a database on power transformer failures and dissolved gas measurements maintained by the Institute for Electrical Power & Energy, Technische Universität Darmstadt [8.41]. The necessary data was extracted after careful filtering and verification of its plausibility [8.42]. In particular, all transformers in the database for which relevant information[20] was missing have been excluded from further investigations. In addition, the plausibility of the available loading classification has been checked in accordance with section 8.1. Again, data entries which appeared to be implausible have been excluded. The resulting database used for this case study is summarised in table 8.2.

As expected, the number of step-down transformers in the database is significantly higher, reflecting the situation in actual transmission systems. However, monitoring intensity by means of DGA for such transformers is lower than for generator step-up or system intertie transformers, as demonstrated by the average number of gas measurements per transformer (approximately 8 measurements compared to 27 and 22, respectively). This is due to the higher importance of the latter units.

It has to be stressed out that information on dissolved gases is only provided for the years after 1970. It seems that utilities participating in the survey either did not follow a systematic DGA plan prior to that time, or –most probably– older measuring results are only provided in

[20] Following information was regarded as essential during data filtering: rated voltage (primary/secondary), rated power, installation year, loading classification (generator/grid/step-down/distribution/industrial/other), presence or absence of an on-load tap-changer, manufacturer and serial number.

Table 8.2.: Extract from the database on power transformer failures and dissolved gas measurements used in this case study [8.41]. In total, three transformer types were investigated. Datasets have been filtered so as to exclude incomplete or implausible data entries.

	Generator step-up	System intertie	Step-down
number of transformers	86	127	1205
on-load tap-changer (with/without)	82/4	81/46	1,159/46
installation year (from ... to ...)	1957 – 1998	1929 – 2003	1935 – 2004
average service age (in years)	31.3	40.5	34
number of gas measurements	2,331	2,772	9,752
number of registered failures	80	159	243

paper form and are not digitised yet. Nevertheless, the information available in the database (approximately 15,000 respective entries[21]) is regarded to be sufficient for the present case study, also taking into account that failures in power transformers are more likely to happen with increasing service age.

The available data on dissolved gases were analysed so as to obtain typical gas concentrations for the power transformers in the database. In particular, the 90 and 95-percentiles for the different transformer loading types were determined as proposed in IEC 60599. Table 8.3 shows the 90-percentiles for the relevant gases. For all investigations to follow, these values are regarded as *typical gas concentrations*. More detailed statistical information on the measured gas concentrations is provided in appendix G.4.

The typical gas concentrations evaluated for generator and step-down transformers seem to be in line with values reported in the literature [8.32]. On the other hand, values obtained for system intertie transformers were significantly higher for reasons not yet clarified. One possible explanation is that higher gas concentrations could be a result of the higher average service age for such transformers. Design issues[22] or issues related with the applied transformer oil in earlier years may also play a role.

Table 8.3.: 90-percentiles of the relevant dissolved gases for the transformer fleet of table 8.2. The last row is an extract of typical concentrations provided by the IEC TC 10 [8.32]. All values are in parts per million (ppm).

Transformer type	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
Generator step-up	146	60	53	203	80	667	12,000
System intertie	263	237	48	591	250	500	5,407
Step-down	91	30	78	60	30	283	4,567
IEC TC 10 [8.32]	60–150	40–110	3–50	60–280	50–90	540–900	5,100–13,000

21 Note that each data entry comprises a complete measurement series, that is a series of measuring results for all relevant dissolved gases.

22 System intertie transformers are sometimes designed as shell-type units. According to Cigré statistics, shell-type transformers demonstrate higher gas concentrations during service (compare table 6.6).

Data from dissolved gas measurements is the one source of information needed by the learning fuzzy system described in the previous section 8.2; the other source comprises the respective fault classification. Table 8.2 also summarises the available information on transformer failures. Approximately 480 faults are registered in the database, together with their date of occurrence and any potential alarm notification by the protection system. In the original database, registered faults are classified by their fault location[23], failure mode and failure effect. Although the available fault classification scheme was not designed for the purpose of FMEA, it has considerable similarities with such an approach[24].

The aforementioned fault classification is –in its original form– not suitable for training the learning fuzzy model of section 8.2. Instead, a classification of faults in the categories "partial discharge", "dielectric fault" and "thermal fault" is necessary. Accordingly, the 210 fault types defined in the database were mapped to these three general fault classes by subjective assessment[25]. The last column of table G.3 in appendix G.5 shows the assessment results. As can be seen there, for most failure modes a doubtless classification is not possible because of missing information in their description (the respective failure modes are labelled as "not defined"). Keeping this in mind, a detailed classification in low and high-energy faults as in table 6.12 did not seem reasonable, therefore dielectric and thermal faults were grouped together in one class each. Also note that some failure modes in table G.3 may be linked to more than one of the three general fault classes.

Generally speaking, most failure modes of the secondary system (control and protection) as well as those of external causes were assumed to have no influence on the transformer's internal insulation. Furthermore, for transformers equipped with an on-load tap-changer all failure modes of the diverter have been excluded, since all such transformers in the database featured a separate oil compartment for the diverter switch [8.43]. On the other hand, failures of the tap selector have been considered, because the latter is often located inside the transformer's main tank [8.5].

After re-classification, a total of 86 entries for partial discharge failures, 81 entries for dielectric failures and 20 entries for thermal failures were identified for training the learning fuzzy model[26]. The next task is to investigate the dissolved gas measurements available in the database and to classify them as such corresponding to healthy transformers or to transformers registered with a partial discharge, dielectric or thermal fault.

Following procedure has been adopted for this purpose: With regard to each of the three general fault classes, transformers have been categorised to units either affected or not affected by the particular fault. All dissolved gas entries obtained from measurements at healthy units were then stored as non-indicative for the respective fault class (i.e. the consequence of interpreting

23 The location of the fault is identified by the affected *system* (tank, active parts, cooling system, bushings, on-load tap-changer, control system), *component* (e.g. cooling pump, winding or core) down to the failed *part* (e.g. bearing of the cooling pump). A more detailed classification is given in table G.3, appendix G.5.

24 A *Failure Mode and Effect Analysis* (FMEA) is an analytic procedure used in production development for identifying potential failure modes. Failures are assessed in a hierarchical way (top-down approach) along with their probability of occurrence and severity. In contrary to the classification provided by the failure database in this case study, FMEA is an a priori procedure, i.e. failures are assessed prior to their occurrence.

25 Table 23.1 in [8.4] provides an example for linking failures grouped by the affected component with one of the three general fault categories.

26 As some transformers had more than one registered fault of the same type, the respective number for transformers failing is somewhat lower (63, 61 and 13 transformers for partial discharges, dielectric and thermal faults, respectively).

Table 8.4.: Number of entries in the database to be used for learning purposes. Each data entry comprises a complete set of measurements for all relevant dissolved gases.

Entries indicative for ...	partial discharges	dielectric fault	thermal fault
... positive diagnosis	183	182	26
... negative diagnosis	13,668	13,727	14,530

these measuring results should be a negative fault diagnosis). On the other hand, for units affected by the particular fault, only dissolved gas measurements obtained within five years prior to failure have been considered and labelled as indicative for a positive diagnosis. The resulting number of dissolved gas measurements available for training is given in table 8.4 for each fault class[27]. Obviously, much more data entries linked to a negative diagnosis are available, since transformer failure in service are very seldom.

Approximately only 10 % to 20 % of the data sets in table 8.4 feature measuring results exceeding the respective typical values of table 8.3. However, for training purposes regarding the key gas ratios incorporated in the learning fuzzy models of section 8.2, the input does not have to comprise only abnormal values and all available information should be used in order to enhance the learning performance. It should also be noted that no distinction between the different transformer loading types has been made here, since this aspect is considered within the first step of DGA interpretation (by comparing the measuring results with the typical gas concentrations, refer to figure E.5). The next section gives an overview of the results achieved by training the learning fuzzy models of section 8.2 with the transformer data described above.

8.4 Results and discussion

Before training of the proposed learning fuzzy models can begin, the dissolved gas data described in the previous section have to be transformed to appropriate key gas ratios. In particular, the ratios C_2H_2/C_2H_4, CH_4/H_2 and C_2H_4/C_2H_6 must be calculated. In order to avoid falsification of the results by very low measured concentrations of the gases in the denominator of the aforementioned ratios, all data entries lower than the respective detection limit have been ignored. According to IEC, the detection limit of gases dissolved in oil amounts 1 ppm by volume for hydrocarbons and 5 ppm by volume for hydrogen. These values are valid for measurements during service, lower detection limits apply for laboratory conditions [8.44].

Because of the large mismatch in the size of the training database for positive and negative diagnoses, equation 8.8 was used as performance measure. The fuzzy models of sections 8.2.1 to 8.2.3 were trained individually and needed only 100 to 150 iterations to converge. Table 8.5 shows the original and adapted thresholds for the applied IEC DGA interpretation scheme. Only the scale parameters of the membership functions in equations 8.1, 8.4 and 8.6 are shown here; complete information on both shape and scale parameters prior to and after training is given in appendix G.6.

[27] The fact that the sum of data entries for any fault class does not equal the total number of available dissolved gas measurements (14,855 – compare table 8.2) is because measurements at transformers known to have had the respective fault which were obtained prior to five years before failure are not considered for any diagnosis –positive or negative.

Table 8.5.: DGA interpretation with adapted thresholds resulting from training. The structure of the interpretation scheme is the same as in IEC 60599, only the thresholds are updated (values in parentheses are the original thresholds in the standard, compare table 6.12).

	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	–	$< 0.13^a$ (< 0.1)	< 8.78 (< 0.2)
D1	> 0.975 (> 1)	0.43 to 0.44 (0.1 to 0.5)	> 1.19 (> 1)
D2	0.91 to 2.04^a (0.6 to 2.5)	0.06 to 1.03^a (0.1 to 1)	> 1.76 (> 2)
T1	–	>0 (> 1)	< 1.11 (< 1)
T2	< 0.67 (< 0.1)	> 0 (> 1)	1.11 to 3.20 (1 to 4)
T3	< 0.68 (< 0.2)	> 0 (> 1)	> 3.20 (> 4)

[a] The fuzzy entropy associated with these membership functions is very high due to the corresponding low shape factors (compare appendix G.6). Accordingly, no information can be obtained from the respective inputs; in other words, the respective key gas ratios are irrelevant for the rules they are involved in. Refer also to footnote 28.

The learning algorithm performed quite well and converged after only 100, 150 and 120 iterations for the fuzzy models on partial discharges, dielectric faults, and thermal faults, respectively. In the course of training, the classification accuracy of DGA interpretation was enhanced, as can be seen in table 8.6. Before training, approximately every second dissolved gas measurement was falsely interpreted; after training, the classification error could be significantly decreased down to less than 30 %. Figure 8.8 exemplarily shows the development of the classification error during training for the learning fuzzy model on partial discharges.

During training, the shape parameters of several membership functions converged to very low values (see footnote in table 8.5). For example, the shape parameter of the second ratio's membership function in the first rule of table 6.12 (a_2 in equation 8.1a) approaches zero with ongoing training, as can be seen in appendix G.6. The result is a very high *entropy*[28] of the respective fuzzy set. In other words, the ambiguity of this input variable is high with respect to the particular rule: the second ratio is thus *irrelevant* for the rule. This effect occurred while training the fuzzy models on partial discharges and dielectric faults, but not for the model on thermal faults.

Table 8.6.: Classification error of the learning fuzzy models before and after training, measured by the mean square approximation error ϵ of equation 8.8. Since the value of ϵ is in the range $[0; 1]$, it directly reflects the (in)accuracy of DGA interpretation.

	partial discharges	dielectric faults	thermal faults
before training	50.23 %	57.48 %	52.14 %
after training	26.58 %	16.30 %	28.51 %

[28] The entropy of a fuzzy set describes the ambiguity of associated information: the highest the entropy, the highest will the ambiguity of the fuzzy variable be. Refer to section 2.2.1 for a definition of fuzzy entropy.

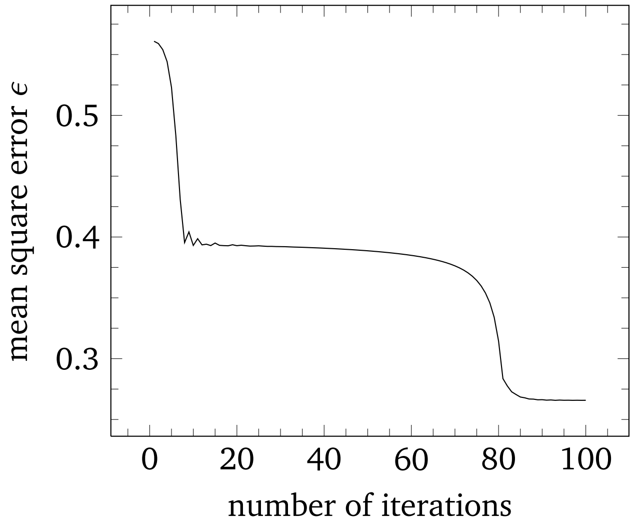

Figure 8.8: Classification error of the fuzzy model on partial discharges as a function of the number of iterations. The learning algorithm converges after overcoming one local minimum.

The reason for this effect is the lack of a specific *pattern* in the training data. If the classification result in the training database is independent of an input variable, the ambiguity associated with this variable is high, and so should also the entropy of the corresponding fuzzy set be. For example, figure 8.9 illustrates the classification pattern of the training database used with the fuzzy model on partial discharges. The dark blue dots are data entries corresponding to negative diagnosis (healthy transformers), while entries for positive diagnoses are denoted by light red dots. Obviously, classification depends more on the value for ratio 3 rather than on ratio 2. For this reason, training focusses on the third ratio, while the algorithm keeps the influence of the second ratio low by increasing its fuzzy entropy, that is by decreasing the shape parameter of the respective membership function.

As can be seen in table 8.5, some thresholds did not change significantly during training (e.g. the threshold for ratio 3 in rule T1), while others changed a lot (e.g. ratio 3 in rule PD). Table 8.6 also makes clear that –generally speaking– training improves the accuracy of DGA interpretation. However, the fact that some sets of the fuzzy models, in particular the ones defined by $\mu_2(r_2)$ (model on partial discharges) as well as $\mu_{1,2}(r_1)$ and $\mu_{2,2}(r_2)$ (model on

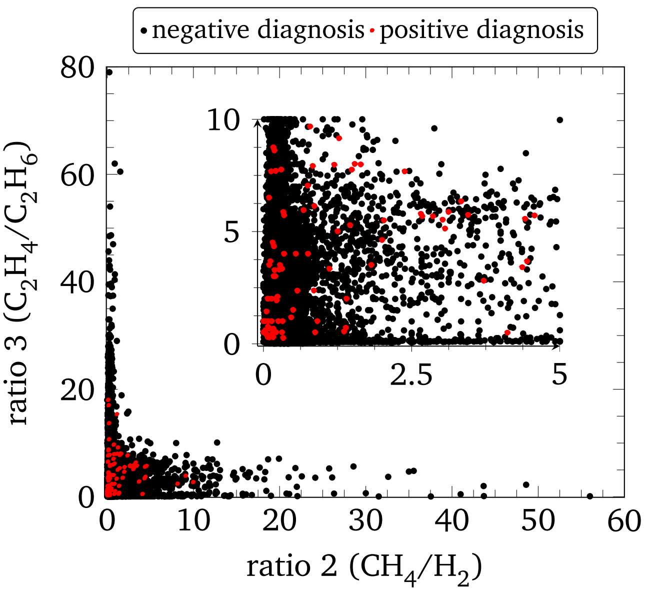

Figure 8.9: Classification pattern of the training database for the learning fuzzy model on partial discharges. The learning algorithm identified ratio 3 as relevant for classification and assigned a very low influence to ratio 2 by decreasing the shape factor of its membership function, thus increasing the associated fuzzy entropy.

dielectric faults), tended to high entropies during training undermines the requirement for a pre-defined interpretation scheme (with a rule base structured as in IEC 60599), since the input variables related to the particular sets are not relevant for the rules any more.

Summing up, following conclusions were drawn from the application of the learning fuzzy models proposed in this thesis to the dissolved gas data of section 8.3:

1. The combination of the learning fuzzy models with the resilient backpropagation algorithm ensured a very reliable and fast learning behaviour. In particular, the learning algorithm could overcome local minima and converge to values well beyond the initial values assumed for the parameters of the membership functions (compare figure 8.8). Keeping in mind the very fast learning behaviour (resulting from the use of derivatives in the update formulae), it is also possible to define a rough partitioning of the solution space and run the learning algorithm for several initial conditions. Such investigations were made exemplarily while training the fuzzy model on partial discharges and showed that the initial conditions had little influence on the final result.

2. When the learning algorithm is applied to models with high number of parameters (one speaks of *high-dimensional optimisation problems*) a slight modification of the standard RPROP algorithm was found to deliver better results with respect to learning speed and stability. In particular, the update formula 2.45a in figure 2.4 was extended by a random coefficient $\beta^t_{i,j} \in [0;1]$:

$$p^{t+1}_{i,j} = p^t_{i,j} - \beta^t_{i,j} \cdot h^t_{i,j} \cdot \operatorname{sgn}\left(\frac{\partial \epsilon^t}{\partial p_{i,j}}\right) \tag{8.9}$$

   Since the random coefficient is only applied when updating the parameters, but not while calculating each parameter's learning rate $h^t_{i,j}$, its average influence on the training result can be neglected for a sufficiently high number of iterations (note that the learning rate at each step $h^t_{i,j}$ is calculated from the learning rate in the previous step $h^{t-1}_{i,j}$, compare equation 2.45b in figure 2.4). The main objective of introducing the random coefficients is to provide some means of time shift when updating the model's parameters. This is especially important for high-dimensional problems, where updating one parameter might have some influence on other parameters. The modified learning algorithm was applied while training the fuzzy model on dielectric faults (15 parameters in total).

3. The training database from section 8.3 was found to have no obvious or simple patterns for DGA interpretation (compare figure 8.9 for the training database on partial discharges). Therefore, fitting the IEC interpretation scheme to the available data did not work well in all cases, especially not for the fuzzy models on partial discharges and dielectric faults. In these two cases, training the parameters for several membership functions ($\mu_2(r_2)$ for the model on partial discharges, equation 8.1, and $\mu_{1,2}(r_1)$, $\mu_{2,1}(r_2)$ as well as $\mu_{2,2}(r_2)$ for the model on dielectric faults, equation 8.4) failed insofar as the respective fuzzy sets turned to be absolutely ambiguous. In other words, the resulting degree of membership for these input variables would always amount 50 % no matter the input value; the particular input variables would therefore be irrelevant for the interpretation result.

   The reason for this effect is obvious: by trying to impose a specific type of membership function, e.g. a "lower than ..." type in the interpretation rule for partial discharges, to the data, we run the risk of poor data fitting. For the example in figure 8.9, a "between . . . " type membership function would provide better results. If the accuracy of the best possible classification with the assumed membership function type does not exceed the threshold of 50 %, the learning algorithm will tend to "turn off" the respective input variable.

4. Finally, the quality of the training data itself is not optimal. The first problem is related with the structure of the database: faults are classified by their location and not according to more general characteristics, that is if they are of dielectric or thermal nature. It is thus difficult to identify which dissolved gas data correspond to which general fault class.

   However, this is not the only drawback of the database used in this case study. Other aspects, too, demonstrate that the database has not been designed with DGA as main objective in mind. For example, no information on the oil preservation system of the power transformers is provided. Furthermore –and much more important– the type of transformer oil is not listed, although it has large influence on the transformer's gassing behaviour. It must always be kept in mind that even the best adaptive DGA interpretation scheme cannot perform better that background data allows.

In this chapter, a learning DGA interpretation method has been proposed and implemented. The main requirement was to maintain the structure of the IEC interpretation scheme and update only its threshold values. For this reason, learning fuzzy models were developed and trained according to a large power transformer failures and DGA database. The main conclusion is that:

> *When a data-driven, adaptive DGA interpretation scheme based on fuzzy logic is asked for, it makes little sense to prescribe the complete layout of the fuzzy model (rule base and type of membership functions).*

Applying black box models e.g. artificial neural networks or support vector machines, or adaptive fuzzy models where the rule base results from training, is rather a more appropriate choice for data-driven DGA optimisation.

9 Conclusions

During the last two decades the importance of maintenance for electricity supply systems has increased due to the changing business environment. Effective assessment of the condition of installed equipment can assist in making the right decisions on servicing or replacing and therefore boost the performance of maintenance. This thesis demonstrates the potential of fuzzy logic for the purpose of condition assessment and diagnostic analysis in electric power systems by means of practical examples.

At first the notion of condition assessment has been defined in chapter 3 as "a process of analysis and synthesis for estimating the condition of a piece of equipment according to a set of criteria". A systematic approach has been presented which derives the scope of condition assessment from the general scope of decision making on maintenance. It involves the identification of appropriate condition indicators according to which relevant information must then be collected. The second step in condition assessment aggregates several condition indicators into one estimate for the condition of the equipment. The most common aggregation method applied in practice uses condition assessment matrices, featuring a set of weights for the various condition indicators. The discussion in chapter 3 addressed some inherent limitations of this aggregation method, by showing its resemblance to multi-criteria decision making. The major limitation has been identified in the inconsistency of the assessment result in case of missing information. In view of this discussion, and by considering the fact that condition assessment matrices cannot properly treat uncertainty, which however is inherent in the assessment process, the thesis proposed the use of fuzzy systems for this purpose.

The first fuzzy system, presented in chapter 4, has been designed in consultation with maintenance experts from an electric power utility for strategic condition assessment of high-voltage circuit breakers with the objective of assisting in planning long and medium-term maintenance and replacement. Assessment of different types of circuit breakers was made on the basis of the accumulated service experience with the applied technology, the utility's overall maintenance experience and the average cost of maintenance. The fuzzy rule base has been defined in a simple heuristic way and consisted of approximately sixty rules. An advantage of this approach is that fuzzy rules can be derived from a condition assessment matrix, in case such a matrix is already available. The required consistency of assessment results obtained from the fuzzy system in case of missing information could also be confirmed.

The design of a fuzzy system for operational condition assessment, focusing on day-to-day maintenance rather than medium to long term maintenance optimisation, in a heuristic manner can be quite tedious due to the high number of available information sources. For this reason, an alternative design approach has been proposed in chapter 5 using once again the example of condition assessment of high-voltage circuit breakers. The circuit breakers have been divided into functional units comprising the drive mechanism, the live parts, the inner and outer insulation, the switching unit and the control unit. Assessment was based on data obtained from on-line monitoring systems or from diagnostic tests conducted during preventive maintenance activities as well as on the combination of the general service experience, expressed in the form of statistics, with information about the stresses a particular circuit breaker has been subjected to during service. Every source of information has been then correlated to each functional unit by means of confidence factors which describe the degree of insight the first can provide into the condition of the latter. The determination of confidence factors was mainly based on maintenance recommendations by Cigré. With confidence factors thus resolving the problem of potentially contradictory sources of information, the rule base could be greatly simplified. The presented design approach allows for easy realisation of fuzzy systems for operational condition assessment and provides a good overview of the implemented rule base.

In the second part of the thesis, the application of fuzzy logic for diagnostic analysis has been discussed using the example of Dissolved Gas Analysis (DGA) of oil-filled equipment. In chapter 6 the theoretical background of evolution of gases in oil-impregnated paper insulating systems was described and a categorisation of available interpretation schemes for DGA into a general scheme has been elaborated. The extension of DGA interpretation by fuzzy logic has been then studied on the basis of the standard interpretation scheme according to IEC 60599.

In order to evaluate the added value by applying fuzzy reasoning to DGA, chapter 7 presented a case study on DGA of high-voltage instrument transformers according to both the standard and extended interpretation scheme. The case study not only confirmed the superior detection accuracy of fuzzy DGA interpretation, but also demonstrated how a confidence factor can be provided for the proposed diagnostic finding. From the devices known to have an internal fault (e.g. by measurement of partial discharges or by means of visual inspection after disassembly) some were detected by the extended interpretation scheme, but not by the standard one. In addition, the provided confidence factor can be used as a measure of how reliable the finding is, thus better supporting decision making on further maintenance. A sensitivity analysis further demonstrated that, although the choice of the parameters of the fuzzy system has an influence on the resulting confidence factors, this effect is weak and can be easily counteracted by filtering diagnostic findings whose overall confidence factor is lower than a defined threshold. In summary, the case study in chapter 7 showed that the extension of existing interpretation schemes by fuzzy reasoning provides effective means for enhancing the applicability, accuracy and overall performance of dissolved gas analysis.

Finally, chapter 8 introduced an adaptive fuzzy system for DGA interpretation. The motivation has been to adapt the IEC interpretation scheme to a large sample of power transformers for which both measurements of dissolved gas concentrations as well as information about failures and defects during service were available. Using a fuzzy system for this purpose rather than a black-box model e.g. an artificial neural network allows for a direct comparison of the adapted interpretation scheme with the initial, standard one. The rule base of the fuzzy interpretation system has been a priori defined according to the IEC scheme, and the underlying fuzzy sets included in the rules' premises have been described parametrically. These parameters were then adapted by means of supervised learning. A comparative investigation of possible learning algorithms provided evidence of the superior performance of the resilient backpropagation algorithm, which was then employed for learning. Before training the fuzzy system on the sample data, a series of trials were successfully conducted in order to ensure that the system can adapt to patterns in the training data base.

Data used for training the fuzzy system originated from a large data base on high-voltage power transformers, including failure statistics and measurements of dissolved gas concentrations. However, it quickly became obvious that the data base has not been originally designed with DGA as main objective in mind: faults and defects were not labelled according to their nature, but rather according to the location of the fault. For this reason, and because of the large size of the data base, measurements corresponding to healthy and faulty transformers have been identified by means of automatic indexing.

The learning behaviour of the developed fuzzy system was limited by mainly two factors: The information available in the database was found to be insufficient for the purpose of adaptive DGA interpretation. For instance, no information was given about the type of insulating oil, which however has an large influence on its gassing behaviour and thus on the concentration of gases in the oil. Furthermore, the implemented process of automatic indexing could not effectively identify irrelevant measurements falsifying the result. The second limiting factor was a systematic one, originating from the design of the fuzzy system itself. Due to the strict requirement on the layout of the fuzzy rules, fitting the interpretation scheme to the pattern in the training data base did not work well in all cases. In some cases, training the parameters of the membership functions failed insofar as the respective fuzzy sets turned to be absolutely ambiguous. If the accuracy of the best possible classification with the assumed layout of a rule does not exceed the threshold of 50 %, the learning algorithm tends to "turn off" the respective input variable in order to enhance the overall accuracy of the interpretation scheme. The rules involved were then made irrelevant for the interpretation result. This of course undermines the requirement for a rule base according to the IEC interpretation scheme. In summary, the case study in chapter 8 demonstrated that when a data-driven, adaptive DGA interpretation scheme based on fuzzy logic is asked for, it makes little sense to prescribe the complete layout of the fuzzy model (rule base and type of membership functions).

Nevertheless, the applicability of fuzzy logic for the purpose of condition assessment and diagnostic analysis in electric power systems has been confirmed by the presented case studies. Fuzzy inference systems can properly treat the inherent uncertainties (inaccuracy of measurements, incomplete knowledge of applied stresses, approximate knowledge of failure and ageing mechanisms etc.) and yield useful results for decision making on further maintenance. Electric power utilities are therefore encouraged to introduce fuzzy logic to the process of condition assessment and diagnostic analysis; the case studies included in this thesis can serve as a guideline.

9.1 Recommendations and future work

Despite the wide acceptance of fuzzy logic in the scientific community, its application to maintenance issues in electric power systems has not been seriously considered yet. One of the objective of this thesis has been to identify possible fields of application, especially with regard to condition assessment and diagnostic analysis. The case studies presented here demonstrate the practicality of fuzzy inference systems in these fields. In order to further promote the introduction of fuzzy logic for maintenance in electric power systems, the co-operation of three actors is necessary.

Power utilities play the most crucial role in this process. As the owner and user of apparatus it is they that finally will decide whether fuzzy inference systems should be implemented or not, and how. Should power utilities show little willingness to develop and introduce fuzzy techniques for condition assessment processes, as unfortunately is the case today, no significant progress can be expected in the field. The reserved attitude of the electricity supply business is more than understandable – after all, the equipment is expected to be in operation for more than thirty years; introducing new risks is something one would want at least. However, without their wide service and maintenance experience, the design of fuzzy inference systems that reflect real-life ageing and failure mechanisms and provide meaningful recommendations for decision making is difficult.

The recommendation to power utilities would therefore be to develop simple fuzzy inference systems for the purpose of strategic condition assessment, as shown in the first case study of this thesis. This process can be based on existing assessment schemes, will require little time, take place in-house and involve only a handful of maintenance experts and ERP programmers. In case no existing assessment scheme is available, but is planned to be developed, a fuzzy inference system can be introduced right from the beginning. In addition, due to the simplicity of the system architecture, no deep knowledge of fuzzy logic is required.

Furthermore, power utilities should show their willingness to study the introduction of fuzzy techniques for maintenance purposes by bridging the gap to the fuzzy research community and exploring possible application fields. Being aware of the fact that the application of fuzzy logic or other techniques of artificial intelligence cannot be defined by any binding standard, they should take the initiative and launch pilot projects.

The second key player are equipment manufacturers. Similar to maintenance experts in electric power companies, manufacturers also have a deep insight in the failure mechanisms of their apparatus. It is remarkable, that although manufacturers are increasingly taking over maintenance from power utilities in the course of outsourcing, little effort has been yet made in order to capture maintenance and general engineering knowledge by means of fuzzy inference systems.

On the other hand, manufacturers are also in charge of introducing and developing diagnostic techniques. In some cases, as with dissolved gas analysis, many manufacturers offer computer-aided interpretation tools that feature fuzzy techniques besides the specified interpretation schemes. Further development of fuzzy systems can assist in extending the scope of such applications. For instance, the interpretation of graphical signals e.g. the timing characteristic of a circuit breaker or the comparison of two patterns used in the so-called “fingerprints method” could constitute interesting research areas for fuzzy logic. Of course, manufacturers can only introduce maintenance support tools based on fuzzy logic as long as utilities are willing to adopt and use them.

The third key player is the scientific community, especially the fuzzy research community. By means of research projects and practical case studies, researchers can help overcome the reserves of the electricity supply business. Research topics of particular interest may include the introduction of fuzzy inference systems for treating risks in maintenance and –more general– asset management as well as the use of extended fuzzy sets and fuzzy preference theory in order to provide fuzzy system for condition assessment which combine the experience of several knowledge carriers.

A Annex to chapter 2

A.1 Today's significance of fuzzy logic

Renowned journals on fuzzy logic, fuzzy sets and systems:

- Fuzzy Optimization and Decision Making
- Fuzzy Sets and Systems
- Fuzzy Systems and Soft Computing
- IEEE Transactions on Fuzzy Systems
- International Journal of Fuzzy Systems
- International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems
- International Review of Fuzzy Mathematics
- Journal of Intelligent & Fuzzy Systems
- Journal of Japan Society for Fuzzy Theory and Systems

Common application fields of fuzzy logic [A.1]:

- Mathematical modelling (approximation of non-linear equations)
- Natural language
- Data mining and knowledge engineering
- Bioinformatics
- Fuzzy control
- Pattern recognition
- Decision making
- Fuzzy visualization techniques [A.3]
- Fuzzy classification [A.4]:
  - Fuzzy rules by learning from examples [A.5, A.6]
  - Fuzzy decision trees [A.7]
  - Subsethood based method (SBM) [A.8]
  - Weighted fuzzy subsethood based rule induction method (WSBM) [A.9]
  - Hierarchical fuzzy systems [A.10]
  - Fuzzy signatures [A.11]

Table A.1.: Published research work on fuzzy logic (figures for July 2008 based on [A.12–A.15]): *general* publications on fuzzy sets and systems, *mathematical* publications on fuzzy logic.

	General research	Mathematical research
1970 – 1979	569	444
1980 – 1989	2403	2466
1990 – 1999	23220	5487
2000 – present	32655	7819
total number	58847	16216

A.2 Example for fuzzy supervised learning for given membership functions

Table A.2.: Output y^{ν} of the fuzzy model in example 7.1 according to equations 2.51 and 2.53 for the first three iterations of the RPROP algorithm. The mean square error ϵ decreased from 19.04 % in the first iteration to 17.64 % after the third iteration.

Respondent	Reference	Iteration 1	Iteration 2	Iteration 3
1	1.000	0.0383	0.0582	0.0850
2	0.000	0.9667	0.9526	0.9303
3	1.000	0.8388	0.8224	0.8009
4	0.000	0.0000	0.0000	0.0000
5	1.000	0.0040	0.0078	0.0152

Table A.3.: Evolution of the partial derivatives of the mean square approximation error ϵ with respect to each parameter for example 7.1.

Partial derivative	Iteration 1	Iteration 2	Iteration 3
$\partial\epsilon/\partial p_{1,1}$	0.0038	0.0062	0.0084
$\partial\epsilon/\partial p_{1,2}$	0.0066	0.0082	0.0098
$\partial\epsilon/\partial p_{2,1}$	0.0010	0.0008	−0.0002
$\partial\epsilon/\partial p_{2,2}$	−0.0026	−0.0034	−0.0043

Table A.4.: Sign flags for all parameters over the first three iterations according to equation 2.45c in figure 2.4. For the first iteration, only the term $\partial \epsilon^t / \partial p_{i,j}$ is considered.

Sign flag	Iteration 1	Iteration 2	Iteration 3
$a_{1,1}$	0.000	0.2330	0.5184
$a_{1,2}$	0.000	0.5390	0.8007
$a_{2,1}$	0.000	0.0081	−0.0024
$a_{2,2}$	0.000	0.0898	0.1480

Table A.5.: Evolution of the learning rates for the first three iterations in example 7.1. An initial value of $h_{i,j} = 0.1$ has been assumed for all parameters. The values for η^+ and η^- were set to 1.05 and 0.7, respectively.

Learning rate	Iteration 1	Iteration 2	Iteration 3
$h_{1,1}$	0.1000	0.1050	0.1103
$h_{1,2}$	0.1000	0.1050	0.1103
$h_{2,1}$	0.1000	0.1050	0.0735
$h_{2,2}$	0.1000	0.1050	0.1103

Table A.6.: Parameter estimates over the first three iterations for example 7.1. Each parameter is changed by its own learning rate in the opposite direction of its partial derivative.

Parameter estimate	Iteration 1	Iteration 2	Iteration 3
$p_{1,1}$	1.000	0.900	0.795
$p_{1,2}$	24.800	24.700	24.595
$p_{2,1}$	1.000	0.900	0.795
$p_{2,2}$	19.400	19.500	19.605

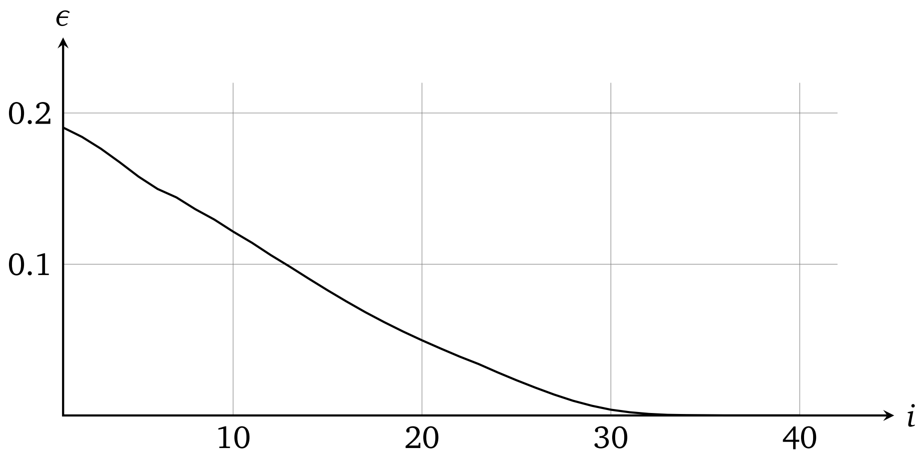

Figure A.1.: Mean square error ϵ of the fuzzy model in example 7.1. The resilient backpropagation algorithm converges quickly, even for high-dimensional optimisation problems, as each parameter is adapted individually (i is the number of iteration).

B Annex to chapter 3

B.1 Examples of condition assessment matrices

Table B.1.: Excerpt of a scheme for operational condition assessment of high-voltage circuit breakers [B.1].

Condition Indicator	Score		Weight	Result
Service age	< 20	1	1	
	$20 - 25$	2		
	$26 - 30$	3		
	$31 - 35$	4		
	$36 - 40$	5		
	> 40	6		
Experience with equipment type	positive	1	3	
	negative	6		
Maximum breaking capacity	$< 80\,\%$	1	3	
	$80 - 90\,\%$	2		
	$91 - 99\,\%$	3		
Number of operations	low	1	1	
	high	6		
Number of short-circuit current interruptions	low	1	2	
	high	6		
Extinguishing medium	SF_6	1	1	
	minimum oil	3		
	air-blast	4		
Results of diagnostic tests	good	1	4	
	poor	6		

Table B.2.: Example of a scheme for strategic condition assessment of high-voltage circuit breakers [B.2]. Instead of evaluating the weighted mean, decision making is based rather on the weighted sum, as shown in the footnote of the table.

Condition Indicator	Score		Weight	Result
Service age	$20-25$	1		
	$25-30$	2		
	$30-35$	3		
	$35-40$	4		
	$40-50$	5		
	>50	6		
Reliability	high	1		
	low	6		
Risk/consequence major failure	low	1		
	high	6		
Risk/consequence minor failure	low	1		
	high	6		
Risk – personnel safety	low	1		
	high	6		
Risk – environment	low	1		
	high	6		
Repair or refurbishment cost	low	1		
	high	6		
OEM support	yes	1		
	no	6		
Spare parts availability	yes	1		
	no	6		
Orphans? (<5 units)	no	1		
	yes	6		
Operator's level of satisfaction	high	1		
	low	6		
Personnel's level of expertise	high	1		
	low	6		
Visual inspection results	good	1		
	bad	6		
Technical review results	good	1		
	bad	6		

total score: $r_t = \sum_i r_i$

Maintenance decision

maintenance in service	$r_{t,min} \leq r_t \leq 0.8^2\,(r_{t,max} - r_{t,min})$
rebuild, refurbish or replace	$0.8^2\,(r_{t,max} - r_{t,min}) \leq r_t \leq 0.8\,(r_{t,max} - r_{t,min})$
replace	$r_t \geq 0.8\,(r_{t,max} - r_{t,min})$

Table B.3.: Example of a multiple-level condition assessment matrix for strategic assessment of high-voltage circuit breakers [B.3]. Missing weighting factors in the table were not available in the reference.

Level	Condition Indicator	Score		Weight	Result
1	*Technical condition*			5	
1.1	Service age	low high	1 6	6	
1.2	Technical review results	good poor	1 6	10	
1.3	Time to next maintenance	short long	1 6	2	
2	*Service & maintenance experience*			5	
2.1	Drive technology	mechanic hydraulic pneumatic	1 2 4	5	
2.2	Extinguishing medium	SF_6 (single-pressure) SF_6 (double-pressure) minimum oil air-blast	1 3 3 5	7	
2.3	Mean failure rate p.a. (minor & major)	$\leq 10\,\%$ $10 - 20\,\%$ $20 - 30\,\%$ $30 - 40\,\%$ $40 - 50\,\%$ $\geq 50\,\%$	1 2 3 4 5 6	12	
2.4	*Service*			12	
2.4.1	After-sales service			#	
2.4.1.1	Manufacturer's know-how	good poor	1 6	#	
2.4.1.2	Personnel training	good poor	1 6	#	
2.4.1.3	Applied measuring techniques	state-of-the-art obsolete	1 6	#	
2.4.1.4	Support	good poor	1 6	#	

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Level	Condition Indicator	Score		Weight	Result
2.4.2	Corrective maintenance support			#	
2.4.2.1	Personnel availability	good	1	#	
		poor	6		
2.4.2.2	Spare parts availability	good	1	#	
		poor	6		
2.4.3	Preventive maintenance support			#	
2.4.3.1	Cost of spare parts	low	1	#	
		high	6		
2.4.3.2	Down time	$1-2$ interrupting units (mechanical drive)	1	#	
		$1-2$ interrupting units (hydraulic drive)	2		
		$1-2$ interrupting units (N_2 energy storage)	3		
		4 interrupting units (N_2 energy storage)	4		
		>4 interrupting units	5		
		pneumatic drive / double-pressure SF_6	6		
2.4.3.3	Spare parts quality (age)	≤ 5 years	1	#	
		$5-10$ years	3		
		≥ 5 years	5		

C Annex to chapter 4

C.1 Assessment of service and maintenance experience

Table C.1.: Rule base for strategic assessment of service & maintenance experience. Values for the linguistic variables are determined according to section 4.2. The linguistic variable "good availability of spare parts" also accounts for utility-own stock keeping. Aggregation of linguistic variables is performed by AND-connectives.

Spare parts availability	Systematic failures	OEM support	Maintenance know-how	Assessment
good	none	high	sufficient	A
good	none	high	some	A–
good	none	high	discontinued	B
good	none	medium	sufficient	B
good	none	medium	some	B–
good	none	medium	discontinued	C
good	none	low	sufficient	B
good	none	low	some	C+
good	none	low	discontinued	C–
good	minor	high	sufficient	B
good	minor	high	some	B–
good	minor	high	discontinued	B–
good	minor	medium	sufficient	B
good	minor	medium	some	C+
good	minor	medium	discontinued	C
good	minor	low	sufficient	C+
good	minor	low	some	C
good	minor	low	discontinued	D+
good	major	high	sufficient	C
good	major	high	some	C–
good	major	high	discontinued	D+
good	major	medium	sufficient	C–
good	major	medium	some	D+
good	major	medium	discontinued	D+
good	major	low	sufficient	D+
good	major	low	some	D

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Spare parts availability	Systematic failures	OEM support	Maintenance know-how	Assessment
good	major	low	discontinued	D
limited	none	high	sufficient	A–
limited	none	high	some	B+
limited	none	high	discontinued	C
limited	none	medium	sufficient	B
limited	none	medium	some	B–
limited	none	medium	discontinued	C–
limited	none	low	sufficient	C–
limited	none	low	some	D+
limited	none	low	discontinued	D
limited	minor	high	sufficient	B–
limited	minor	high	some	C
limited	minor	high	discontinued	D+
limited	minor	medium	sufficient	C
limited	minor	medium	some	D+
limited	minor	medium	discontinued	D
limited	minor	low	sufficient	C–
limited	minor	low	some	D
limited	minor	low	discontinued	D
limited	major	high	sufficient	C
limited	major	high	some	D+
limited	major	high	discontinued	D
limited	major	medium	sufficient	C–
limited	major	medium	some	D
limited	major	medium	discontinued	D
limited	major	low	sufficient	D+
limited	major	low	some	D
limited	major	low	discontinued	D

C.2 Strategic condition assessment of HVCBs

Table C.2.: High-level rule base for strategic assessment of circuit breakers. Values for the linguistic variables result from the fuzzy inference systems at lower level. Refer to page 81 for more information.

Technology	Service & maintenance	Cost of maintenance	Assessment
A	A	low / normal	A
A	A	high	B
A	B	low	A
A	B	normal / high	B
A	C	low	B
A	C	normal / high	C
A	D	low / normal	C
A	D	high	D
B	A	low / normal	A
B	A	high	B
B	B	low–high	B
B	C	low	B
B	C	normal / high	C
B	D	low	C
B	D	normal / high	D
C	A	low	A
C	A	normal	B
C	A	high	C
C	B	low / normal	B
C	B	high	C
C	C	low–high	C
C	D	low	C
C	D	normal–high	D
D	A	low / normal	C
D	A	high	D
D	B	low	C
D	B	normal / high	D
D	C	low	C
D	C	normal–high	D
D	D	low–high	D

D Annex to chapter 5

D.1 Failure statistics on HVCBs

Table D.1.: Functional failures modes of high-voltage circuit breakers. The values in the table describe the distribution of major failures between the failure modes and are no failure rates. They were determined by the first and second survey by Cigré [D.1].

Failure mode	2nd enquiry	1st enquiry
Does not close on command	24.6 %	33.7 %
Does not open on command	8.3 %	14.1 %
Closes without command	1.1 %	1.7 %
Opens without command	7.0 %	5.2 %
Does not make the current	1.7 %	1.6 %
Does not break the current	3.0 %	1.9 %
Fails to carry the current	1.5 %	2.5 %
Breakdown to earth	3.2 %	2.6 %
Breakdown between poles	1.5 %	0.5 %
Breakdown across open pole (internal)	3.6 %	4.0 %
Breakdown across open pole (external)	1.5 %	1.2 %
Locking in open or closed position	28.4 %	not specified
Other	14.6 %	31.0 %

Table D.2.: Contribution of functional units to the high-level failure modes defined in table D.1.

Failure mode	Drive	Live parts	Insulation	Interrupter	Control
Does not close on command	✓				✓
Does not open on command	✓				✓
Closes without command	✓				✓
Opens without command	✓				✓
Does not make the current		✓		✓	
Does not break the current				✓	
Fails to carry the current		✓			
Breakdown to earth			✓		
Breakdown between poles			✓		
Breakdown across open pole (internal)			✓		
Breakdown across open pole (external)			✓		
Locking in open or closed position	✓	✓			✓
Other	✓	✓	✓		✓

D.2 Assessment of information content

Table D.3.: Assessment of necessity for condition indicators. The table is filled in vertically according to figure 5.1.

Condition indicator	drive	current path	insulation	interrupter	control
service-based indicators					
Location	–	–	–	–	–
Service age	–	–	–	–	–
Number of operations	–	–	–	–	–
Load current	–	–	–	–	–
Number of short-circuit interruptions	–	–	–	–	–
Arcing energy $\int_{t_{arc}} I^2\,dt$	–	–	–	–	–
Diagnostics-based indicators					
SF_6 density	–	–	++	+	–
SF_6 leak	–	–	–	–	–
SF_6 purity	–	+	+++	+	–
Moisture content	–	–	–	–	–
Partial discharge	–	++	+++	–	–
Insulation resistance	–	–	++	–	–
Leakage current	–	–	++	–	–
Power factor	–	–	+	–	–
Contact resistance	+	+++	–	–	–
Contact temperature	+	+++	–	–	–
Dynamic contact resistance	–	++	–	++	–
Main contact's end position	+	+	–	–	–
Contact travel characteristics	+++	+	–	+	–
Operating time	++	–	–	+	–
Vibration	++	–	–	+	–
Pole discrepancy	–	–	–	–	–
Charging power	+	–	–	–	–
Motor running time	+	–	–	–	–
Coil current	++	–	–	–	–
Minimum trip voltage	++	–	–	–	–
Visual inspections	++	–	++	–	++

+++ high information content
++ medium information content
+ low information content
– no information content

Table D.4.: Assessment of likelihood for condition indicators. The table is filled in horizontally according to figure 5.1.

Condition indicator	drive	current path	insulation	interrupter	control
service-based indicators					
Location	++	–	++	–	++
Service age	++	+	+	++	++
Number of operations	++	–	+	++	–
Load current	–	+++	–	+	–
Number of short-circuit interruptions	+	+	++	+++	–
Arcing energy $\int_{t_{arc}} I^2\,dt$	–	–	+	++	–
Diagnostics-based indicators					
SF_6 density	–	–	+++	–	++
SF_6 leak	+	–	+++	–	–
SF_6 purity	–	++	+++	++	–
Moisture content	–	+++	++	–	–
Partial discharge	–	++	++	+	–
Insulation resistance	–	–	+++	–	–
Leakage current	–	–	+++	–	–
Power factor	–	–	+++	–	–
Contact resistance	+	+++	+	+	–
Contact temperature	+	+++	+	+	–
Dynamic contact resistance	+	++	–	++	–
Main contact's end position	++	++	–	++	–
Contact travel characteristics	+++	+	–	++	–
Operating time	++	–	–	++	–
Vibration	+	+	+	+	+
Pole discrepancy	++	–	–	++	–
Charging power	+++	–	–	–	–
Motor running time	+++	–	–	–	–
Coil current	+++	–	–	–	–
Minimum trip voltage	+++	–	–	–	–
Visual inspections	+++	–	+++	–	+++

+++ high information content
++ medium information content
+ low information content
– no information content

D.3 Example reference values for operational condition assessment

Table D.5.: Reference values for selected condition indicators of HVCBs. Example values for the diagnostics-based indicators presented here correspond to a 145 kV SF_6 circuit breaker [D.2].

Condition Indicator	Reference value
service-based indicators	
Service age	expected lifetime 35–40 years
Number of operations	84 p.a. (95-percentile reported in [D.1])
Number of short-circuit interruptions	< 7 per pole
Diagnostics-based indicators	
SF_6 density	6 bar
Contact resistance	$40\,\mu\Omega$
Operating time	27,5 ms (closing), 21.5ms (opening)
Pole discrepancy	< 3 ms
Motor running time	< 11 s
Coil current	< 1 A
Minimum trip voltage	66 V

E Annex to chapter 6

E.1 Brief theoretical discussion of dielectric properties

E.1.1 Electrical conductivity

In the presence of an electric field, mobile charge carriers e.g. free electrons or positive/negative charged ions experience an accelerating force and begin to move within the material. During their movement they interact with molecules through collisions and release their kinetic energy so that an average charge carrier drift velocity is reached, which is proportional to the average current density $\vec{J}$. The latter is related to the electric field strength $\vec{E}$ by the electrical conductivity of the material σ.

Definition E.1 *Electrical conductivity: The electrical conductivity or specific conductance σ is defined as the ratio of the current density $\vec{J}$ to the magnitude of the electric field $\vec{E}$:*

$$\vec{J} = \sigma \vec{E} \tag{E.1}$$

The electrical conductivity is a measure of a material's ability to conduct an electric current. Occasionally, the Greek letters κ (especially in electrical engineering, compare [E.1]) or γ (compare [E.2]) are used in literature for the electrical conductivity. Generally speaking, conductivity may be divided into electronic and ionic conductivity. In the following, some aspects of conductivity of dielectric fluids and solids will be discussed. Charge transfer in dielectric fluids mainly occurs by positive or negative ion migration. Such ions are released by dissociation from the fluid itself in the course of ageing or due to introduced impurities. The contribution of electronic mobility is only significant in higher electric fields and may be neglected otherwise. Conductivity of dielectric fluids decreases with increasing application time of an electric field. In accordance with figure E.1(a), we can distinguish between following four regions [E.2]:

region I: current in this first region is due to orientation of electric dipoles (polarisation current) and should not be confused with ionic conductivity.

region II: ionic migration under the influence of the electric field. This initial conductivity is defined by the equilibrium between formation and recombination of charge carriers, predominantly ions. Such an equilibrium is apparent for alternating fields of industrial frequency, as no effective transfer of carriers takes place (in average). Therefore, conductivity in this region is also called *ac conductivity* $\sigma_{\sim}$.

region III: further migration of charge carriers to the electrodes leads to generation of space charges in their vicinity as well as to carrier depletion. Consequently carrier concentration and electrical conductivity decreases. The associated transit time is indirectly proportional to carrier mobility.

region IV: once all charge carriers initially present in the fluid have been depleted, a new equilibrium is reached, where the rate of formation of new carriers by dissociation equals the rate of carrier recombination. The corresponding conductivity $\sigma_=$ is thus called *dc conductivity*.

Similar to fluids, electrical conductivity of dielectric solids is governed mainly by ionic mobility, with electron conductivity setting in only at high field strengths close to dielectric breakdown. However, in dielectric solids conductivity reaches its continuous value (dc conductivity) asymptotically over a long time period –of several hours, depending on the geometry– due to long-lasting polarisation effects (compare figure E.1(b)). The latter effects include for example polarisation of electric dipoles and charge carrier migration within restricted areas of the material. Consequently, conductivity of dielectric solids is usually divided into *transient* conductivity, which includes the aforementioned polarisation effects and will be discussed in section E.1.2, and *stationary* or dc conductivity [E.2]. Stationary conductivity is given at the equilibrium state where the rate of carrier formation due to dissociation of external molecules (e.g. diffused air, moisture or impurities) equals the rate of carrier depletion due to recombination or discharge at the electrodes in course of migration.

Conductivity of dielectric materials largely depends on two parameters: *temperature* and *electric field strength*. Increasing temperature leads to higher molecule oscillation which in turn increases the probability of collision between moving charge carriers and molecules. In other words the mean free path of charge carriers decreases and so does also the conductivity. This is especially true for metals. On the other hand, both charge carrier concentration as well as viscosity of dielectric fluids are temperature dependent. Subsequently, and for a specified temperature range, electrical conductivity follows van't Hoff's law:

$$\sigma = \sigma_0 \cdot e^{-\frac{E_A}{k_B T}} \tag{E.2}$$

where k_B is the Boltzmann constant, E_A is the activation energy specific to the considered material and T is the absolute temperature. Accordingly, electrical conductivity of dielectric fluids increases with rising temperature in the specified temperature range.

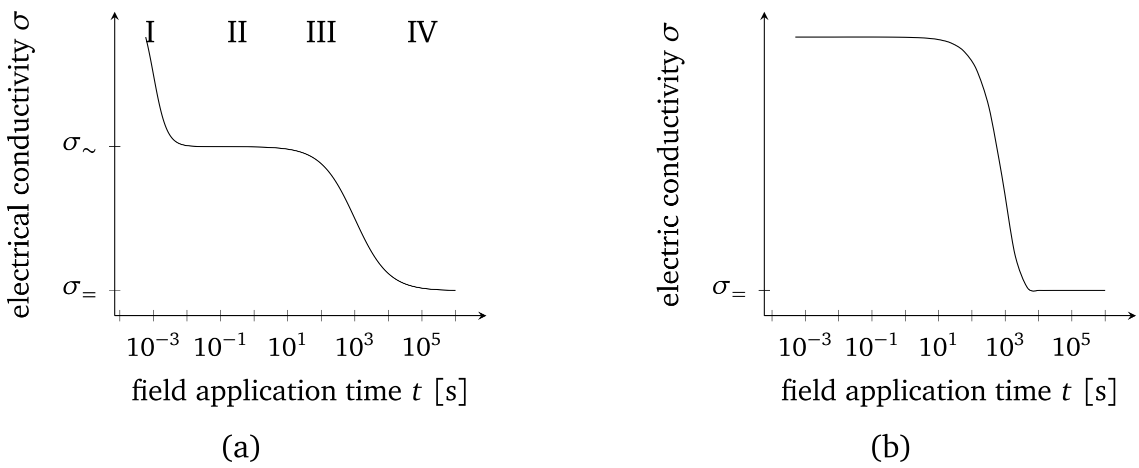

Figure E.1.: Conductivity of dielectric fluids (a) and solids (b) as a function of constant electric field application time (based on [E.1, E.2]). For usual service frequency, ac conductivity $\sigma_\sim$ is applicable, which is higher than dc conductivity $\sigma_=$.

With regard to the influence of electric field strength on conductivity of dielectric fluids, it is important to note that the linear relationship between current density $\vec{J}$ and electric field strength $\vec{E}$ as implied by definition E.1 is only valid up to a field strength specific to the particular fluid as well as to its degree of impurity. Once this field strength is exceeded, increased formation of mobile charge carriers due to dissociation takes place, leading to increased conductivity (Wien electrolytic effect). Moreover, the rate of carrier formation also rises with increasing temperature or increasing degree of impurity. However, no significant influence of dissolved gases on carrier formation rate has been documented.

Figure E.2(b) shows the basic relationship between stationary electrical conductivity of dielectric solids and the applied electric field. We may distinguish between following three regions [E.2]:

region I: conductivity is due to ionic migration and does not depend on the applied field.

region II: with increasing field strength, both ionic and electronic conductivity become apparent. The transition field strength depends on the material, its degree of impurity as well as on temperature, however, a typical value of 1 kV/mm may be used as an approximation.

region III: conductivity is mainly due to electron migration and follows the power law: $\sigma \sim E^n$.

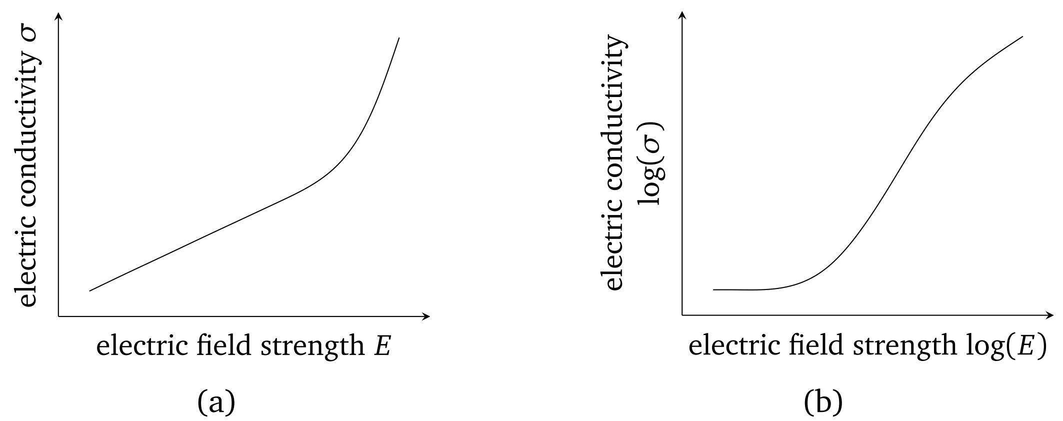

Figure E.2.: Influence of electric field strength $\vec{E}$ on electric dc conductivity of dielectric fluids (a) and solids (b), based on [E.1, E.2].

E.1.2 Polarisation effects

In the presence of an electric field, bound charges potentially existent in a dielectric material (or induced by the field itself) are displaced in such a way as to align with the electric flux lines. This so-called *polarisation effect* may be governed by following mechanisms [E.1–E.3]:

deformation polarisation: in general, deformation polarisation is a microscopic process taking place within atoms or molecules which are normally homopolar. Accordingly, we can further distinguish between two mechanisms of deformation polarisation:

- *electronic* polarisation: atoms consist of a negative charged electron cloud surrounding a positive point charge at its center, the nucleus. If an electric field is applied, the electron cloud is distorted, leading to atom's deformation and formation of an electric dipole which may in turn interact with the electric field.

- *atomic* polarisation: a similar effect may also occur within a molecule consisting of several atoms carrying different charges. In this case, the molecule itself is deformed.

ionic polarisation: this mechanism is apparent in ionic crystals (e.g. NaCl) where positive and negative ions are chemically bound. In ionic crystals lattice or molecular vibrations due to temperature induce relative displacements of the atoms. As a result positive and negative charges might be in different locations, which –under to influence of an external electric field– leads to polarisation of molecules in the crystal.

orientation or dipolar polarisation: this mechanism is particularly significant for polar molecules. Such molecules feature permanent electric dipoles resulting from the nature of their chemical bonds and will retain polarisation in the absence of an external electrical field. Perhaps the most common polar molecule is water (H_2O) where asymmetric bonds between oxygen and hydrogen atoms cause permanent polarisation. In the presence of an external electric field polar molecules interact with the field and rotate so as to align with the electric flux lines.

interface or boundary polarisation: in anisotropic dielectric materials, electric charges may be trapped in interface boundaries. Under the influence of an external field the so-formed electric dipoles may become oriented to some degree and thus contribute to the polarisation of the material. This mechanism is especially pronounced in mixed dielectrics, e.g. in oil-impregnated paper insulation systems with press board barriers as used in power transformers (compare section 6.1.3).

Some or all of these mechanisms may act simultaneously. For example, atomic polarisation is always present in any material and thus becomes superimposed on whatever other mechanism there might be [E.3]. Following definition can be given in order to quantify the degree of polarisation:

Definition E.2 *Polarisation density: The polarisation density $\vec{P}$ describes the density of permanent or induced electric dipole moments in a dielectric material. It is defined as the dipole moment per unit volume and is related to the electric displacement field $\vec{D}$ and the electric field strength $\vec{E}$ as:*

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \tag{E.3}$$

with ε_0 being the electric permittivity of vacuum ($\varepsilon_0 \approx 8.85 \cdot 10^{-12}\,\text{F/m}$, compare also section E.1.3).

Polarisation of a dielectric material depends on following parameters [E.1]:

temperature: rising temperature increases on the one hand the mobility of available electric dipoles, thus enhancing polarisation, on the other hand, however, thermal oscillation of molecules may disturb dipole orientation and reduce polarisation density.

frequency of the applied electric field: polarisation is subject to certain inertia, as dipoles need to overcome forces in order to align with the electric field (or *re*-align in case of an alternating field). Inertia depends on the mass of the respective electric dipoles with electronic polarisation characterised by minimal inertia. As a result of inertia, polarisation gradually decreases with increasing frequency.

electric field strength: in specific cases, especially for dielectric solids, a dependency of polarisation on field strength –even for fields significantly below breakdown levels– has been documented.

A more in-depth discussion of polarisation dependency on temperature and frequency will be given in section E.1.4.

E.1.3 Permittivity and dissipation factor

After discussing the fundamentals of electrical conductivity (section E.1.1) and the various polarisation mechanisms (section E.1.2), we will now introduce two further important concepts of electrostatics.

Definition E.3 *Dielectric permittivity: The permittivity of a dielectric material ε describes its ability to polarise in response to an applied electric field, thereby reducing the total electric field. It is given by the fundamental material equation:*

$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 \varepsilon_r \vec{E} \tag{E.4}$$

where ε_0 is the electric permittivity of vacuum (also called dielectric constant) and ε_r is the *relative permittivity* of the dielectric material (occasionally referred to as relative dielectric constant).

Generally speaking, the relative permittivity ε_r for any dielectric material is greater than unity, as some polarisation will always take place inside the material. Another way of describing relative permittivity is by considering two imaginary identical capacitors: the first one features vacuum as dielectric and has a capacitance C_0 while the second one is filled with a certain dielectric material and has a capacitance C_x. In this case the relative permittivity ε_r is defined by the capacitance ratio C_x to C_0 [E.2].

In section E.1.2 we already highlighted the fact that –generally speaking– material polarisation $\vec{P}$ *lags behind* the applied electric displacement field $\vec{D}$, mainly because of dipole inertia. The qualitative current graphs in figures E.1(a) and E.1(b) also manifest this time lag: upon application of a dc voltage (constant displacement field), polarisation processes are completed only after some characteristic time after which dc conductivity sets in.

Summing up, polarisation of a dielectric material should be regarded as a system answer, with the displacement field $\vec{D}$ as input and the resulting electric field $\vec{E}$ as output. The time lag between these two quantities can be expressed in the frequency domain as a *phase difference* caused by the permittivity of the dielectric material. Accordingly, we may rewrite equation E.4 using a *complex relative permittivity* $\underline{\varepsilon}_r$:

$$\underline{\vec{D}} = \varepsilon_0 \underline{\varepsilon}_r \underline{\vec{E}} = \varepsilon_0 (\varepsilon_r^{'} - j\varepsilon_r^{''}) \underline{\vec{E}} \tag{E.5}$$

where $\underline{\vec{D}}$ and $\underline{\vec{E}}$ are the phasors[1] of the displacement field and the electric field, respectively.

[1] A *phasor* is a representation of a sinusoidal variable $a = \sin(\omega t + \theta)$ of constant amplitude A, phase θ and angular frequency ω in the frequency domain. The transformation bases on Euler's formula ($e^{jx} = \cos x + j \sin x$), with the phasor of a being defined as a complex number by $\underline{A} = Ae^{j\theta} e^{j\omega t}$. In common applications of electrical engineering, however, only the first term ($Ae^{j\theta}$) is significant, as all respective phasors (i.e. currents and voltages) share the same forced frequency in quasi-steady state. When using phasors, linear differential equations can be reduced to algebraic ones, which significantly simplifies calculations.

Following the definition of complex permittivity, we shall now endeavour to set up a general phasor diagram for a dielectric on the basis of equations E.1 and E.3. The total current flow through a dielectric can be calculated by superimposing the current due to dc conductivity (section E.1.1) and the displacement current due to the various polarisation effects (section E.1.2) – let us start with the latter. In general, the displacement current density J_D is given by differentiating equation E.3 with respect to time:

$$\vec{J}_D = \varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \frac{\partial \vec{P}}{\partial t} \tag{E.6}$$

Under the assumption of a sinusoidal electric field with constant angular frequency ω, we may rewrite equation E.6 in the frequency domain using the complex permittivity $\underline{\varepsilon}_r$ and the phasors $\underline{\vec{D}}$ and $\underline{\vec{E}}$:

$$\begin{aligned} \underline{\vec{J}}_D &= j\omega\underline{\vec{D}} = j\omega(\varepsilon_0\underline{\vec{E}} + \underline{\vec{P}}) \\ &= j\omega\varepsilon_0\varepsilon_r\underline{\vec{E}} = j\omega\varepsilon_0(\varepsilon_r^{'} - j\varepsilon_r^{''})\underline{\vec{E}} = \omega\varepsilon_0\varepsilon_r^{''}\underline{\vec{E}} + j\omega\varepsilon_0\varepsilon_r^{'}\underline{\vec{E}} \end{aligned} \tag{E.7}$$

where $\underline{\vec{J}}_D$ is the phasor of the displacement current density.

As for the current flow through a dielectric due to dc conductivity, it is defined by Ohm's law in equation E.1. By transformation into the frequency domain, we obtain the phasor of current density due to dc conductivity $\underline{\vec{J}}_C$:

$$\underline{\vec{J}}_C = \sigma\underline{\vec{E}} \tag{E.8}$$

Basing on equations E.5, E.7 and E.8 above, we may now set up the corresponding phasor diagram: starting with the electric field $\underline{\vec{E}}$ we use equation E.5 to draw the displacement field $\underline{\vec{D}}$. The corresponding displacement current density $\underline{\vec{J}}_D$ is then leading by 90 degrees (equation E.7). Finally, the current density due to dc conductivity $\underline{\vec{J}}_C$ is in phase with the electric field $\underline{\vec{E}}$, as indicated by equation E.8. The superposition of $\underline{\vec{J}}_D$ and $\underline{\vec{J}}_C$ yields the total current density through the dielectric $\underline{\vec{J}}$. Figure E.3 shows the complete phasor diagram.

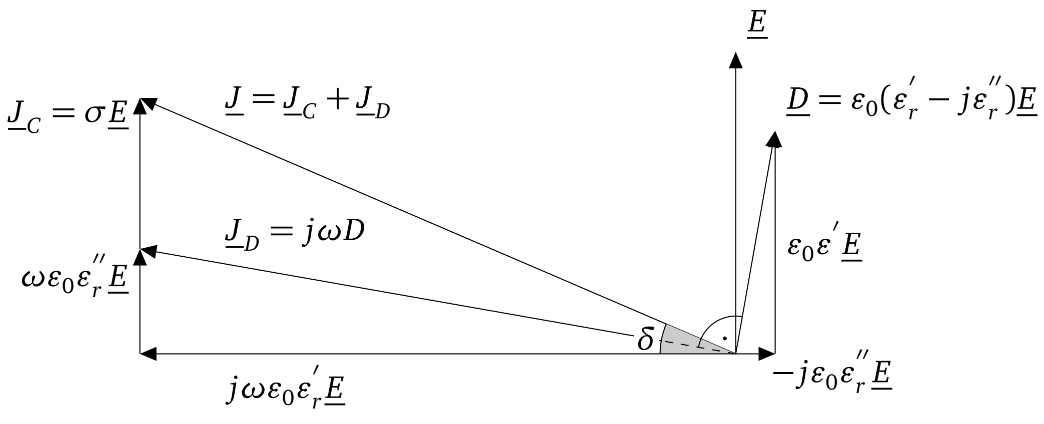

Figure E.3.: General phasor diagram of a dielectric material (based on [E.1].)

Definition E.4 *Dissipation factor: The dissipation (or power) factor* $\tan\delta$ *describes the tendency of dielectric materials to absorb energy when an alternating electric field is applied. It is defined by the ratio of power loss due to conductance and polarisation to the capacitive charging power necessary for polarisation of the material:*

$$\tan\delta = \frac{\text{power loss due to conductance and polarisation}}{\text{reactive power needed for polarisation}} \tag{E.9}$$

From the phasor diagram in figure E.3 we can calculate the dissipation factor as[2]:

$$\tan\delta = \frac{\Re\mathfrak{e}\{\underline{\vec{E}}\cdot\underline{\vec{J}}^*\}}{\Im\mathfrak{m}\{\underline{\vec{E}}\cdot\underline{\vec{J}}^*\}} = \frac{\underline{\vec{E}}(\sigma\underline{\vec{E}}+\omega\varepsilon_0\varepsilon_r^{''}\underline{\vec{E}})}{\underline{\vec{E}}\cdot\omega\varepsilon_0\varepsilon_r^{'}\underline{\vec{E}}} = \frac{\sigma+\omega\varepsilon_0\varepsilon_r^{''}}{\omega\varepsilon_0\varepsilon_r^{'}} \tag{E.10}$$

We may identify two terms in equation E.10: the first one ($\tan\delta_C = \sigma/\omega\varepsilon_0\varepsilon_r^{'}$) accounts for the power loss due to conductance according to Joule's law (in dielectrics mainly ionic conductance), while the second one ($\tan\delta_D = \varepsilon_r^{''}/\varepsilon_r^{'}$) represents the power loss due to polarisation. Indeed, during polarisation electric dipoles have to overcome forces while aligning with the electric field thus absorbing energy.

E.1.4 Influencing factors on permittivity and dissipation factor

Three factors have a large influence on permittivity and, thus, on the dissipation factor of dielectrics: the *frequency* of the applied field, the *temperature* of the material, and the electric field *strength*. In the next paragraphs we shall investigate these influencing factors in more detail.

The dependence of permittivity on frequency is determined by the dielectric relaxation of the material, which describes the time lag governing molecular polarisation. As already described in section E.1.2, electric dipoles (both permanent and induced by the electric field) experience microscopic forces when aligning with an external field, which they have to overcome. This leads to some sort of polarisation or dielectric "hysteresis"; from a macroscopic point of view, permittivity depends thus on frequency.

The dielectric relaxation response of dielectrics with chemically bound, permanent electric dipoles has been extensively studied by the physical chemist Peter Debye (1884-1966). His equation describes the fundamental relationship between complex permittivity and frequency [E.2, E.4]:

$$\underline{\varepsilon}_r(\omega) = \varepsilon_{r\infty} + \frac{\varepsilon_{rs}-\varepsilon_{r\infty}}{1+j\omega\tau} \tag{E.11}$$

where τ is the characteristic time of the dielectric relaxation mechanism, ε_{rs} is the real part of complex permittivity at frequencies significantly below relaxation frequency and $\varepsilon_{r\infty}$ is the real part of complex permittivity at frequencies significantly above relaxation frequency.

Transforming equation E.11 into the frequency domain yields:

$$\varepsilon_r^{'}(\omega) = \varepsilon_{r\infty} + \frac{\varepsilon_{rs}-\varepsilon_{r\infty}}{1+(\omega\tau)^2} \quad \text{and} \quad \varepsilon_r^{''}(\omega) = \frac{\varepsilon_{rs}-\varepsilon_{r\infty}}{1+(\omega\tau)^2}\omega\tau \tag{E.12}$$

[2] In this calculation, volume power densities (in W/m^3) are considered resulting from the multiplication of electric field strength (in V/m) and current density (in A/m^2).

Depending on the dielectric and the dominant polarisation mechanism, several modifications of Debye's equation are used (e.g. the Clausius-Mossotti relation for homopolar dielectrics). On basis of equation E.11 we may now investigate the influence of frequency on the dissipation factor $\tan\delta$. In section E.1.3 we already identified the contribution of power loss due to conductance as:

$$\tan\delta_C = \frac{\sigma}{\omega\varepsilon_0\varepsilon_r^{'}} \tag{E.13}$$

Conductance is only significant at low frequency, we may thus approximate $\varepsilon_r^{'}$ by ε_{rs} (compare equation E.12 for $\omega = 0\,°/\mathrm{s}$):

$$\tan\delta_C = \frac{\sigma}{\omega\varepsilon_0\varepsilon_{rs}} \tag{E.14}$$

Accordingly, the share of power loss due to conductance in the total dissipation factor decreases hyperbolically with increasing frequency. On the other hand, the contribution of polarisation losses to the total dissipation factor equals:

$$\tan\delta_D = \frac{\varepsilon_r^{''}}{\varepsilon_r^{'}} = \frac{\varepsilon_{rs} - \varepsilon_{r\infty}}{\varepsilon_{rs} + \varepsilon_{r\infty}(\omega\tau)^2}\omega\tau \tag{E.15}$$

The above expression shows a pronounced maximum at angular frequency:

$$\omega_m = \sqrt{\frac{\varepsilon_{rs}}{\varepsilon_{r\infty}}}\frac{1}{\tau} \tag{E.16}$$

By superimposing equations E.14 and E.15 we obtain the total dissipation factor $\tan\delta$. Figure E.4(a) depicts the dissipation factor together with the real part of the complex permittivity ($\varepsilon_r^{'}$) as a function of applied frequency. It is obvious that conductivity dominates at especially low and high frequency (region I and III), while losses due to polarisation are more pronounced near the characteristic frequency in equation E.16 (region II).

Usually, several polarisation effects with different characteristic relaxation times are apparent simultaneously. In this case the $\tan\delta$ vs. temperature curve would be a superposition of all polarisation mechanisms.

Increasing temperature leads to higher mobility of electric dipoles through a decrease in microscopic viscosity. In other words, the ability of dipoles to follow an alternating electric field increases and so does permittivity. However, at even higher temperatures the thermal motion of molecules disturbs the orientation of dipoles and acts against polarisation. As a result, permittivity decreases again.

The influence of increasing temperature on dissipation factor is even more difficult to assess. The reason lies at the increasing electrical conductivity (compare section E.1.1). In general, a characteristic as in figure E.4(c) is typical. At higher temperatures, losses due to conductance dominate the dissipation factor $\tan\delta$.

The influence of frequency and temperature on the dissipation factor is complicated and should always be regarded in combination of both factors. Especially when assessing the condition of an insulation system by means of a dissipation factor measurement, one as to ensure comparison of the measuring results with *corresponding* reference data (i.e. both temperature and applied frequency have to comply).

Similar to temperature, the influence of electric field strength on permittivity and dissipation factor is mainly determined by losses due to conductance. As indicated in section E.1.1, conductivity of dielectrics, especially of fluids, may rise with increasing field strength as a result of enhanced charge carrier formation (Wien effect). Figure E.4(b) shows the $\tan\delta$ vs. field strength characteristic for an insulating oil.

Another important effect which leads to an increase of the dissipation factor and is related to field strength are *partial discharges*. Whilst the applied field strength underlies the inception threshold no partial discharges occur, at the moment this threshold is reached, partial discharged set in resulting into power loss due to ionisation. Further increase of field strength leads to linear growth of ionisation losses; however, the dissipation factor decreases hyperbolically, as capacitive charging power (the denominator in equation E.9) involves the square field strength [E.2].

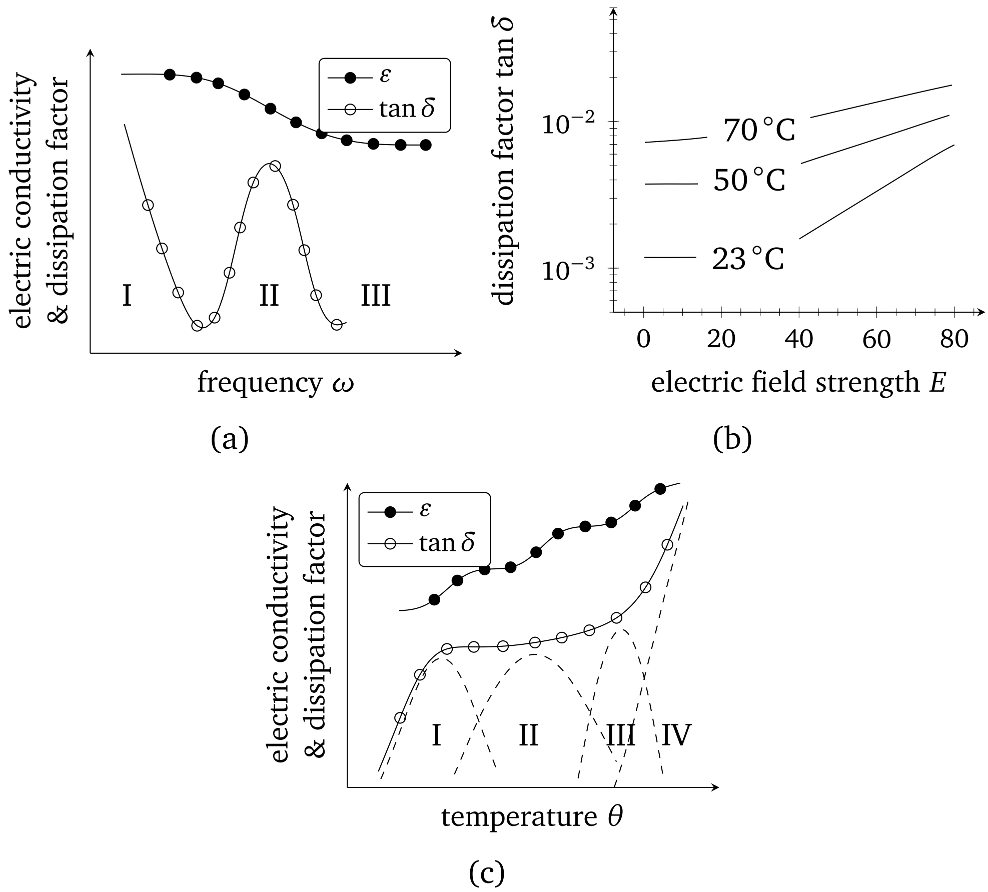

Figure E.4.: The main parameters influencing electric conductivity and dissipation factor are: frequency (a), temperature (c), and electric field [E.1, E.2]. Conductivity is important at low and high frequency, regions I and III in figure (a) and at high temperature, region IV in figure (c). Orientation of dipoles –regions I and III, figure (c)– and/or of interfacial charges –region II– are also important.

E.2 Historical development of insulating liquids for electrotechnical applications

The development of insulating oils commenced with the introduction of the first oil-filled power transformers in the early 1890s. These first transformers, introduced both in Europe and the USA, featured mineral oil as insulating and cooling medium. By the end of the 19th century, commercial production of mineral oil specifically designed for power transformer applications had already started [E.6]. At the same time, investigations of natural ester liquids as a potential insulating medium for electrotechnical purposes have also been performed, but such plans were abandoned quickly, since ester liquids proved to have inferior oxidation stability, higher pour point and higher viscosity than mineral oil at that time [E.7].

Generally speaking, mineral insulating oils have always been the standard solution for power transformers from the early beginnings until now, mainly because their low price, good insulating and cooling properties and ready availability [E.8]. Alternatives to mineral oils have also been investigated and introduced when more stringent requirements concerning fire resistance (flash point), electric permittivity, gas absorption or pour point are dictated by the particular application e.g. for railway traction transformers or built-in distribution transformers. Table E.1 gives a brief historical overview of the development of insulating oils from the very beginnings up to now [E.6, E.8, E.9].

The first synthetic insulating oils where introduced in the 1930s. They were mixtures of chlorinated aromatic hydrocarbons prepared from biphenyl and benzene [E.8] and were distributed under various trademarks as askarel® or Clophen®. Because of their general chemical composition they are nowadays referred to as PCBs (*polychlorinared biphenyls*). The main reason for their development was the need for a higher flash point so as to reduce the fire hazard in built-in applications. After some initial experimentations [E.10, E.11], these liquids could reach excellent chemical stability and a much higher permittivity than mineral oils. Unfortunately, PCBs proved to be toxic to living organisms due to their structural similarity to dioxin. As a result of increased public concern and also because of several large-scale environmental contamination incidents [E.12], PCBs were banned by the US congress in 1979. Other industrial countries followed this example in the following years.

The withdrawal of PCBs lead to increased research efforts so as to develop a fire-resistant, yet non-toxic insulating oil for power transformers. Several alternatives have been proposed from the mid 1970s to the mid 1980s, including synthetic silicone oils, high molecular weight hydrocarbons (HMWH) as well as synthetic ester oils, table E.1. *Silicone oils* had been developed and used as specialist fluids since the beginning of the 20th century [E.8], but preliminary investigations on their applicability for power transformers were first performed in the late 1970s [E.13, E.14]. Nowadays, silicone oils feature flash points over 300 °C and are therefore classified as insulating liquids of class K according to IEC 60076-2 (refer to section 8.1.1 for more information of the thermal classification of transformer oils). IEC 60836 and ASTM D 2225 are the most important specification standards for silicone oils. Their cost dropped from approximately 10 times the equivalent cost of mineral oil in 1980 [E.8] down to 1.3 times in 2010 [E.9] (table E.2). Although much less toxic than PCBs, silicone oils do contain dimethyl-polysiloxanes which generate formaldehyde at high temperatures and can cause eye and skin irritations [E.9, E.14]. Another drawback of silicone oils is that they are not compatible with mineral oils and should not be mixed.

Table E.1.: Historical development of the most important insulating liquids for electrotechnical applications [E.6, E.8, E.9]

Year	Developments in the field of insulating oils
1892	General Electric® produces the first-known application of mineral oil in a distribution transformer.
1899	Commercial production of mineral oil specifically designed for transformers starts.
at the same time	Trials with natural ester fluids (vegetable oils) demonstrate inferior oxidation stability and higher pour point, electric permittivity and viscosity compared to mineral oils. Application of natural esters for electrotechnical purposes is abandoned.
1930s	Commercialisation of PCB-filled transformers.
mid – late 1970s	PCBs are identified as toxic through a series of incidents. Banning of further production and commercialisation of PCBs in many industrial countries.
mid 1970s – early 1980s	Introduction of silicone oils as substitute for PCBs.
mid 1980s	Introduction of mineral-oil-based high molecular weight hydrocarbons (HMWH).
at the same time	Synthetic esters (most commonly polyol esters) are used in compact railway traction transformers.
early 1990s	As a result of environmental regulations, extensive R&D effort is put into the development of natural esters.
since mid 2000s	Pilot application of natural esters in large power transformers.

High molecular weight hydrocarbons (HMWH, also called synthetic hydrocarbons) were introduced in parallel with silicone oils in the mid 1980s. They are specified within IEC 60867 and feature flash points in the range of 230 °C to 270 °C [E.9, E.15] which does not prove them equivalent to class K insulating oils, although they are considered to be "less flammable" according to US National Electrical Code specifications. HMWHs have better electrical and gas-absorbing properties than mineral oils and, due to their proven compatibility with aramid insulation materials, are nowadays used in high-temperature transformers rated for 115 °C [E.6].

The third PCB substitute developed and commercialised in the mid 1980s were *synthetic ester oils*. Similar to silicone oils and HMWHs, synthetic ester oils are non-toxic, but, in addition, they are largely biodegradable. Due to their higher cost as well as some problems related to hydrolytic stability (which have, however, been solved by the use of appropriate inhibitors [E.8]), synthetic esters did not reach a breakthrough in electrotechnical applications.

As a result, and almost one century after the initial experimentations with *natural ester liquids*, significant research effort has been put into their development since the early 1990s. The main objective was to ensure low production cost while maintaining the main advantages of synthetic esters. Nowadays, natural esters feature high biodegradability, no toxicity, high flash points and good electrical properties. Examples of natural ester oils (also called *vegetable oils*) are trademarks as BIOTEMP® and Envirotemp®.

In the last decade significant research was conducted regarding the ageing behaviour of transformer insulation consisting of dielectric paper (Kraft paper) impregnated with natural ester oils [E.16–E.23]. Generally speaking, the ageing rate of cellulose in natural-ester-impregnated paper insulating systems is lower than the respective rate when mineral oil is used as impregnant [E.22–E.24]. The reason lies in the higher water solubility of natural ester oils; accordingly, at equilibrium, the oil absorbs more water from the paper, thus reducing the paper's hydrolytic ageing [E.16–E.18] (refer to section 6.1.3 for a more detailed explanation of water equilibrium characteristics of oil-paper systems). Nowadays, natural ester oils are considered to be suitable for power transformer applications [E.19–E.21] as demonstrated by several pilot projects on large high-voltage power transformers. Also, the possibility of mixing natural esters with mineral oil (an important prerequisite for retrofilling older mineral-oil-filled power apparatus with natural esters) has been investigated in [E.25, E.26]. Standardisation is also progressing in the field of natural ester liquids within IEC task committee 10.

Table E.2 shows some key physical and electrical properties of all aforementioned insulating oils. A description of these properties as well as their relevance for electrotechnical purposes has already been given in section 6.1.2.

Table E.2.: Overview of relevant physical and electrical properties of the most common insulating liquids for electrotechnical applications. Information in this table has been collected from [E.6, E.8, E.9, E.14, E.15, E.18, E.24, E.27–E.29] as well as from technical documentation of oils currently available on the market.

Property	Mineral oils	PCBs	Silicone oils	HMWHs	Synthetic esters	Natural esters
viscosity at 100 °C $\left[\mathrm{mm^2/s}\right]$	2.3–2.7	2.5–3.6	15–17	approx. 12	5.6–6	approx. 8
specific weight at 20 °C $[\mathrm{g/ml}]$	0.87–0.89	1.2–1.57	0.96	0.83–0.91	0.97–0.99	0.92
specific heat $[\mathrm{kJ/kg{\cdot}K}]$	1.85	1.09–1.38	1.45-1.55		2.09	
flash point [°C]	140–148	170–380	285–310	230–285	250–270	325–330
fire point [°C]	150–165	none	340-370	305–315	305-320	355-360
pour point [°C]	−50 to −57	−18 to −39	−50 to −60	−20 to −30	approx. −50	approx. −20
dielectric strength (VDE) $[\mathrm{kV/2.5mm}]$	45–70	> 45	40–50	approx. 50	45-75	55-75
electric permittivity at 20 °C, 50 Hz	2.2	4.8–5.3 [a]	2.7	2.1–2.3	3.2–3.3	3.2
acquisition cost [b]	1	8	10	2–3	6	4–8
IEC specification	60296	60588	60836	60867	61099	none [c]

[a] The value for the electric permittivity of PCBs has been evaluated at higher temperature, 90 °C.

[b] Acquisition costs listed here are for the year 1980 [E.8] and are scaled to the respective cost of mineral oils. The price difference nowadays is significantly lower, for example synthetic HMWHs or silicone oils cost approximately 1.2 to 1.3 times more than mineral oils [E.9].

[c] Currently, a specification standard on natural esters is potential working item (PWI) 5 of the IEC task committee 10 (insulating oils).

E.3 Relevant standards on dielectric paper and pressboard

Table E.3.: Standards regarding cellulose-based dielectric paper and board by the American Society for Testing and Materials (ASTM).

Code	Year	Title
ASTM C1616	2007	Standard Test Method for Determining the Moisture Content of Organic and Inorganic Insulation Materials by Weight
ASTM D149	2008	Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies
ASTM D150	2004	Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation
ASTM D202	2008	Standard Test Methods for Sampling and Testing Untreated Paper Used for Electrical Insulation
ASTM D1030	2007	Test Method for Fiber Analysis of Paper and Paperboard
ASTM D1305	2009	Standard Specification for Electrical Insulating Paper and Paperboard-Sulfate (Kraft) Layer Type
ASTM D2413	2009	Standard Practice for Preparation of Insulating Paper and Board Impregnated with a Liquid Dielectric
ASTM D3376	2009	Test Methods of Sampling and Testing Pulps to be Used in the Manufacture of Electrical Insulation
ASTM D3394	2009	Test Methods for Sampling and Testing Electrical Insulating Board
ASTM D4063	2009	Standard Specification for Pressboard for Electrical Insulating Purposes
ASTM D4243	2009	Standard Test Method for Measurement of Average Viscometric Degree of Polymerization of New and Aged Electrical Papers and Boards
ASTM D5470	2006	Standard Test Method for Thermal Transmission Properties of Thermally Conductive Electrical Insulation Materials
ASTM D229	2009	Standard Test Methods for Rigid Sheet and Plate Materials Used for Electrical Insulation

Table E.4.: Standards regarding cellulose-based dielectric paper and board by the International Electrotechnical Commission (IEC).

Code	Year	Title
IEC 60450	2007	Measurement of the average viscometric degree of polymerization of new and aged cellulosic electrically insulating materials
IEC 60554-1	1977	Specification for cellulosic papers for electrical purposes. Part 1: Definitions and general requirements
IEC 60554-2	2001	Cellulosic papers for electrical purposes - Part 2: Methods of test
IEC 60554-3-1	1979	Specification for cellulosic papers for electrical purposes. Part 3: Specifications for individual materials. Sheet 1: General purpose electrical paper
IEC 60554-3-2	1983	Specification for cellulosic papers for electrical purposes. Part 3: Specifications for individual materials. Sheet 2: Capacitor paper
IEC 60554-3-3	1980	Specification for cellulosic papers for electrical purposes. Part 3: Specifications for individual materials. Sheet 3: Crêpe paper
IEC 60554-3-4	1979	Specification for cellulosic papers for electrical purposes. Part 3: Specifications for individual materials. Sheet 4: Electrolytic capacitor paper
IEC 60554-3-5	1984	Specification for cellulosic papers for electrical purposes. Part 3: Specifications for individual materials. Sheet 5: Special papers
IEC 60641-1	2007	Pressboard and presspaper for electrical purposes - Part 1: Definitions and general requirements
IEC 60641-2	2004	Pressboard and presspaper for electrical purposes - Part 2: Methods of tests
IEC 60641-3-1	2008	Pressboard and presspaper for electrical purposes - Part 3: Specifications for individual materials - Sheet 1: Requirements for pressboard, types B.0.1, B.0.3, B.2.1, B.2.3, B.3.1, B.3.3, B.4.1, B.4.3, B.5.1, B.5.3 and B.6.1
IEC 60641-3-2	2007	Pressboard and presspaper for electrical purposes - Part 3: Specifications for individual materials - Sheet 2: Requirements for presspaper, types P.2.1, P.4.1, P.4.2, P.4.3 and P.6.1
IEC 60667-1	1980	Specification for vulcanized fibre for electrical purposes. Part 1: Definitions and general requirements

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Code	Year	Title
IEC 60667-2	1982	Specification for vulcanized fibre for electrical purposes. Part 2: Methods of test
IEC 60667-3-1	1986	Specification for vulcanized fibre for electrical purposes. Part 3: Specifications for individual materials. Sheet 1: Flat sheets
IEC 60763-1	2010	Laminated pressboard for electrical purposes - Part 1: Definitions, classification and general requirements
IEC 60763-2	2007	Specification for laminated pressboard - Part 2: Methods of test
IEC 60763-3-1	2010	Laminated pressboard for electrical purposes - Part 3: Specifications for individual materials - Sheet 1: Requirements for laminated precompressed pressboard, Types LB3.1A.1 and LB3.1A.2
IEC 61628-1	1997	Corrugated pressboard and presspaper for electrical purposes - Part 1: Definitions, designations and general requirements
IEC 61628-2	2007	Corrugated pressboard and presspaper for electrical purposes - Part 2: Methods of test

E.4 Relevant standards on insulating mineral oils

Table E.5.: Standards regarding insulating mineral oils by the American Society for Testing and Materials (ASTM).

Code	Year	Title
ASTM D117	2010	Standard Guide for Sampling, Test Methods, and Specifications for Electrical Insulating Oils of Petroleum Origin
ASTM D923	2007	Standard Practices for Sampling Electrical Insulating Liquids
ASTM D924	2008	Standard Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids
ASTM D1169	2009	Standard Test Method for Specific Resistance (Resistivity) of Electrical Insulating Liquids
ASTM D1275	2006	Standard Test Method for Corrosive Sulfur in Electrical Insulating Oils
ASTM D1524	2008	Standard Test Method for Visual Examination of Used Electrical Insulating Oils of Petroleum Origin in the Field
ASTM D1533	2005	Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration
ASTM D1534	2008	Standard Test Method for Approximate Acidity in Electrical Insulating Liquids by Color-Indicator Titration
ASTM D1698	2008	Standard Test Method for Sediments and Soluble Sludge in Service-Aged Insulating Oils
ASTM D1816	2004	Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes
ASTM D1903	2008	Standard Practice for Determining the Coefficient of Thermal Expansion of Electrical Insulating Liquids of Petroleum Origin, and Askarels
ASTM D1934	2005	Standard Test Method for Oxidative Aging of Electrical Insulating Petroleum Oils by Open-Beaker Method
ASTM D2112	2007	Standard Test Method for Oxidation Stability of Inhibited Mineral Insulating Oil by Pressure Vessel
ASTM D2140	2008	Standard Practice for Calculating Carbon-Type Composition of Insulating Oils of Petroleum Origin
ASTM D2300	2008	Standard Test Method for Gassing of Electrical Insulating Liquids Under Electrical Stress and Ionization (Modified Pirelli Method)

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Code	Year	Title
ASTM D2440	2004	Standard Test Method for Oxidation Stability of Mineral Insulating Oil
ASTM D3300	2006	Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Under Impulse Conditions
ASTM D3455	2002	Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin
ASTM D3487	2009	Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus
ASTM D4059	2010	Standard Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquids by Gas Chromatography
ASTM D5222	2008	Standard Specification for High Fire-Point Mineral Electrical Insulating Oils
ASTM D6180	2005	Standard Test Method for Stability of Insulating Oils of Petroleum Origin Under Electrical Discharge
ASTM D6871	2008	Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus

Table E.6.: Standards regarding insulating mineral oils by the International Electrotechnical Commission (IEC).

Code	Year	Title
IEC 60156	1995	Insulating liquids - Determination of the breakdown voltage at power frequency - Test method
IEC 60247	2004	Insulating liquids - Measurement of relative permittivity, dielectric dissipation factor (tan d) and d.c. resistivity
IEC 60296	2003	Fluids for electrotechnical applications - Unused mineral insulating oils for transformers and switchgear
IEC 60422	2005	Mineral insulating oils in electrical equipment - Supervision and maintenance guidance
IEC 60475	1974	Method of sampling liquid dielectrics
IEC 60590	1977	Determination of the aromatic hydrocarbon content of new mineral insulating oils
IEC 60666	2010	Detection and determination of specified additives in mineral insulating oils
IEC 60814	1997	Insulating liquids - Oil-impregnated paper and pressboard - Determination of water by automatic coulometric Karl Fischer titration

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Code	Year	Title
IEC 60897	1987	Methods for the determination of the lightning breakdown voltage of insulating liquids
IEC 61039	2008	Classification of insulating liquids
IEC 61065	1991	Method for evaluating the low temperature flow properties of mineral insulating oils after ageing
IEC 61125	1992	Unused hydrocarbon based insulating liquids - Test methods for evaluating the oxidation stability
IEC 61144	1992	Test method for the determination of oxygen index of insulating liquids
IEC 61198	1993	Mineral insulating oils - Methods for the determination of 2-furfural and related compounds
IEC 61203	1992	Synthetic organic esters for electrical purposes - Guide for maintenance of transformer esters in equipment
IEC 61619	1997	Insulating liquids - Contamination by polychlorinated biphenyls (PCBs) - Method of determination by capillary column gas chromatography
IEC 61868	1998	Mineral insulating oils - Determination of kinematic viscosity at very low temperatures
IEC/TR 61946	2007	Mineral insulating oils - Characterization of paraffinic/naphthenic nature - Low temperature differential scanning calorimetry (DSC) test method
IEC 62021-1	2003	Insulating liquids - Determination of acidity - Part 1: Automatic potentiometric titration
IEC 62021-2	2007	Insulating liquids - Determination of acidity - Part 2: Colourimetric titration
IEC/TR 62036	2007	Mineral insulating oils - Oxidation stability test method based on differential scanning calorimetry (DSC)
IEC 62535	2008	Insulating liquids - Test method for detection of potentially corrosive sulphur in used and unused insulating oil

Table E.7.: Standards regarding insulating mineral oils by the British Standards' Institution (BS).

Code	Year	Title
BS 148	2009	Specifications for reclaimed mineral insulating oil for transformers and switchgear
BS 2000-315	1998	Methods of test for petroleum and its products
BS 6522	1984	Methods for determination of percentage water saturation of insulating oil

Shell Diala Oil G

Gasabsorbing non-inhibited insulating oil

Properties
Shell Diala Oil G is a specially refined naphthenic mineral oil with high oxidation stability, good electrical properties, excellent low temperature properties and is gasabsorbing under conditions of electrical stress.

Application
Shell Diala Oil G is preferably used in electric equipment with high field strengths. It retains its high oxidation stability and long service life also at high thermal loads. Its main use is in transformers of high to extreme voltage ratings as well as in instrument transformers and capacitors.

Typical Data
Shell Diala Oil G meets the following specifications:
- DIN 57370-1 / VDE 0370 Part 1, Class A
- IEC 296, Class II

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Deutsche Shell Aktiengesellschaft, Vertriebszentrum Schmierstoffe

			Requirements of DIN 57370-1/VDE 0370 Part 1 Class A	Shell Diala Oil G
Appearance		*DIN 57370*	*clear, free of solids*	*complies*
Density at 15°C *at 20°C*	*kg/m³* *kg/m³*	*DIN 51757* *DIN 51757*	*≤898* *≤895*	*887* *884*
Kinematic viscosity *at 20°C* *at -30°C*	 *mm²/s* *mm²/s*	*DIN 51562-1*	 *≤25* *≤1800*	 *19* *1080*
Flash point P.M.	*°C*	*DIN EN 22719*	*≥130*	*136*
Neutralisation value	*mg KOH/g*	*DIN 51558-2*	*≤0,03*	*<0,03*
Corrosive sulphur		*DIN 51353*	*non-corrosive*	*non-corrosive*
Breakdown voltage (after treatment)	*kV*	*DIN EN 60156*	*≥50*	*>60*
Dielectric dissipation factor at 90°C (after treatment)		*DIN 57370*	*≤0,005*	*0,001*
Oxidation stability *Baader (140 h/110°C)* *Saponification value* *Sludge content* *Dielectric dissipation factor at 90°C*	 *mg* *KOH/g* *%m*	*DIN 51554*	 *≤0,60* *≤0,05* *≤0,18*	 *0,2* *0,02* *0,01*
Oxidation stability (164 h/100°C) *Neutralisation value* *Sludge content*	 *mg* *KOH/g* *%m*	*IEC 1125 A*	 *≤0,30* *≤0,06*	 *<0,03* *0,04*
Gassing tendency	*mm³/min*	*IEC 628 A*	*-*	*-10*

E.6 Interpretation of dissolved gas analysis

Table E.8.: Experimental data on gassing of mineral oils under electrical and thermal stress published by Cigré [E.30]. Contrary to table 6.9, carbon dioxide and hydrocarbons with three carbon atoms are also considered here when evaluating the percentage concentration of each gas. All values in the table are in % by volume and refer to the concentration of gases dissolved in the oil.

Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	C_3H_x	CO	CO_2
low-energy discharge	88	7	2	–	–	1	1	1
high-energy discharge	55	7	5	6	15	6	1	6
disruptive discharge	39	10	–	6	35	3	4	2
overheating, oil 300 °C	–	37	13	19	–	31	–	–
overheating, oil 500 °C	17	25	8	25	–	23	–	–
overheating, oil 800 °C	16	16	6	41	–	21	–	–
overheating, paper 300 °C	26	1	–	–	–	–	–	73
overheating, paper 500 °C	6	1	–	–	–	–	33	59
overheating, paper 800 °C	9	8	1	4	–	1	50	25

Table E.9.: Interpretation scheme for DGA applied to mineral oil-filled power transformers by the UK Central Electric Generating Board, after its first revision in 1975 [E.31] (the table presented here has been rearranged).

Fault type	$\frac{CH_4}{H_2}$	$\frac{C_2H_6}{CH_4}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_2}{C_2H_4}$
normal deterioration	0	0	0	0
partial discharge	5	0	0	0
slight overheating < 150 °C	1/2	0	0	0
slight overheating 150 °C – 200 °C	1/2	1	0	0
slight overheating 200 °C – 300 °C	0	1	0	0
general conductor overheating	0	0	1	0
winding circulating currents	1	0	1	0
core and tank circulating currents	1	0	2	0
flashover without power flow through	0	0	0	1
arc with power flow through	0	0	1/2	1/2
continuous sparking to floating potential	0	0	2	2
partial discharge with tracking	5	0	0	1/2
coding of gas concentrations (in ppm by volume)				
code 0	0.1–1.0	< 1.0	< 1.0	< 0.5
code 1	1.0–3.0	≥ 1.0	1.0–3.0	0.5–3.0
code 2	≥ 3.0	–	≥ 3.0	≥ 3.0
code 5	≤ 0.1	–	–	–

Table E.10.: DGA interpretation scheme by Rogers after its revision in 1978 [E.32]. Apart from the deletion of the ratio of ethane to methane concentration, the ranges of the remaining ratios have been modified. Obviously, combinations of ratios not considered in the scheme might occur, which has been one of the major objections to Rogers's method.

Fault type	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
no fault	0	0	0
low-energy partial discharge	not significant	1	0
high-energy partial discharge	1	1	0
low-energy discharge	$1 \rightarrow 2$	0	$1 \rightarrow 2$
high-energy discharge	1	0	2
thermal fault $< 150\,^\circ$C	0	0	1
thermal fault $150\,^\circ$C – $300\,^\circ$C	0	2	0
thermal fault $300\,^\circ$C – $700\,^\circ$C	0	2	1
thermal fault $> 700\,^\circ$C	0	2	2
coding of gas concentrations (in ppm by volume)			
< 0.1	0	1	0
0.1–1.0	1	0	0
1.0–3.0	1	2	1
> 3.0	2	2	2

Table E.11.: Recommended sampling intervals depending on the total concentration of dissolved combustible gases, in ppm by volume, and on the respective rate of increase, in ppm per day, according to IEEE C57.104 [E.33]. The total concentration of dissolved combustible gases (TDCG) does not consider carbon dioxide, since it is not combustible.

Condition	TDCG	TDCG rate	Sampling interval
condition 4	$> 4,630$	> 10	daily
		< 10	weekly
condition 3	1920–4630	> 10	weekly
		< 10	monthly
condition 2	720–1920	> 10	monthly
		< 10	quarterly
condition 1	< 720	> 30	monthly
		10–30	quarterly
		< 10	annual

Table E.12.: Typical concentrations of decomposition gases dissolved in the oil of power transformers (predominantly sealed equipment), according to IEEE C57.104 [E.33]. All values are in ppm by volume.

Condition	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
1	< 100	< 120	< 65	< 50	< 2	< 350	$< 2,500$
2	100–700	120–400	65–100	50–100	2–9	350–570	2,500–4,000
3	700–1,800	400–1,000	100–150	100–200	10–35	570–1,400	4,000–10,000
4	$> 1,800$	$> 1,000$	> 150	> 200	> 35	$> 1,400$	$> 10,000$

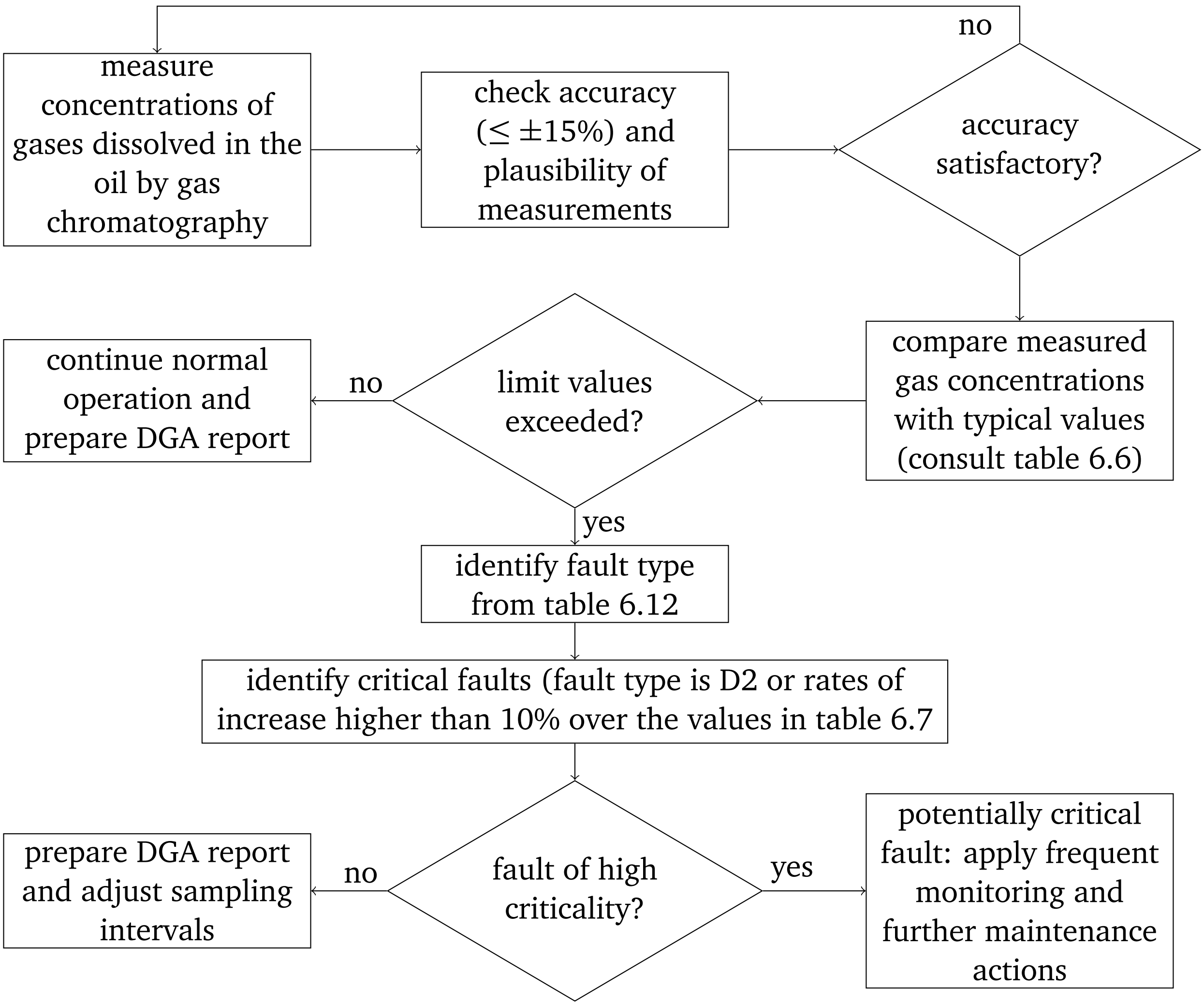

Figure E.5.: Recommended procedure for dissolved gas analysis according to IEC 60599 [E.34].

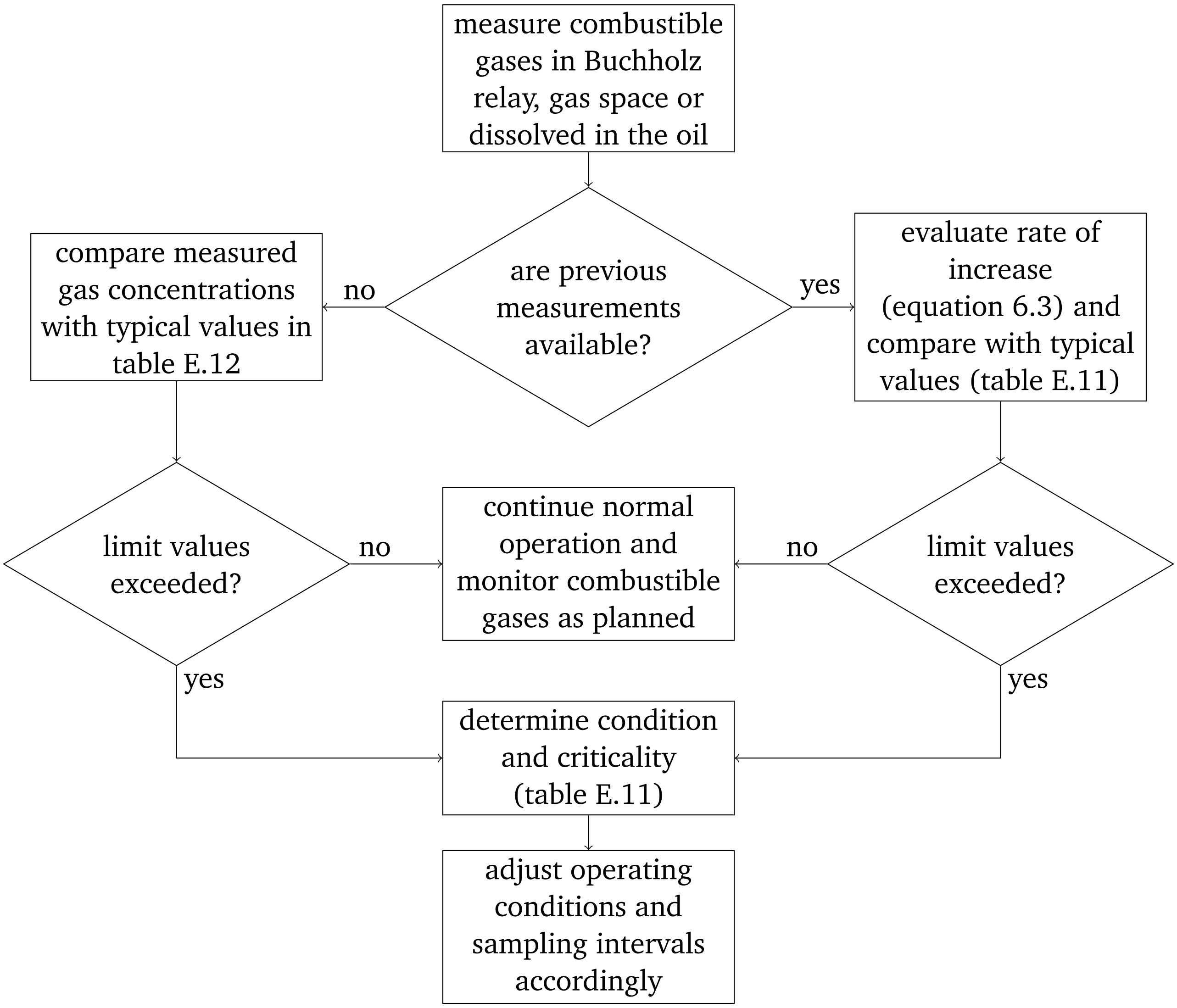

Figure E.6.: Flowchart for gas analysis of power transformers according to IEEE C57.104 [E.33].

F Annex to chapter 7

F.1 Second Cigré survey on high-voltage instrument transformers

Table F.1.: Distribution of high-voltage instrument transformers by type, insulating system and voltage rating (abstract). The survey conducted by Cigré between 1985 and 1995 comprised a total of 131,207 units from 16 utilities [F.1].

		Oil & paper	SF_6 gas	Cast resin
inductive current transformer	72.5 kV – 245 kV	90.7 %	0.9 %	8.4 %
	245 kV – 420 kV	97.0 %	3.0 %	–
	> 420 kV	88.3 %	11.7 %	–
inductive voltage transformer	72.5 kV – 245 kV	98.5 %	1.3 %	0.2 %
	245 kV – 420 kV	94.1 %	5.9 %	–
	> 420 kV	97.0 %	3.0 %	–
total		96.0 %	1.9 %	2.1 %

F.2 Additional information on the test sample

Table F.2.: Ratings of the instrument transformers used in the case study of chapter 7 [F.2].

Attribute	Rating
primary voltage	400 kV
secondary voltage	2 × 100 V
accuracy class	0.2
rated frequency	50 Hz
rated burden	100 VA
rated secondary current	2 × 40 A
oil content	370 kg
specifications	IEC 186[a]
basic insulation level (BIL)	1425 kV
power-frequency voltage withstand test	1.9 U_n, 4 h

[a] IEC 186 has been superseded 1997 by the first edition of IEC 60044-2.

F.3 Results of fuzzy DGA interpretation

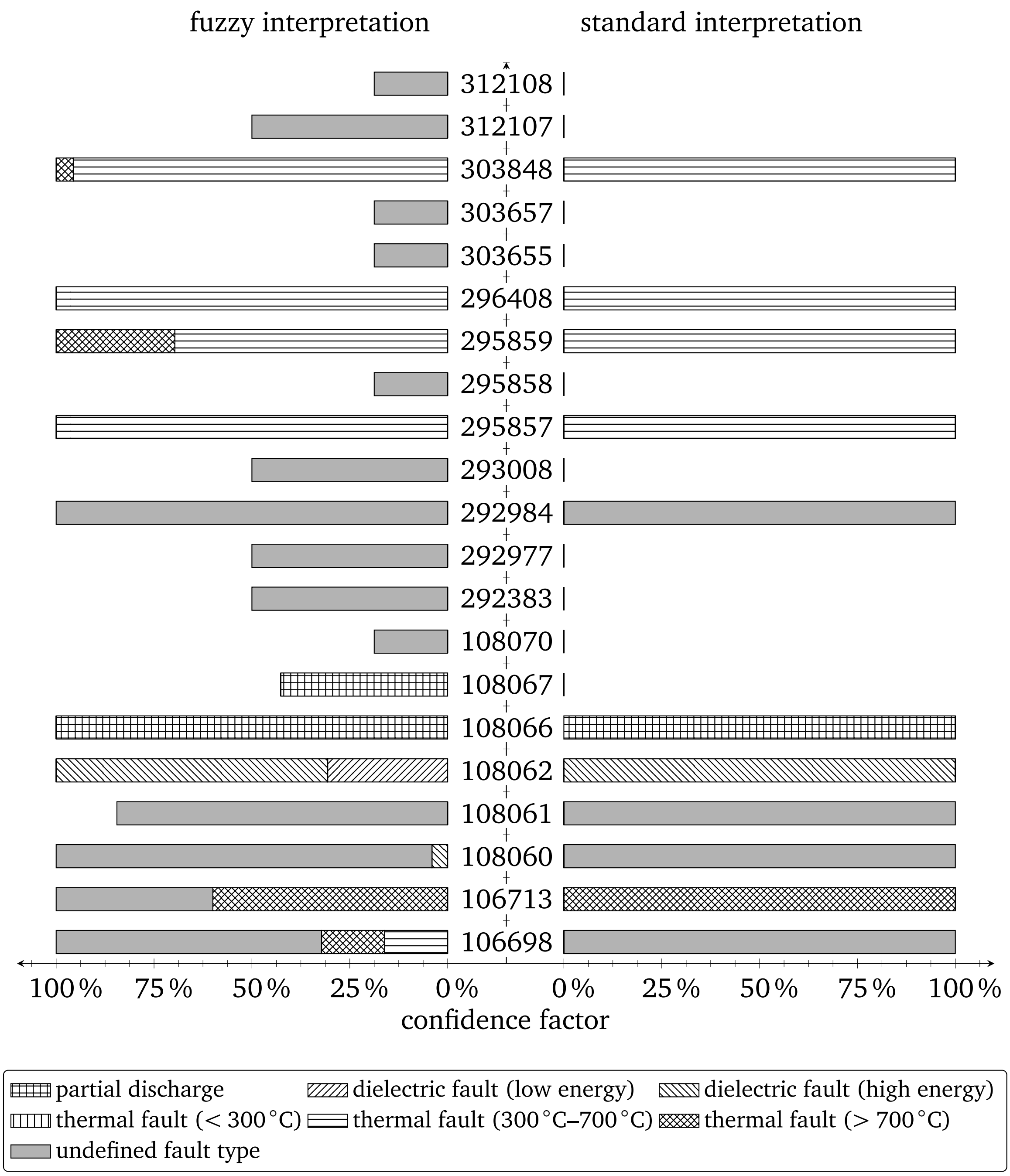

Figure F.1.: Diagnostic findings of the detailed fuzzy interpretation scheme for fuzzification level 2 (typical gas concentrations obtained from the 95-percentile). Values in the y axis correspond to the ID code of equipment.

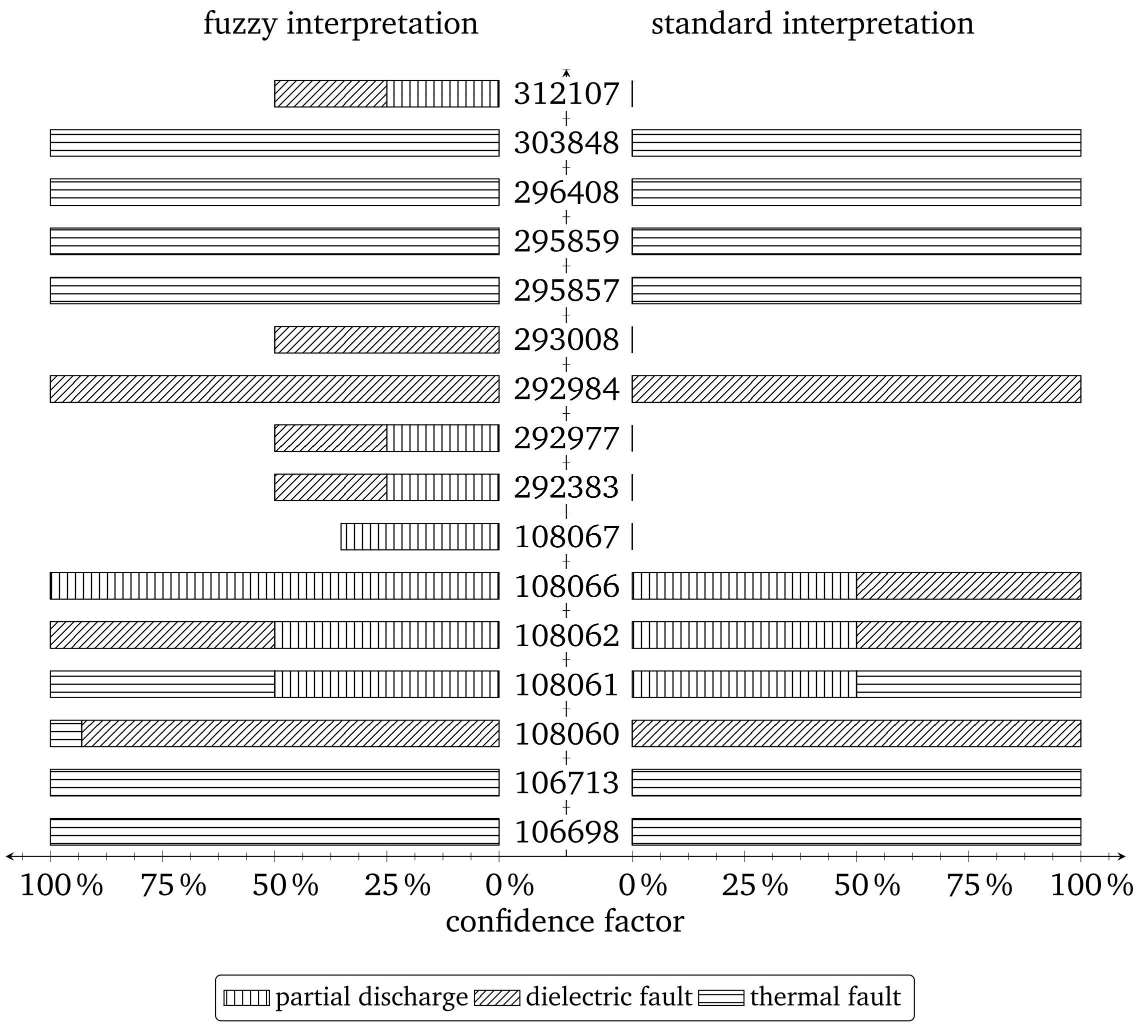

Figure F.2.: Diagnostic findings of the simplified fuzzy interpretation scheme for fuzzification level 1 (typical gas concentrations obtained from the 95-percentile).

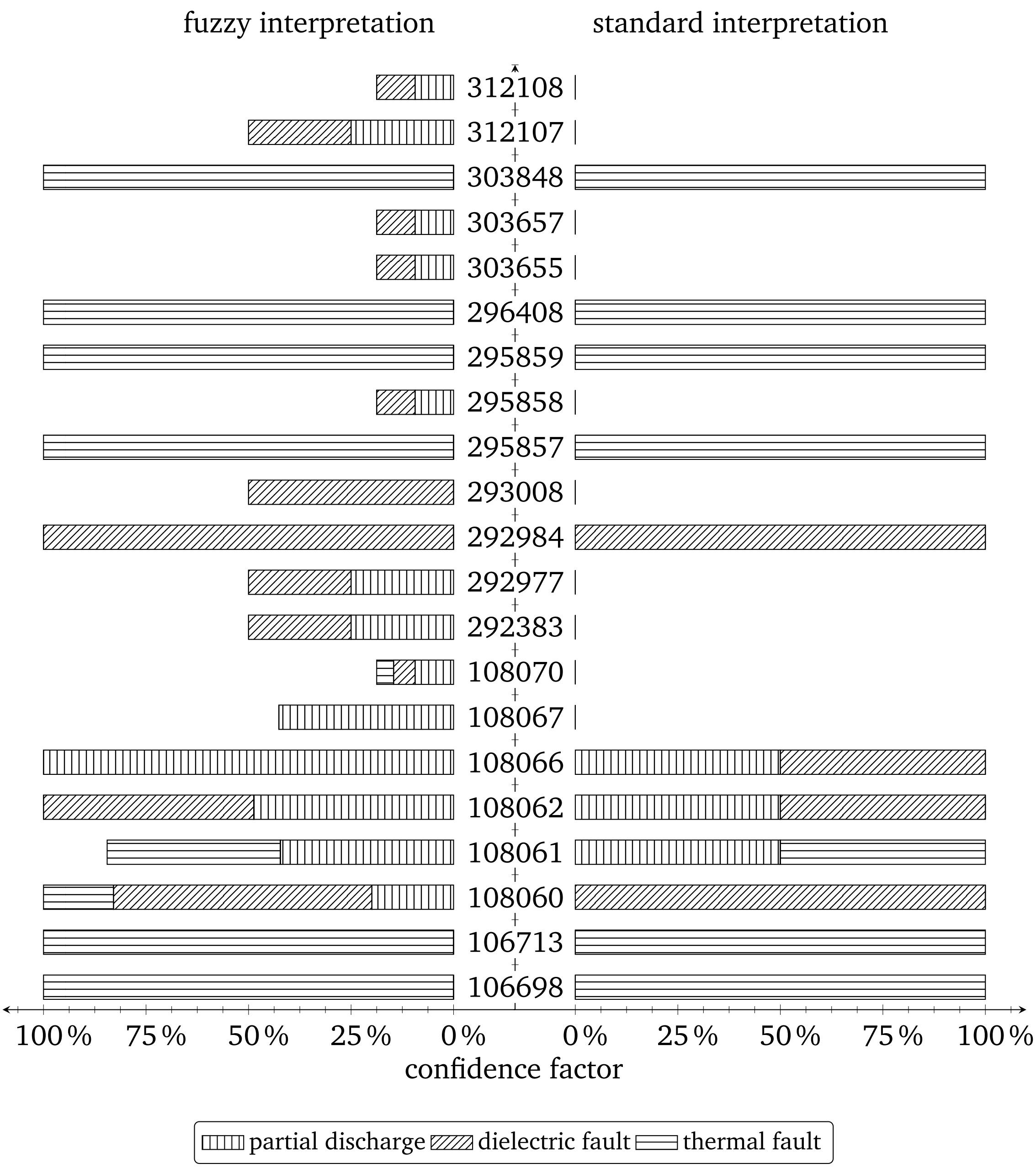

Figure F.3.: Diagnostic findings of the simplified fuzzy interpretation scheme for fuzzification level 2 (typical gas concentrations obtained from the 95-percentile).

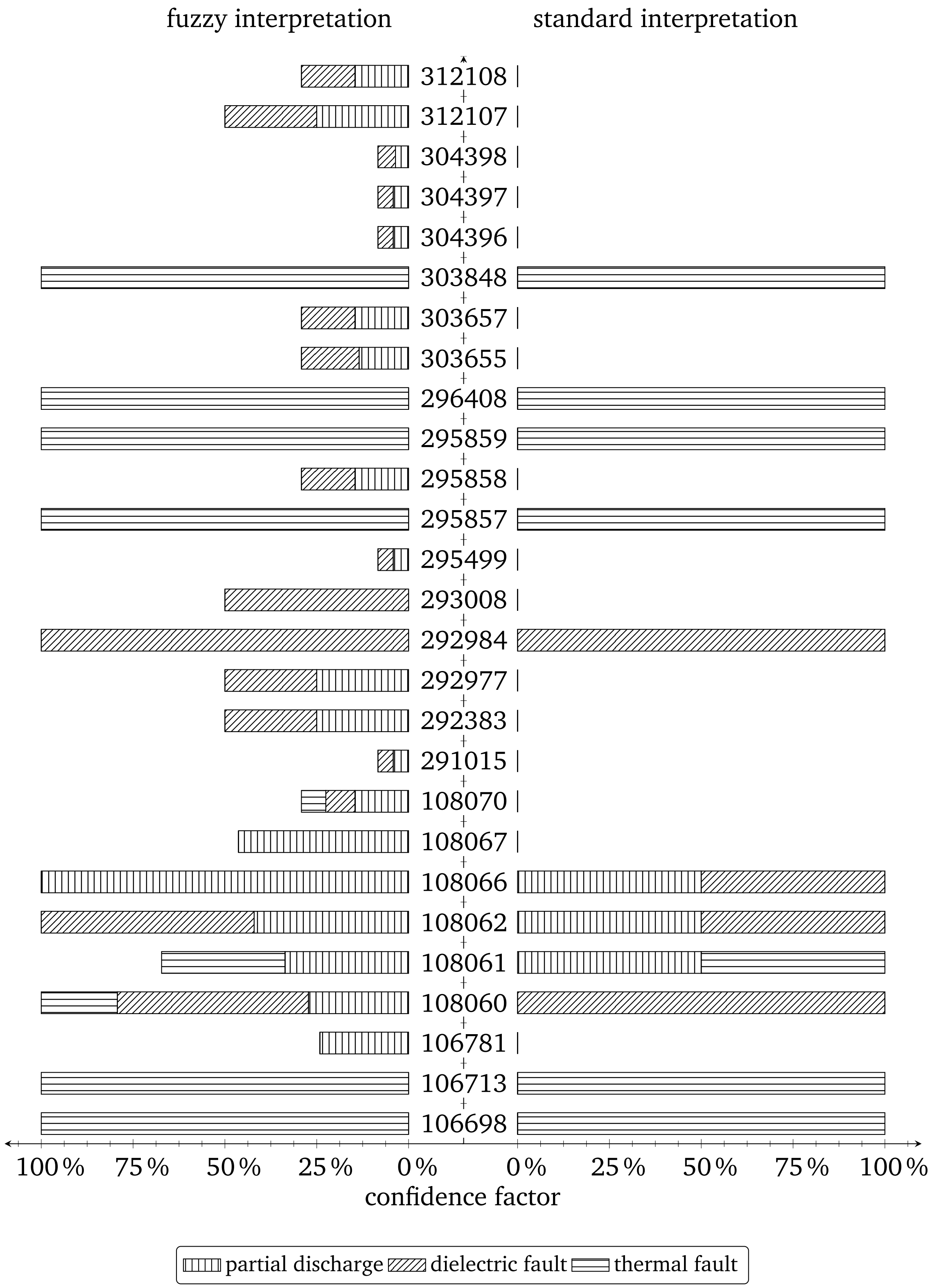

Figure F.4.: Diagnostic findings of the simplified fuzzy interpretation scheme for fuzzification level 3 (typical gas concentrations obtained from the 95-percentile).

G Annex to chapter 8

G.1 Used membership functions and their partial derivatives

Throughout chapter 8 three relations are used in the fuzzy rules: the “lower than ...”, “higher than ...” and “between ...” relation. The membership functions shown below are used so as to model these relations. Their main advantage (for example over the ramp of triangular membership functions) is the fact that they are continuously differentiable, which makes them suitable for application with the backpropagation algorithm.

G.1.1 Monotonically increasing sigmoid membership function

Increasing sigmoid membership functions are used so as to model “higher than ...” relations. They are defined by equation G.1:

$$\mu_x(x) = \frac{1}{1+e^{-a(x-c)}} \tag{G.1}$$

with $a > 0$. Parameter a is the *form* or *shape* parameter, whereas c is the *scale* parameter. Figure G.1 shows their influence.

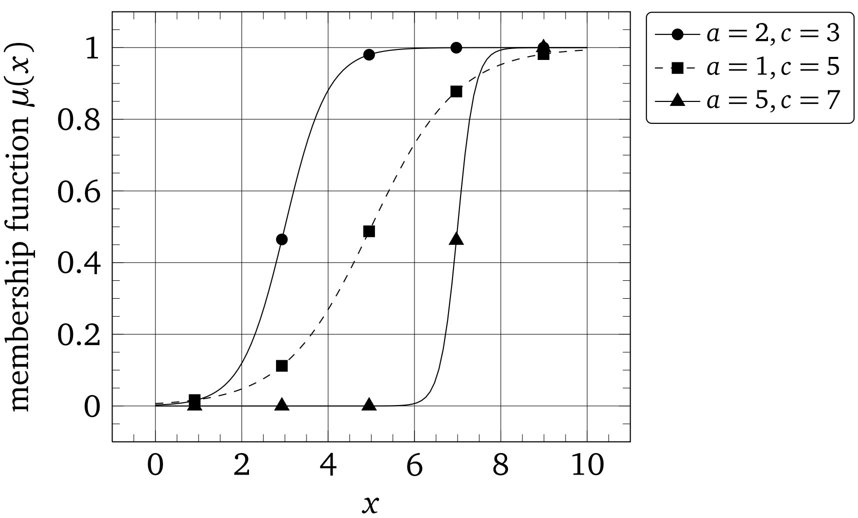

Figure G.1.: Monotonically increasing sigmoid membership function. The scale parameter c controls the location of the membership function ($\mu(c) = 0.5$), while the shape parameter a influences its form: the higher a the steeper the function will be.

The partial derivatives of the increasing sigmoid function with respect to its parameters are:

$$\frac{\partial \mu_x(x)}{\partial a} = \frac{(x-c)\cdot e^{-a(x-c)}}{\left(1+e^{-a(x-c)}\right)^2} \tag{G.2a}$$

$$\frac{\partial \mu_x(x)}{\partial c} = \frac{-a\cdot e^{-a(x-c)}}{\left(1+e^{-a(x-c)}\right)^2} \tag{G.2b}$$

G.1.2 Monotonically decreasing sigmoid membership function

Decreasing sigmoid membership functions are used so as to model "lower than ..." relations. They are defined by equation G.3:

$$\mu_x(x) = \frac{e^{-a(x-c)}}{1+e^{-a(x-c)}} \tag{G.3}$$

with $a > 0$. Again, a and c are the shape and scale parameters, respectively. Figure G.2 graphically shows a decreasing sigmoid function.

The partial derivatives of the decreasing sigmoid function with respect to its parameters are:

$$\frac{\partial \mu_x(x)}{\partial a} = \frac{-(x-c)\cdot e^{-a(x-c)}}{\left(1+e^{-a(x-c)}\right)^2} \tag{G.4a}$$

$$\frac{\partial \mu_x(x)}{\partial c} = \frac{a\cdot e^{-a(x-c)}}{\left(1+e^{-a(x-c)}\right)^2} \tag{G.4b}$$

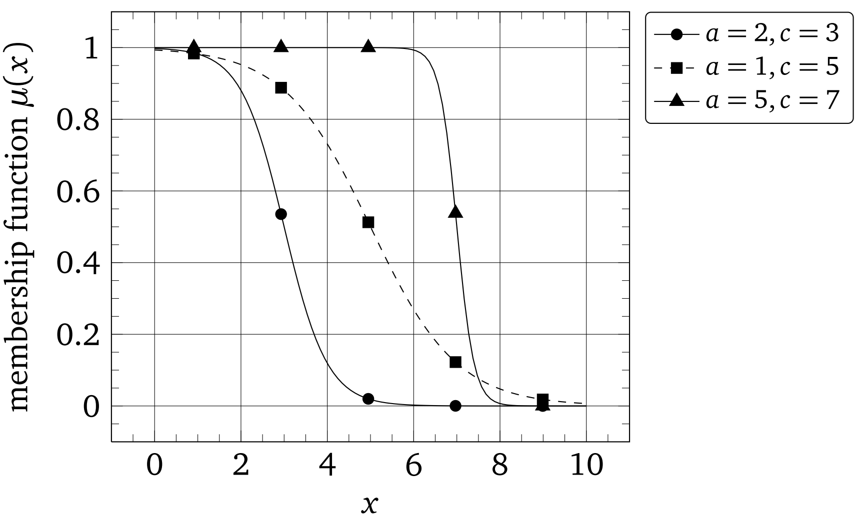

Figure G.2.: Monotonically decreasing sigmoid membership function. Obviously, the decreasing sigmoid function is complementary to its increasing counterpart (figure G.1). Also, shape and scale parameters act similarly.

G.1.3 Generalised bell-shaped membership function

Generalised bell-shaped membership functions are used so as to model "between ..." relations. They are defined by equation G.5:

$$\mu_x(x) = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}} \tag{G.5}$$

with $b > 0$. Here, a and b are the shape parameters, and c is the scale parameter. Figure G.3 shows their influence.

The partial derivatives of the generalised bell-shaped function with respect to its parameters are:

$$\frac{\partial \mu_x(x)}{\partial a} = \frac{\frac{2b}{|a|} \cdot \left|\frac{x-c}{a}\right|^{2b} \cdot \operatorname{sgn}(a)}{\left(1 + \left|\frac{x-c}{a}\right|^{2b}\right)^2} \tag{G.6a}$$

$$\frac{\partial \mu_x(x)}{\partial b} = \frac{-2\left|\frac{x-c}{a}\right|^{2b} \cdot \ln\left(\left|\frac{x-c}{a}\right|\right) \cdot \operatorname{sgn}(b)}{\left(1 + \left|\frac{x-c}{a}\right|^{2b}\right)^2} \tag{G.6b}$$

$$\frac{\partial \mu_x(x)}{\partial c} = \frac{\frac{2b}{|x-c|} \cdot \left|\frac{x-c}{a}\right|^{2b} \cdot \operatorname{sgn}(x-c)}{\left(1 + \left|\frac{x-c}{a}\right|^{2b}\right)^2} \tag{G.6c}$$

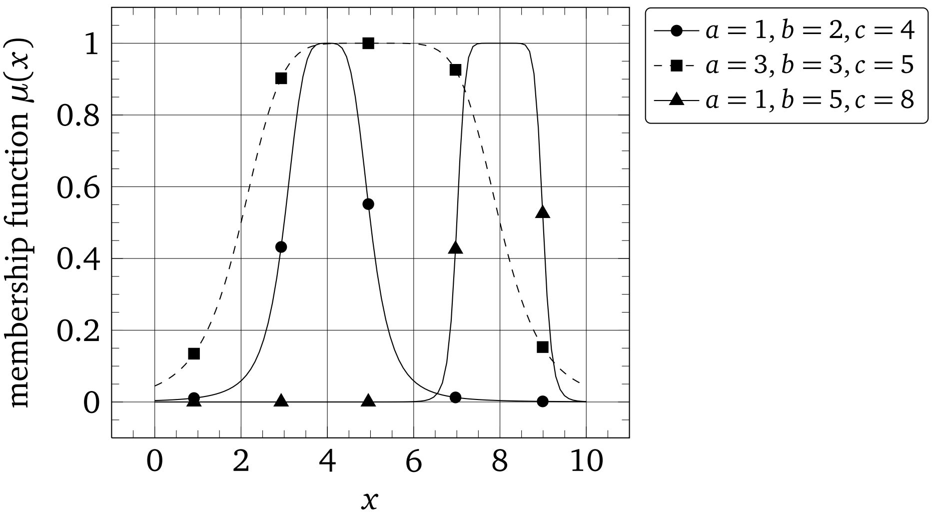

Figure G.3.: Generalised bell-shaped membership function. Scale parameter c controls the location of the membership function ($\mu(c) = 1$). On the other hand, shape parameter b influences the form: the higher b the steeper the function will be. Finally, a controls the width of the bell: the inflexion points are $\mu(a-c) = \mu(a+c) = 0.5$

G.2 Comparative results of modified learning algorithms for section 8.2

The performance of the learning algorithm has been examined with regard to following questions:

1. *Do learning algorithms other the resilient backpropagation deliver better results*? In total, four algorithms have been investigated: standard backpropagation, backpropagation with momentum term[1] as well as superSAB[2] and RPROP.

2. *Is it perhaps possible to enhance the performance of the learning algorithm by searching only for some and not all model parameters*? In order to answer this question, the shape parameters of the respective membership functions have to be pre-defined, and only the scale parameters (which are the most relevant for modelling) should be estimated. This would lead to a simplification of the problem, because of a lower dimensionality (i.e. less parameters have to be estimated), however, approximation accuracy will depend on the assumed values for the pre-defined parameters.

3. *Instead of using the mean square approximation error ϵ over the whole dataset, would it be perhaps better to use the error with respect to each individual data pair ϵ^{ν}*? Using individual deviations for learning is equivalent to "on-line" learning, where data pairs are entered sequentially. In case a larger dataset is available for learning, as in our case, one speaks of "off-line" learning. According to the literature, on-line learning –generally speaking– performs better [G.2].

The fuzzy model in section 8.2.1 served as case study. A total of $s = 1000$ reference input-output data pairs served as input for the learning algorithms. Learning was terminated as soon as the mean square error was lower than a threshold.

With respect to the first question, both standard backpropagation as well as backpropagation with momentum failed to perform and were excluded from further considerations. The reasons lies in the fact that some model parameters (in particular the shape parameters) require significantly larger steps than others, so that the algorithm will either fail to converge or –in case the step width is increased– will yield poor estimates for the more "sensitive" parameters.

The remaining two algorithms (superSAB and RPROP) were examined simultaneously with respect to question 1 and 2 above. An overview is given in table G.2. Obviously, RPROP performs better than the superSAB algorithm in all cases. Regarding question 2, learning might potentially be enhanced by pre-defining some parameters (compare the column with $a = 2000$ for RPROP), however, it could also form an obstacle in case of poor assumptions (columns $a = 1000$ and $a = 10000$).

Generally speaking, no significant benefit with respect to calculation cost should be expected by reducing the dimensionality of the problem. The reason is that the backpropagation algorithm searches individually for each parameter ("parallel processing").

[1] Refer to [G.1] and [G.2] for an introduction to standard backpropagation and backpropagation with momentum.

[2] SuperSAB is a modification of standard backpropagation, where the step width is increased in case the sign of the partial derivative remains constant over several steps, and decreased otherwise. The algorithm was introduced in [G.3] and is also used by RPROP.

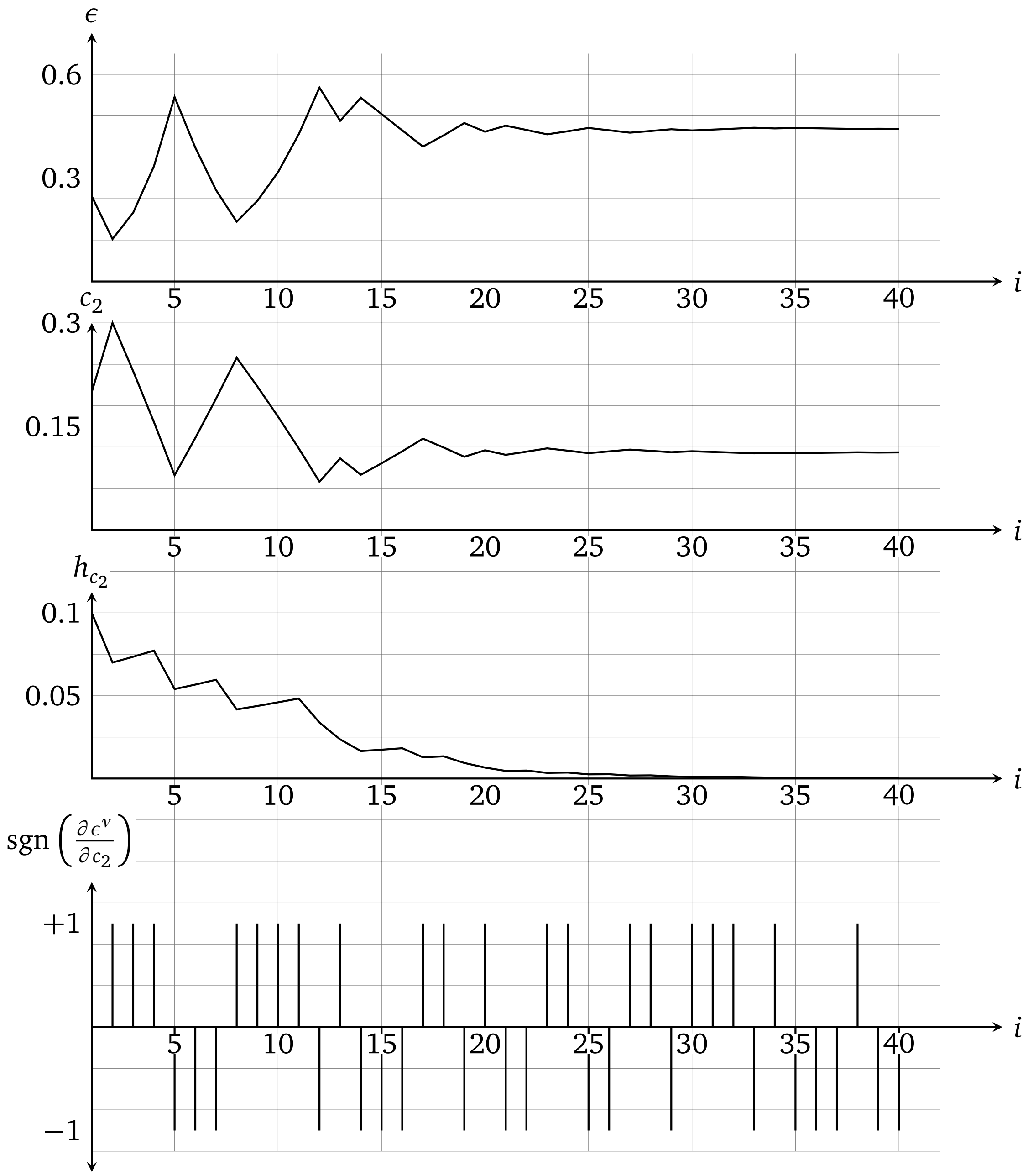

Figure G.4.: Visualisation of the problems related with on-line learning. Due to continuous sign changes of the partial derivative with respect to the most significant parameter $\partial \epsilon^{\nu} / \partial c_2$ (lower graph), the corresponding step width h_{c_2} decreases rapidly (third graph from top). This leads to stagnation of the parameter estimate c_2 (second graph from top). The learning algorithm is trapped in a local minimum after only $t = 40$ iterations (upper graph).

Table G.1.: Comparison of the superSAB and RPROP learning algorithms. The fuzzy model of section 8.2.1 was used as case study, with $s = 1000$ reference input-output data pairs. Learning rates were set to $h = 0.1$, $\eta^+ = 1.05$ and $\eta^- = 0.7$ for both algorithms. The number of iterations i as well as the total computation time t reflect the learning performance: the lower their values, the better the performance. Several combinations did not yield any solution with the required approximation accuracy. Obviously, the learning was trapped in local minima in these cases. The labels "bound" versus "free" inform whether the shape parameters were pre-defined or not (question 2).

		superSAB				RPROP			
		free	bound ($a = \ldots$) 1000	2000	10000	free	bound ($a = \ldots$) 1000	2000	10000
$\epsilon < 10^{-3}$	i	322				103	5	5	–
	t	3.1 s				1.8 s	1.2 s	1.2 s	
$\epsilon < 10^{-9}$	i	604		no solution possible		130	–	5	–
	t	4.7 s				1.9 s		1.2 s	
$\epsilon < 10^{-15}$	i	887				141	–	17	–
	t	6.4 s				2.0 s		1.2 s	

As for the question of on-line versus off-line learning, expectations of better performance with on-line learning could not be met. It appears that applying on-line learning (where the sign of the partial derivatives of the approximation error change much more often than with off-line learning) undermines the main search mechanism of superSAB and RPROP: continuous sign changed of the partial derivatives lead to reduction of the step width (compare equation 2.45 in figure 2.4) and the algorithm is "trapped" at a local minimum. This effect can be identified in figure G.4.

G.3 Partial derivatives used for learning in section 8.2

This section provides the learning formulae to be use with the fuzzy models for dielectric and thermal fault classification (sections 8.2.2 and 8.2.3 respectively).

G.3.1 Fuzzy interpretation model for dielectric fault classification

Equation G.7 is used for training of the first part in the rule's premise (*if* ratio 1 higher than 1 *and* ratio 2 between 0.1 and 0.5 *and* ratio 3 higher than 1):

$$\frac{\partial \epsilon}{\partial a_{1,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{2,1}}(\tilde{r}_2^\nu) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{1,1}}(\tilde{r}_1^\nu)}{\partial a_{1,1}} \tag{G.7a}$$

$$\frac{\partial \epsilon}{\partial c_{1,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{2,1}}(\tilde{r}_2^\nu) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{1,1}}(\tilde{r}_1^\nu)}{\partial c_{1,1}} \tag{G.7b}$$

$$\frac{\partial \epsilon}{\partial a_{2,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,1}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{2,1}}(\tilde{r}_2^\nu)}{\partial a_{2,1}} \tag{G.7c}$$

$$\frac{\partial \epsilon}{\partial b_{2,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,1}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{2,1}}(\tilde{r}_2^\nu)}{\partial b_{2,1}} \tag{G.7d}$$

$$\frac{\partial \epsilon}{\partial c_{2,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,1}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{2,1}}(\tilde{r}_2^\nu)}{\partial c_{2,1}} \tag{G.7e}$$

$$\frac{\partial \epsilon}{\partial a_{3,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,1}}(\tilde{r}_1^\nu) \cdot \mu_{r_{2,1}}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial a_{3,1}} \tag{G.7f}$$

$$\frac{\partial \epsilon}{\partial c_{3,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1 > \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,1}}(\tilde{r}_1^\nu) \cdot \mu_{r_{2,1}}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial c_{3,1}} \tag{G.7g}$$

where $y_{res}^\nu = \max\Big\{\mu_{r_{1,1}}\left(\underline{p}_{r_{1,1}}, \tilde{r}_1^\nu\right) \cdot \mu_{r_{2,1}}\left(\underline{p}_{r_{2,1}}, \tilde{r}_2^\nu\right) \cdot \mu_{r_{3,1}}\left(\underline{p}_{r_{3,1}}, \tilde{r}_3^\nu\right),$

$$\mu_{r_{1,2}}\left(\underline{p}_{r_{1,2}}, \tilde{r}_1^\nu\right) \cdot \mu_{r_{2,2}}\left(\underline{p}_{r_{2,2}}, \tilde{r}_2^\nu\right) \cdot \mu_{r_{3,2}}\left(\underline{p}_{r_{3,2}}, \tilde{r}_3^\nu\right)\Big\}$$

and s_1 is the number of reference datasets leading to a higher aggregation result in the first part of the premise ($\mu_{ag}^1 > \mu_{ag}^2$). Likewise, equation G.8 is used for training of the second part in the rule's premise (*if* ratio 1 between 0.6 and 2.5 *and* ratio 2 between 0.1 and 1 *and* ratio 3 higher than 2):

$$\frac{\partial \epsilon}{\partial a_{1,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{2,2}}(\tilde{r}_2^{\nu}) \cdot \mu_{r_{3,2}}(\tilde{r}_3^{\nu}) \cdot \frac{\partial \mu_{r_{1,2}}(\tilde{r}_1^{\nu})}{\partial a_{1,2}} \tag{G.8a}$$

$$\frac{\partial \epsilon}{\partial b_{1,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{2,2}}(\tilde{r}_2^{\nu}) \cdot \mu_{r_{3,2}}(\tilde{r}_3^{\nu}) \cdot \frac{\partial \mu_{r_{1,2}}(\tilde{r}_1^{\nu})}{\partial b_{1,2}} \tag{G.8b}$$

$$\frac{\partial \epsilon}{\partial c_{1,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{2,2}}(\tilde{r}_2^{\nu}) \cdot \mu_{r_{3,2}}(\tilde{r}_3^{\nu}) \cdot \frac{\partial \mu_{r_{1,2}}(\tilde{r}_1^{\nu})}{\partial c_{1,2}} \tag{G.8c}$$

$$\frac{\partial \epsilon}{\partial a_{2,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^{\nu}) \cdot \mu_{r_{3,2}}(\tilde{r}_3^{\nu}) \cdot \frac{\partial \mu_{r_{2,2}}(\tilde{r}_2^{\nu})}{\partial a_{2,2}} \tag{G.8d}$$

$$\frac{\partial \epsilon}{\partial b_{2,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^{\nu}) \cdot \mu_{r_{3,2}}(\tilde{r}_3^{\nu}) \cdot \frac{\partial \mu_{r_{2,2}}(\tilde{r}_2^{\nu})}{\partial b_{2,2}} \tag{G.8e}$$

$$\frac{\partial \epsilon}{\partial c_{2,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^{\nu}) \cdot \mu_{r_{3,2}}(\tilde{r}_3^{\nu}) \cdot \frac{\partial \mu_{r_{2,2}}(\tilde{r}_2^{\nu})}{\partial c_{2,2}} \tag{G.8f}$$

$$\frac{\partial \epsilon}{\partial a_{3,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^{\nu}) \cdot \mu_{r_{2,2}}(\tilde{r}_2^{\nu}) \cdot \frac{\partial \mu_{r_{3,2}}(\tilde{r}_3^{\nu})}{\partial a_{3,2}} \tag{G.8g}$$

$$\frac{\partial \epsilon}{\partial c_{3,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2 > \mu_{ag}^1} \left(y_{res}^{\nu} - \tilde{y}^{\nu} \right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^{\nu}) \cdot \mu_{r_{2,2}}(\tilde{r}_2^{\nu}) \cdot \frac{\partial \mu_{r_{3,2}}(\tilde{r}_3^{\nu})}{\partial c_{3,2}} \tag{G.8h}$$

where s_2 is the number of reference datasets leading to a higher aggregation result in the second part of the premise ($\mu_{ag}^2 > \mu_{ag}^1$). The partial derivatives of the increasing sigmoid function as well as of the generalised bell-shaped function may be found in appendix G.1.

G.3.2 Fuzzy interpretation model for thermal fault classification

Equation G.9 is used for training of the first part in the rule's premise (*if* ratio 2 higher than 1 *and* ratio 3 lower than 1). The partial derivatives of the sigmoid function as well as of the generalised bell-shaped function may be found in appendix G.1.

$$\frac{\partial \epsilon}{\partial a_2} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_2}(\tilde{r}_2^\nu)}{\partial a_2} \tag{G.9a}$$

$$\frac{\partial \epsilon}{\partial c_2} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{3,1}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_2}(\tilde{r}_2^\nu)}{\partial c_2} \tag{G.9b}$$

$$\frac{\partial \epsilon}{\partial a_{3,1}} = \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial a_{3,1}} \tag{G.9c}$$

$$\begin{aligned}\frac{\partial \epsilon}{\partial a_{3,2}} &= \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial c_{3,1}} \cdot \frac{\partial c_{3,1}}{\partial a_{3,2}} \\ &= \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{-\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial c_{3,1}} \end{aligned} \tag{G.9d}$$

$$\begin{aligned}\frac{\partial \epsilon}{\partial c_{3,2}} &= \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial c_{3,1}} \cdot \frac{\partial c_{3,1}}{\partial c_{3,2}} \\ &= \frac{1}{s_1} \sum_{\nu:\mu_{ag}^1>\mu_{ag}^2,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,1}}(\tilde{r}_3^\nu)}{\partial c_{3,1}} \end{aligned} \tag{G.9e}$$

where $y_{res}^\nu = \max\Big\{\mu_{r_2}\left(\underline{p}_{r_2}, \tilde{r}_2^\nu\right) \cdot \mu_{r_{3,1}}\left(\underline{p}_{r_{3,1}}, \tilde{r}_3^\nu\right), \mu_{r_{1,2}}\left(\underline{p}_{r_{1,2}}, \tilde{r}_1^\nu\right) \cdot \mu_{r_2}\left(\underline{p}_{r_2}, \tilde{r}_2^\nu\right) \cdot$
$\cdot \mu_{r_{3,2}}\left(\underline{p}_{r_{3,2}}, \tilde{r}_3^\nu\right), \mu_{r_{1,3}}\left(\underline{p}_{r_{1,3}}, \tilde{r}_1^\nu\right) \cdot \mu_{r_2}\left(\underline{p}_{r_2}, \tilde{r}_2^\nu\right) \cdot \mu_{r_{3,3}}\left(\underline{p}_{r_{3,3}}, \tilde{r}_3^\nu\right)\Big\}$

and s_1 is the number of reference datasets resulting to the highest aggregation result within the first part of the premise ($\mu_{ag}^1 > \mu_{ag}^2, \mu_{ag}^3$). Likewise, equation G.10 is used for training of the second part in the rule's premise (*if* ratio 1 lower than 0.1 *and* ratio 2 higher than 1 *and* ratio 3 between 1 and 4):

$$\frac{\partial \epsilon}{\partial a_{1,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2>\mu_{ag}^1,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \mu_{r_{3,2}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{1,2}}(\tilde{r}_1^\nu)}{\partial a_{1,2}} \tag{G.10a}$$

$$\frac{\partial \epsilon}{\partial c_{1,2}} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2>\mu_{ag}^1,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \mu_{r_{3,2}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{1,2}}(\tilde{r}_1^\nu)}{\partial c_{1,2}} \tag{G.10b}$$

$$\frac{\partial \epsilon}{\partial a_2} = \frac{1}{s_2} \sum_{\nu:\mu_{ag}^2>\mu_{ag}^1,\mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,2}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_2}(\tilde{r}_2^\nu)}{\partial a_2} \tag{G.10c}$$

(G.10d)

$$\frac{\partial \epsilon}{\partial c_2} = \frac{1}{s_2} \sum_{\nu: \mu_{ag}^2 > \mu_{ag}^1, \mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,2}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_2}(\tilde{r}_2^\nu)}{\partial c_2} \tag{G.10e}$$

$$\frac{\partial \epsilon}{\partial a_{3,2}} = \frac{1}{s_2} \sum_{\nu: \mu_{ag}^2 > \mu_{ag}^1, \mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,2}}(\tilde{r}_3^\nu)}{\partial a_{3,2}} \tag{G.10f}$$

$$\frac{\partial \epsilon}{\partial b_{3,2}} = \frac{1}{s_2} \sum_{\nu: \mu_{ag}^2 > \mu_{ag}^1, \mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,2}}(\tilde{r}_3^\nu)}{\partial b_{3,2}} \tag{G.10g}$$

$$\frac{\partial \epsilon}{\partial c_{3,2}} = \frac{1}{s_2} \sum_{\nu: \mu_{ag}^2 > \mu_{ag}^1, \mu_{ag}^3} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,2}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,2}}(\tilde{r}_3^\nu)}{\partial c_{3,2}} \tag{G.10h}$$

where s_2 is the number of reference datasets leading to highest aggregation result in the second part of the premise ($\mu_{ag}^2 > \mu_{ag}^1, \mu_{ag}^3$).

Finally, equation G.11 is used for training of the third part in the rule's premise (*if* ratio 1 lower than 0.2 *and* ratio 2 higher than 1 *and* ratio 3 higher than 4):

$$\frac{\partial \epsilon}{\partial a_{1,3}} = \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \mu_{r_{3,3}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{1,3}}(\tilde{r}_1^\nu)}{\partial a_{1,3}} \tag{G.11a}$$

$$\frac{\partial \epsilon}{\partial c_{1,3}} = \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \mu_{r_{3,3}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_{1,3}}(\tilde{r}_1^\nu)}{\partial c_{1,3}} \tag{G.11b}$$

$$\frac{\partial \epsilon}{\partial a_2} = \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,3}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,3}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_2}(\tilde{r}_2^\nu)}{\partial a_2} \tag{G.11c}$$

$$\frac{\partial \epsilon}{\partial c_2} = \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,3}}(\tilde{r}_1^\nu) \cdot \mu_{r_{3,3}}(\tilde{r}_3^\nu) \cdot \frac{\partial \mu_{r_2}(\tilde{r}_2^\nu)}{\partial c_2} \tag{G.11d}$$

$$\begin{aligned}\frac{\partial \epsilon}{\partial a_{3,2}} &= \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,3}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,3}}(\tilde{r}_3^\nu)}{\partial c_{3,3}} \cdot \frac{\partial c_{3,3}}{\partial a_{3,2}} \\ &= \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,3}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{-\partial \mu_{r_{3,3}}(\tilde{r}_3^\nu)}{\partial c_{3,3}}\end{aligned} \tag{G.11e}$$

$$\begin{aligned}\frac{\partial \epsilon}{\partial c_{3,2}} &= \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,3}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,3}}(\tilde{r}_3^\nu)}{\partial c_{3,3}} \cdot \frac{\partial c_{3,3}}{\partial c_{3,2}} \\ &= \frac{1}{s_3} \sum_{\nu: \mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2} \left(y_{res}^\nu - \tilde{y}^\nu\right) \cdot \mu_{r_{1,3}}(\tilde{r}_1^\nu) \cdot \mu_{r_2}(\tilde{r}_2^\nu) \cdot \frac{\partial \mu_{r_{3,3}}(\tilde{r}_3^\nu)}{\partial c_{3,3}}\end{aligned} \tag{G.11f}$$

where s_3 is the number of reference datasets leading to highest aggregation result in the last part of the premise ($\mu_{ag}^3 > \mu_{ag}^1, \mu_{ag}^2$).

G.4 Statistical analysis of dissolved gas measurements

Table G.2.: 95-percentiles of dissolved gas concentrations in case study 4, in parts per million.

Transformer type	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
Generator step-up	338	112	95	496	141	790	15118
System intertie	894	446	124	1525	586	646	8833
Step-down	167	82	151	111	151	430	6932

G.5 Power transformer fault classification

Table G.3 shows an abstract of the original 210 failure modes listed in the database. The last column provides the result of subjective assignment of each failure mode in one or more of the general fault classes “partial discharges”, “dielectric faults” and “thermal faults”.

Table G.3.: Abstract of fault classification in case study 4. Faults are described by the affected system, subsystem, component down to the failed part [G.4]. Information on failure modes and effects is also provided. The last column contains the assignment of each failure mode to one of the three general classes "partial discharge", "dielectric" and/or "thermal" fault (noted as *PD*, *D* and *T* respectively). Cases where no such assignment is possible or doubtless are denoted by the label "not defined".

System	Subsystem	Component	Part	Failure mode	Failure effect	Fault class
active parts	core	yoke	lamination	discharge marks	rise in fault gases	D
active parts	design	bolting	shoulder bolts	discharge marks	rise in fault gases	PD
active parts	winding	connection	terminal	faulty assembly	poor contact	PD
active parts	winding	insulation	insulating tape	damaged	not defined	PD
active parts	winding	insulation	insulating tape	damaged	short circuit	D
active parts	winding	insulation	not defined	not defined	not defined	not defined
active parts	winding	not defined	not defined	part. discharges	not defined	PD
active parts	winding	shield electrode	not defined	faulty assembly	short circuit	PD/D
active parts	winding	shield electrode	soldered joint	defect	breakdown	PD/D
active parts	winding	shield electrode	terminal	defect	arcing spots	PD/D
bushing	bushing	110 kV bushing	not defined	not defined	not defined	not defined
bushing	bushing	220 kV bushing	not defined	not defined	not defined	not defined
bushing	bushing	380 kV bushing	not defined	not defined	not defined	not defined
bushing	bushing	380 kV bushing	not defined	leakage	oil leakage	not defined
bushing	bushing	380 kV bushing	plug connection	deformed	poor contact	PD
bushing	bushing	seal	shield electrode	part. discharges	rise in fault gases	PD
control system	accessories	control cabinet	not defined	not defined	not defined	not defined
control system	accessories	control cabinet	not defined	faulty assembly	not defined	not defined
control system	accessories	noise barriers	not defined	defect	not defined	not defined
control system	accessories	terminal box	not defined	damaged	not defined	not defined
control system	control system	relay	air circ. relay	false adjustment	false alarm	not defined
control system	control system	relay	auxilliary switch	defect	false alarm	not defined

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System	Subsystem	Component	Part	Failure mode	Failure effect	Fault class
control system	control system	relay	paddle vabe	false adjustment	false alarm	not defined
control system	prot. system	Buchholz relay	coil	defect	false alarm	not defined
control system	prot. system	Buchholz relay	not defined	not defined	false alarm	not defined
control system	prot. system	motor protection	not defined	not defined	not defined	not defined
control system	prot. system	pressure monitor	micro switch	defect	false alarm	not defined
control system	prot. system	pressure monitor	not defined	faulty assembly	false alarm	not defined
cooling system	drive unit	air fan	bearing	wear	not defined	T
cooling system	drive unit	air fan	not defined	defect	not defined	T
cooling system	drive unit	air fan motor	not defined	defect	not defined	T
cooling system	drive unit	pump	winding	defect	not defined	T
cooling system	piping	radiator	not defined	contamination	overheating	T
external	accessories	sprinkler	not defined	defect	not defined	not defined
external	prot. system	overvoltage prot.	not defined	defect	not defined	not defined
tank	busbar	not defined	not defined	breakdown	not defined	PD/D
tank	conservator	not defined	not defined	discharge marks	not defined	PDs
tank	not defined	not defined	not defined	not defined	not defined	not defined
tank	support	not defined	not defined	contamination	breakdown	PD/D
tap-changer	diverter	limit. resistance	not defined	damaged	rise in fault gases	not defined
tap-changer	diverter	limit. resistance	terminal	defect	short circuit	not defined
tap-changer	diverter	limit. resistance	terminal	arcing spots	breakdown	not defined
tap-changer	tap selector	contacts	not defined	discharge marks	overheating	D/T
tap-changer	tap selector	contacts	not defined	oil carbonisation	rise in fault gases	D
tap-changer	tap selector	tap selector	contacts	jammed	short circuit	D
transformer oil	not defined	not defined	not defined	not defined	not defined	not defined

G.6 Training results for the fuzzy learning models

Table G.4.: Parameters of the learning fuzzy model on partial discharges before and after training (100 iterations). Refer to equation 8.1 for explanation of the symbols.

	a_2	a_3	c_2	c_3
initial values	10	10	1	10
after training	$\rightarrow 0$	182.65	0.13	8.78

Table G.5.: Scale parameters of the membership functions in equation 8.4, used for the learning fuzzy model on dielectric faults. Training was completed after 150 iterations.

	$c_{1,1}$	$c_{1,2}$	$a_{1,2}$	$c_{2,1}$	$a_{2,1}$	$c_{2,2}$	$a_{2,2}$	$c_{3,1}$	$c_{3,2}$
initial values	1	1.55	0.95	0.3	0.2	0.55	0.45	1	2
after training	0.98	1.47	0.57	0.43	$\rightarrow 0$	0.55	0.49	1.19	1.76

Table G.6.: Shape parameters of the learning algorithm on dielectric faults, equation 8.4. Since both $b_{1,2}$ and $b_{2,1}$ approach zero, the respective fuzzy sets –described by $\mu_{1,2}(r_1)$ and $\mu_{2,1}(r_2)$– will tend to reach maximal fuzzy entropy.

	$a_{1,1}$	$b_{1,2}$	$b_{2,1}$	$b_{2,2}$	$a_{3,1}$	$a_{3,2}$
initial values	10	10	10	10	10	10
after training	10.5	$\rightarrow 0$	9.58	$\rightarrow 0$	9.79	29.13

Table G.7.: Scale parameters of the membership functions in equation 8.6, used for the fuzzy model on thermal faults. Training was completed after 120 iterations.

	$c_{1,2}$	$c_{1,3}$	c_2	$c_{3,2}$	$a_{3,2}$
initial values	0.1	0.2	1	2.5	1.5
after training	0.67	0.68	< 0	2.16	1.05

Table G.8.: Shape parameters of the learning fuzzy model on thermal faults, equation 8.6.

	$a_{1,2}$	$a_{1,3}$	a_2	$a_{3,1}$	$b_{3,2}$	$a_{3,3}$
initial values	10	10	10	10	10	10
after training	6.82	6.47	1.22	42.54	16.79	12.81

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Curriculum vitae

Personal data

Name:	Athanasios Krontiris
Day of birth:	June 28, 1982
Place of birth:	Cholargos Attikis, Greece
Nationality:	hellenic
Family status:	married to Sabine Kasten

Education

10/2000 – 10/2005	Undergraduate studies in Electrical Engineering Specialisation: Electrical Power Engineering Degree: Diploma
04/2005 – 10/2005	Technische Universität Berlin Diploma thesis within Erasmus exchange programme Topic: Modelling the Three-Phase Core-Type Transformer
10/2000 – 10/2005	National Technical University Athens
09/1994 – 09/2000	Deutsche Schule Athen (secondary school)

Professional career

07/2006 to day	Technische Universität Darmstadt Institute of Electric Power & Energy research assistant
01/2006 – 06/2006	Siemens Power Transmission and Distribution High-voltage test field, Berlin Research engineer
09/2003 – 12/2004	Ldk Concultants Ltd., Athens Projects in building and utility engineering

Research activities within Cigré

08/2010 to day	Corresponding member of Working Group C1.25 (Risk Management and Information Processes for Asset Management)
10/2008 – 10/2010	Contribution to Working Groups B3.06 (Substation Management) and C1.16 (Transmission Asset Risk Management)

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