Commissioning and Service Experience with a ±550 kV DC GIL conducted in Frame of a CIGRE Prototype Installation Test

Martin Hallas, *Member, IEEE*, Claus Neumann, Volker Hinrichsen, Detlev Gross, *Senior Member, IEEE*

***Abstract*—A newly developed ±550 kV DC GIL (direct current gas-insulated transmission line) prototype was erected at a HVDC test facility at the Technical University of Darmstadt to collect first service experience with this new equipment. The 100 m long DC GIL prototype is periodically stressed with DC voltage and DC current as well as superimposed impulse voltage. The test equipment was procured for the project and partly newly developed. The overall procedure follows the prototype installation test recommendations from CIGRE TB 842. This paper presents experience collected during the commissioning and long-term testing of the DC GIL prototype. The commissioning process, events occurred, as well as resulting conclusions for type, factory acceptance and site acceptance tests of DC GIL systems are discussed. The long-term operation of the DC GIL is intended to run continuously. Interruptions occur due to external influences only. Partial discharge events and the overall performance of the DC GIL prototype during long-term stress are presented.**

***Index Terms*— Gas insulation, HVDC transmission, Monitoring, Partial discharges, Testing**

I. INTRODUCTION

THE future grid expansion in Europe is characterized by especially two challenges. First: Renewable energy is often generated far away from load centers and therefore has to be transported over long distances. Second: Compact solutions are required e.g., for offshore platforms, busducts in substations, connections via tunnels or directly buried transmission lines. The latter requirement often arises due to environmental or political aspects. These requirements are often not feasible with the conventional AC technology since compact AC transmission by cable and GIL is limited to only a few kilometers, so that more frequently HVDC installations are being planned.

Gas-insulated systems offer the required compactness and flexibility to efficiently implement HVDC projects for future grid expansion. Therefore, various HVDC technologies have been developed in recent years [1], including the DC GIL technology presented in this contribution [2]. It has been developed for compact point-to-point connections over long distances in tunnels, directly buried or in above ground busduct installation. Major advantage of the GIL technology is the high transmission power of 5 GW in case of ±550 kV operating voltage at a small corridor width of only 6 m. Furthermore, it offers low power losses, low capacitance, high safety in case of internal arcs and it is a non-flammable technology, which does not contribute to fire load. The latter aspect is of high importance for tunnel installation [3]. The ±550 kV DC GIL prototype, presented in this contribution, is based on the experience with AC GIL [2]. The major new developments are adapted insulators and novel particle traps. The DC GIL insulators are made of an adapted epoxy cast resin and an adapted geometry in a way that they are suitable for both, AC and DC voltage stress. The DC GIL particle traps can handle particles at the conductor and at the enclosure and their motion under positive and negative DC voltage [4]. The technical data of the investigated DC GIL prototype is shown in Table I.

TABLE I
TECHNICAL DATA OF DC GIL PROTOTYPE

Rated DC voltage	U_r	±550 kV
Maximum rated DC current	I_r	5000 A
Rated lightning impulse (LI) withstand voltage	U_P	±1425 kV
Rated switching impulse (SI) withstand voltage	U_S	±1050 kV

II. PROTOTYPE INSTALLATION TEST

Critical effects for gas-insulated HVDC systems are especially surface charges and particles [1]. Both effects may lead to electrical failures, and their origin may be design deficiencies or imperfections due to quality issues during manufacturing and assembling. Surface charges are known to take a long transition time to develop [1]. Particles may be activated spontaneously during long-term DC operation. This means that electrical failures due to defects may still appear after a longer voltage stress. Mitigation measures against defects, like particle traps, conductor coating and further measures might be implemented to prevail such spontaneous

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Martin Hallas, Claus Neumann and Volker Hinrichsen are with Technical University of Darmstadt, High Voltage Laboratories, Darmstadt, 64283, Germany (e-mail: martin.hallas@tu-darmstadt.de; neumann@hst.tu-darmstadt.de; volker.hinrichsen@tu-darmstadt.de).

Detlev Gross is with Power Diagnostix Consult, Aachen, 52074 Germany (e-mail: gross@ieee.org).

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effects. However, the behavior of HVDC equipment after practical installations under on-site condition as well as the behavior of mitigation measures against such possible spontaneous defects at DC operation for several days or months is not adequately covered by type testing. This is because type tests are a conformity test to prove the characteristic and ratings of the equipment and usually apply rather short testing times of current and voltage stress.

In general, the probability of defects increases for larger assemblies. In order to avoid failures that may result from this, the overall quality assurance process for larger commercial installations has to be able to detect possible defects as well as the cleanliness level has to be able to avoid possible defects such as particles. Type tests are typically performed on assemblies smaller than real grid installations. Furthermore, staff and facilities to erect the type test assembly of DC GIL may be different from those in later customer projects. The question arises, how a high-quality assembling and commissioning process suitable for HVDC systems is proven for commercial installations. Such prove may become desirable, especially because gas-insulated HVDC systems are rather new with only few installations in the grid and little service experience.

Considering all these aspects, additional testing of newly developed HVDC equipment may be required before an installation in the grid. For this purpose, CIGRE TB 842 [1] introduces a so-called "prototype installation test", which is a one-year long-term test for gas-insulated HVDC equipment to demonstrate the technology readiness level before its application in the grid.

A. Device Under Test

The newly developed ±550 kV DC GIL is therefore installed under typical on-site conditions in a HVDC test facility of the Technical University of Darmstadt, Germany, to perform the prototype installation test (Fig. 1) [3]. In a previous test at the same test site the thermo-mechanical performance of a directly buried version of the DC GIL under variable DC current loads was successfully verified for more than one year [5][6]. The device under test (DUT) is built of eight straight DC GIL modules (2) and two 45° DC GIL angle modules (3), which are connected via flanges and several 90° angle modules and a lateral compensation module (4). The DUT was designed to include all possible module combinations of e.g. gas-tight disk insulators and cylindrical support insulators to be representative for any combination in grid installations. At least five of each DC GIL insulator type are installed to prove a high-quality manufacturing and assembling process at higher quantities. The total current loop is approximately 100 m long, installed above-ground and mostly outdoor. This enables easy access to the modules during testing and furthermore represents a typical practical arrangement [3]. The test arrangement presented in Fig. 1 focused on the horizontal installation position of the DC GIL prototype, since it was developed precisely for such transmission purpose (section I). Due to the harmfulness of particles in general and the risk of accumulation of particles on horizontally arranged disc insulators, vertical arrangements, when necessary, need special attention and should avoid horizontal disc insulators as far as possible. These were, therefore, not part of the investigation.

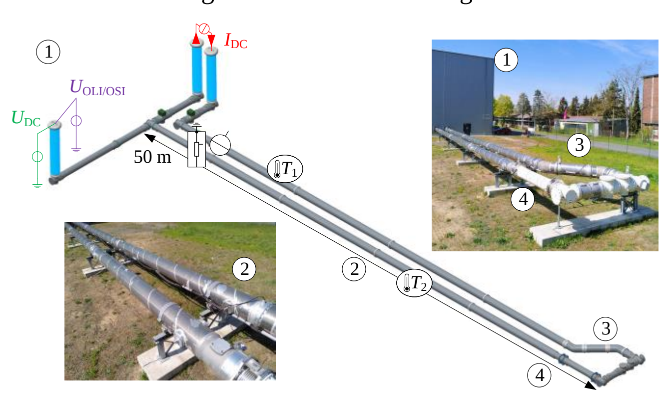

Fig. 1. Device under Test according to [3]: (1) - high voltage test hall ; (2) - straight GIL modules ; (3) - GIL angle modules ; (4) - lateral compensation module

The internal electric field distribution at DC voltage is mainly determined by the temperature dependent conductivities in the mixed gas-solid insulation system. In order to generate high temperature gradients more easily, the wall thickness of the inner GIL conductors was chosen for only approximately 3150 A DC rated current. Simulations showed that the chosen setting results in conductor temperatures similar to values of a larger GIL conductor cross-section stressed with 5000 A rated current. All voltages are measured with an encapsulated RC divider in the DUT [7]. The current is measured with an encapsulated zero flux current transformer.

The test arrangement is equipped with UHF partial discharge (PD) sensors (refer to section II-D), optical light sensors for flashover detection and temperature sensors at two cross-sections (T_1 and T_2 in Fig. 1). The upper and lower enclosure temperature as well as the ambient temperature are measured with PT 100 sensors. The conductor temperatures are contact-less measured with pyrometers. Their infrared transmission characteristic through the N_2/SF_6 atmosphere of the GIL at the installed distance was calibrated in pre-studies and implemented in the control system [8].

B. Test Equipment

The test equipment to feed the DC GIL prototype with current and voltage is installed in a high voltage test hall (see (1) in Fig. 1 and Fig. 2). In the frame of the research project, different options of AC and DC current injection sources for heating the DUT were analyzed [9]. DC current heating is especially advantageous for the 100 m DC GIL DUT, because no reactive power is needed. From the analysis of the various technical solutions, the capacitive current injection concept emerged and was finally applied for establishing a current generator [10]. The DC current source was erected on the two parallel gas-to-air-bushings, so that a maximum of 5000 A DC can be directly injected into the DUT (I_{DC} – Fig. 1 and Fig. 2), which is energized with 660 kV DC according to [1].

DC and impulse voltages (U_{DC} and $U_{OLI/OSI}$ – Fig. 1 and Fig. 2) are applied at one single HVDC bushing. Oscillating lightning and switching impulse (OLI/OSI) voltages are used

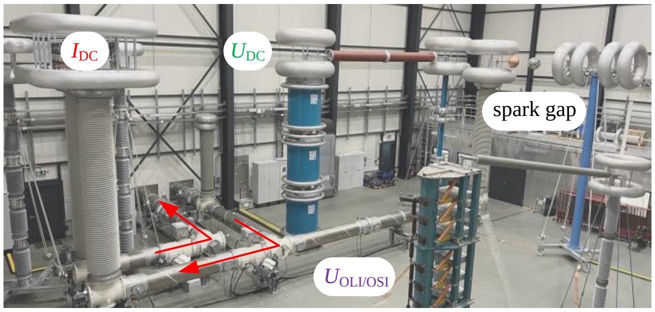

Fig. 2. Test equipment installed in the high voltage hall. I_{DC} – DC current injection generator ; U_{DC} – DC voltage source ; $U_{OLI/OSI}$ – oscillating impulse voltage generator.

rather than conventional lightning and switching (LI/SI) voltages because of the higher generator compactness and voltage efficiency [11]. Pre-studies [12] have shown that OLI/OSI voltage stresses are comparable to LI/SI, which makes both methods equivalent for testing of overvoltage stresses during the prototype installation test. The superposition of the impulse voltage is realized by the use of a spark gap (Fig. 2), which allows compacter test generators and test circuits. Pre-studies [11] have demonstrated that the superposition of OLI/OSI voltages with spark gaps provides a reliable discharge and continuous voltage shapes. Any arc extinguishing effects, as they are reported in the literature for LI/SI voltages superimposed to DC voltage (SIMP) and spark gaps [1], were not observed at OLI/OSI.

The DC source is built as a voltage multiplier fed by isolating transformers (U_{DC} – Fig. 2) [13]. The wire-wound 2 MΩ resistor of the DC voltage source has 6 m insulating length and is suitable to protect the generators from the effects of flashovers as well as during SIMP testing.

C. One-Year Test Procedure

The CIGRE prototype installation test consists of two high load ("HL"-continuous current and DC voltage) and one zero load cycle ("ZL"-continuous DC voltage only) at each DC polarity [1]. Within one cycle, each DC polarity is applied for 30 days, finished with a superimposed OLI or OSI voltage test. The total testing time is 360 days. The CIGRE prototype installation test thereby takes into account all typical HVDC phenomena like surface charging or particle motion at all possible continuous and transient stresses [1]. The sequence of HL, ZL, DC polarity and impulse voltage is allowed to be interchanged, as long as all cycles and defined combinations are performed.

To use the available laboratory time most efficiently, it is beneficial to perform the potentially more critical test cycles at the beginning of the long-term stress. Table II shows the test procedure used during the DC GIL prototype installation test.

The commissioning of the DC GIL prototype is discussed separately in section III-A and Table III. From the HVDC design point of view, the performance at HL is the biggest challenge [1]. The partial discharge (PD) inception voltage at negative polarity is known to be lower [14], which means defects will be triggered during long-term stresses more likely at negative polarity. The test is therefore started with a negative HL cycle. However, it would not be reasonable to perform all negative HL cycles at the beginning of the sequence. E.g., the electric field distribution at HL and ZL is different in the vicinity of solid insulators, which may cause a different behavior of particles or other defects. In a worst case, a defect may not react on the HL stress but on the ZL stress. The test is therefore continued with a negative ZL cycle. The next steps are a positive HL and ZL cycle to cover all polarity combinations at the beginning of the sequence. Afterwards a negative and a positive HL cycle are performed to repeat the most critical HVDC stress. Defects as well as the overall gas insulated system often react more sensitive to LI and OLI than to SI and OSI, especially when the LI and OLI magnitude is much higher than the SI and OSI magnitude [1][15]. All OLI tests are therefore performed at the beginning of the sequence. The sequence is repeated after half of the testing time by performing superimposed OSI tests at the end of each cycle.

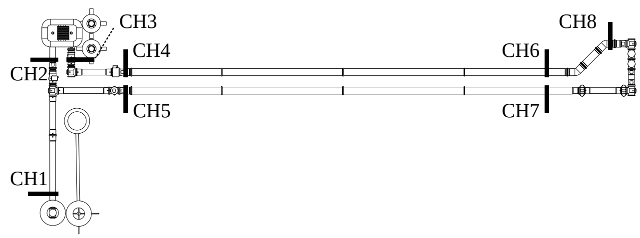

Fig. 3. Position of UHF sensors CH1-CH8 at the DUT [17].

D. UHF PD Monitoring System

A major tool to collect service data during commissioning and operation is the installed UHF PD monitoring system. The measuring sensitivity was determined according to the recommendations given in CIGRE TB 654 [16]. Step 1 determines the magnitude of an artificial PD pulse, applied later during Step 2 of sensitivity verification, by comparison of a real defect measured according to IEC 60270 and the equivalent UHF signal. Step 2 proved sufficient sensitivity of the UHF sensors installed at the DUT (Fig. 3) by injecting the artificial pulse, which amplitude was determined in Step 1. The results of both steps were published in detail in literature [17]. The UHF monitoring system installed is capable to count pulses above threshold values in the time domain. Generally, continuous and pulsed PD with high and low magnitudes could

TABLE II

TEST PROCEDURE OF THE ONE-YEAR PROTOTYPE INSTALLATION TEST

DC Polarity	-		-		+		+		-		+		-		-		+		+		-		+	
Stress	HL	SIMP	ZL	SIMP	HL	SIMP	ZL	SIMP	HL	SIMP	HL	SIMP	HL	SIMP	ZL	SIMP	HL	SIMP	ZL	SIMP	HL	SIMP	HL	SIMP
Days	30	OLI	30	OLI	30	OLI	30	OLI	30	OLI	30	OLI	30	OSI	30	OSI	30	OSI	30	OSI	30	OSI	30	OSI

"HL" = high load → 3150 A / 660 kV DC / "ZL" = zero load → 0 A / 660 kV DC / "SIMP" = ±OLI or ±OSI test superimposed to 550 kV at DC polarity of the cycle / "OLI" = oscillating lightning impulse voltage → 1140 kV peak / "OSI" = oscillating switching impulse voltage → 840 kV peak be well distinguished by this principle. Some general conclusions with the installed system are thereby possible. Identification of the PD defect, as conceivable with PSA (pulse sequence analysis), was not possible with the installed system. PSA methods were investigated in pre-studies [18] and with additional equipment on-site when continuous PD pulses were reproducibly observed [17].

Single pulses at channels CH1, CH2 and CH3 were observed very frequently during the long-term test. By application of the attenuation profile of the different sensors determined in step 2 and the impulse sequence, disturbances were well separable from other impulses. Sporadic PD pulses at a single bushing channel were observed during testing as well but were classified as external surface discharges in air due to dust or other pollution, which are typical under DC stress and are uncritical. PD signals from the DUT (CH4 – CH8 in Fig. 3) were well separable from interferences by use of the results from step 2. Single pulses at different sensors sporadically occurred. They were neglected as long as no continuous or periodic pulse sequences were visible. At CH7 single impulses were observed more often, especially during temperature rises. These PD pulses were assumed to be electrical disturbances due to contact movements of the inner conductor or enclosure at the lateral compensation module ((4) in Fig. 1). Temporary or continuous PD signals indicating possible defects were observed as well. Such PD pulses with DUT origin will be described in sections III and IV.

III. Commissioning

The purpose of the commissioning test is to ensure the integrity before putting the installation into service after erection onsite. For on-site testing, CIGRE TB 842 recommends AC tests because of the comprehensive experience collected with PD testing of gas-insulated AC systems and the lack of experience at DC systems [1]. Additional tests are accepted, but not mandatory. In the frame of the presented research project, the commissioning process at the DC GIL prototype was extended, since it was easily possible with the stationary installed test equipment (Fig. 2). By that, a good DUT condition before starting the long-term test could be ensured. Furthermore, all possible test methods – mandatory as well as non-mandatory according to [1] – could be investigated with respect to their benefit for future test methods.

A. Commissioning Experience

The commissioning included all tests, which were possible with the test equipment (Fig. 2). The DUT was stressed with the tests according to Table III.

TABLE III
Commissioning Tests

1	AC PD	660 kV peak
2	DC PD	±660 kV
3	OLI/OSI	±1140 kV OLI /±840 kV OSI
4	SIMP	±550 kV DC SIMP OLI/OSI
5	ZL	±660 kV / 0 A
6	HL	±660 kV / 3150 A

"HL" = high load / "ZL" = zero load / "SIMP" = superimposed impulse voltage test / "OLI, OSI" = oscillating lightning, switching impulse voltage

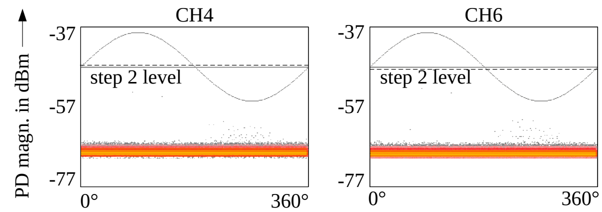

Fig. 4. PRPD patterns at AC PD measurement – 660 kV AC peak/ 1 min [17].

The AC test voltage was generated by a transportable air insulated resonant unit. All test voltages are given as peak values here. A step-by-step AC conditioning [19] was performed prior to the PD measurements. The first step at 220 kV lasted for 5 min (i.e. 5 min at 220 kV). The following steps were 15 min at 350 kV, 15 min at 550 kV, 15 min at 660 kV, 1 min at 825 kV and then back to 660 kV again. Each voltage level was applied for the given duration in order to activate movement of particles of different sizes into the particle traps. The PD measurement was performed at the last step of 660 kV. An AC conditioning is not a problem, as DC GIL has generally to be designed for both, AC and DC voltage stress (refer to section I).

Fig. 4 shows PRPD patterns at the GIL segments between CH4 and CH6 (Fig. 3) at the actual measurement at 660 kV. At 825 kV, signals were detected, which might indicate particles in the gas compartment [17]. However, the measurement at 660 kV in Fig. 4 was assessed as being uncritical, because of the low magnitude, low impulse count and disappearance of PD signals finally after some testing time.

Next, DC voltage was applied step-by-step with the DC generator shown in Fig. 2 (U_{DC}). The voltage was increased stepwise, similar to the AC voltage test. The actual PD measurement was again performed at ±660 kV DC. The measurement at positive polarity was inconspicuous. At negative polarity, high PD magnitudes were observed in the GIL segment between CH4 and CH6 (refer Fig. 3) after some minutes testing time. Evaluating the attenuation profile of these signals according to [16] and by application of the results from step 1 and step 2 [17], the PD turned out to be higher than 5 pC. Its origin was near to CH4. Fig. 5 shows the UHF signals of the affected channels. Evaluations with PSA indicated particles at the inner conductor [18]. Time-of-flight measurements also proved the PD source to be near to CH4 [17]. It is assumed that particles with PD magnitude lower than the 5 pC equivalent at AC, were reactivated and particle motion started under DC voltage stress again. Polarity reversal tests were also performed during the DC PD measurements, since

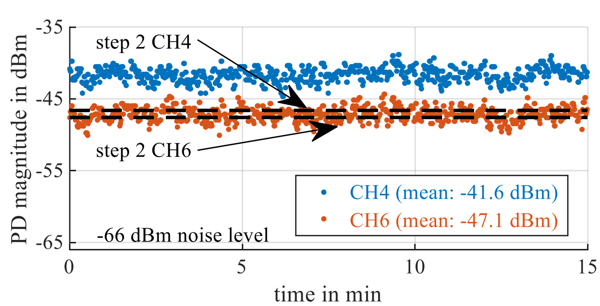

Fig. 5. DC UHF PD oscillograms at -660 kV – continuous measurement according to [17].

they could easily be carried out. However, they did not lead to new results.

The commissioning was continued, despite the potential presence of particles in the GIL compartment, to further investigate the efficiency of the particle trap as well as the efficiency of the following commissioning tests. The OLI/OSI voltage tests were performed with the generator shown in Fig. 2 ($U_{OLI/OSI}$). Three impulses of 1140 kV OLI and 840 kV OSI were applied, which represents 80 % of the rated withstand voltages (see Table I). This procedure is used for impulse tests on-site [20]. The test was successfully passed. Afterwards, SIMP tests with 1140 kV OLI and 840 kV OSI were applied using the spark gap shown in Fig. 2. The ±550 kV DC voltage pre-stress was applied for 2 h, which is in line with test recommendations [1]. The OLI SIMP tests triggered a flashover in the GIL gas compartment between CH4 and CH6 (refer to Fig. 3), where previous PD measurements indicated particles. The gas compartment was opened and inspected. Metallic particles with melting traces were found near the location of failure in the vicinity of a GIL support insulator, for which reason metallic particles are also confirmed to be the origin of the flashover as well as the PD measured at AC and DC. Therefore, it is assumed that the countermeasures taken were not sufficiently effective to capture all metallic particles in the affected area. The particles were activated at DC voltage and led to a flashover at SIMP voltage (further explanation see section III-B). This shows the necessity of particle traps for DC GIL in general, since despite thorough cleanliness measures the presence of particles cannot be excluded in practical installations with on-site assemblies. Furthermore, this shows that the particle trap should be improved in the affected area.

The commissioning procedure starting at point 2 was repeated with the cleaned DUT. AC tests could not be repeated, because the transportable unit was not available anymore. All tests including the SIMP test with a pre-charging time of 2 h according to [1] were successfully passed afterwards. Next, the ZL test was performed with positive and negative polarity at ±660 kV DC for approximately 24 h. The test time was chosen rather short to minimize the time to start the prototype installation test. The test at positive polarity was inconspicuous. At negative polarity, a flashover inside a GIL gas compartment between CH6 and CH8 (refer to Fig. 3) was observed after some hours testing time. CH8 was close to the location of failure. Ten minutes before the flashover, a one second lasting PD lower than the 5 pC equivalent was measured at CH8, which means that no recognizable amount of PD at DC or during the DC long-term stress was detected before the flashover. The defect was not detected as well with impulse or SIMP tests before. The affected gas compartment was opened and inspected. Again, particles were found, but at the surface of a GIL barrier insulator. Therefore, most probably particles were re-activated under DC voltage stress again, moved towards the insulator surface and caused the flashover. This again shows that the particle mitigation measures need to be improved in the affected area.

The affected gas compartment was cleaned, and the commissioning procedure repeated from point 2. Afterwards, DC PD, OLI/OSI, SIMP as well as the 24 h ZL test were successfully passed. The HL test was performed with positive and negative polarity at ±660 kV DC and 3150 A DC by use of the DC voltage and DC current source shown in Fig. 2 (U_{DC} and I_{DC}). Again, the test time was chosen as 24 h to minimize the time to start the long-term test. The HL test was successfully passed without measuring any noticeable PDs.

B. Conclusions on HVDC Defects and their Behavior

The results of the commissioning tests in the previous section III-A are summarized as:

- Detection of mobile metal particles
  - Good detection by DC PD measurement and SIMP testing
  - Unreliable detection by AC PD measurement
  - No detection by OLI/OSI
- Detection of particles on insulators
  - Detection after long-term DC operation (ZL or HL)
  - No detection by AC PD or DC PC measurement, OLI/OSI or SIMP voltage tests with 2 h DC pre-stresses

These results from the full-scale DC-GIL prototype shall be further discussed and compared to previous laboratory studies in literature in order to give a full picture for future commissioning tests. Table IV summarizes the various critical defects in gas-

TABLE IV

TYPICAL DEFECTS IN GAS-INSULATED HVDC SYSTEMS

Defect			**PD characteristic of defect**		**PD detection**		**Test effectiveness for detection**					
Location	**No.**	**Type**	**Magn.**	**Duration**	**AC**	**DC**	**AC PD**	**DC PD**	**HL ZL**	**OLI OSI**	**SIMP**	**Reference**
Ins. Bulk	1.1	Void	med.	AC: cont. / DC: spont.	+	-	X					[24], [25], [26]
	1.2	Cracks					X			(X)	(X)	
Insulator surface	2.1	Inhomogeneities, scratches, traces	low	short, spont., (disc.)	-	-			X			[21], [22], [23], [24], [25], [26], [27], [28], [29]
	2.2	Contamination, abrasion										
	2.3	Non-metallic particles										
	2.4	Metal particles	low	short, spont., (disc.)	-	-	$(X)^{1,2}$		X	$X^{2,3}$	X^4	
Gas-insulation	3.1	Mobile metal particles	high	cont.	0^2	+	$(X)^2$	X			X	[24], [25], [26], [30], [31]
	3.2	Protrusion	low	cont.	0	0	X^1	X^1		X	X	
	3.3	Floating electrodes	high	AC: cont. / DC: disc.	+	0	X	X				

"X" = effective test for DC / "(X)" = less effective test for DC
"+" = good PD detection possible / "0" = on-site PD detection possible / "-" = on-site PD detection hardly possible
"Ins." = Insulator / "med." = medium / "cont." = continuous / "spont." = spontaneous / "disc." = discontinuous
[1] Requires high PD sensitivity on-site. / [2] Neglects the particle motion at DC voltage. / [3] Only effective if particles are already on the insulator surface. / [4] DC voltage pre-stress may be too short to result in particle motion to the insulator.

insulated systems, lists their PD characteristics and activity (UHF and conventional measurement) and summarizes tests sensitive to each defect, based on the presented literature references and the experience collected during commissioning as reported in section III-A.

Defects in the bulk material of insulators (Table IV – 1.1-1.2) can be detected by an AC PD measurement. Under DC stress the PD activity may stop after PD inception but may spontaneously reoccur. Therefore, such defects are hard to measure with DC PD measurement. An AC PD measurement is therefore reasonable for the detection of voids and cracks. Literature [24] reports that cracks also react to impulse voltage stresses to a certain level.

Defects at the insulator surface e.g. due to pollution, abrasion, inclusions or adhering metal particles are especially critical (Table IV – 2.1-2.4). Literature presented in Table IV reports, that such defect may substantially reduce the breakdown voltage of the system at DC, impulse voltage and SIMP voltage. Surface defects (Table IV – 2.1-2.3) may generally change the surface conductivity of the insulator. Particles on insulators (Table IV – 2.4) might locally amplify the surface charge accumulation [21]. Thus, all surface defects may lead to a significantly changed potential distribution on the insulator surface [22][23]. It is known from literature [24] that all such defects generate a low magnitude of partial discharges and discontinuous short pulse repetition rates. Under DC voltage, those defects sometimes even generate pulseless glow-type discharges [25]. The reported GIL insulator particle contamination (section III-A) was not reliably detected by means of PD measurement as well. In conclusion, quality control during production and erection as well as further mitigation measures play an important role to avoid such defects as they may not be detected by short-term AC or DC PD measurements and may result in flashovers in the gas-insulated system in the long-term range. E.g., a surface defect (Table IV – 2.1-2.4) near to the inner conductor will react more sensitive to ZL stresses, because of the higher electric field at the conductor in this case. Defects more towards the enclosure might react more sensitive to HL stresses, because of the higher electric field strength in this area, due to field inversion at HL. To exclude such effects, a trial run of the later current and DC voltage stress during operation is a possible option for defect evaluation, for which reason DC stresses in the range of 24 h with HL and ZL were performed during commissioning of the DC GIL prototype under consideration. By that, the mentioned particle on insulator defect was found, which was not the case by the other commissioning tests. This also shows that such type of defect might be uncritical for AC and other short-time tests, but still may lead to a flashover during DC long-term stress. SIMP tests can be a more effective test to detect particles on the insulator surface than impulse voltage tests without DC voltage, due to the influence of particles on the electric field distribution under simultaneous DC stress as mentioned above. A SIMP test also applies a realistic transient in service stress, which may occur in the DC grid. However, the test results from commissioning also show that the applied DC voltage must be applied long enough. It is assumed that the 2 h DC pre-stress during SIMP test did not yet lead to a particle motion to the insulator and therefore could not detect the particles on the insulator in this specific case.

The electrical withstand capability of the gaseous insulation (Table IV – 3.1–3.3) may also be significantly reduced by defects, especially by mobile metal particles (Table IV – defect 3.1). Generally, particles can be detected by AC PD measurement. However, the particle motion and by that the criticality of particles under DC voltage is different from that under AC voltage stress. Gained experience as reported in section III-A also prove this statement. The AC PD measurement during commissioning did not sufficiently indicate the criticality of the particles under DC. The AC PD magnitude (Fig. 4) was lower than the DC PD magnitude (Fig. 5), due to the different particle movement under AC and DC stress. As observed during commissioning in section III-A, OLI/OSI testing without applied DC voltage is not a sensitive test to detect mobile metal particles. Literature explains that such transient stresses are not lasting long enough to charge and to activate particle motion [32]. In difference, SIMP voltage tests would theoretically trigger flashovers at typical particle motion states, which might occur later in the grid. Such modes are especially lifted-off particles, which are standing still at the enclosure or near to the inner conductor, as well as particles in the firefly mode [33][34]. Particles crossing the gas gap or bouncing between conductor and enclosure could potentially be harmful, too. The DC voltage triggers the particle motion as well as sparking and the impulse voltage verifies, whether the particles are critical. The particle-initiated flashover during commissioning (section III-A) as well as literature [30] confirms this consideration.

Besides mobile particles, fixed particles (e.g. protrusions) may occur either on the HV conductor or on the earthed enclosure (Table IV – 3.2). These defects, already known from AC gas-insulated systems and from the literature presented in Table IV, must be considered at DC systems as well. AC PD as well as DC PD measurements could be applied for protrusion detection, if sufficient PD sensitivity is ensured [24]. Another option is the application of impulse voltage (OLI/OSI), which is used for AC systems in some cases [20]. Since SIMP tests are of similar stress as OLI/OSI in the protrusion case, SIMP tests also seem to be suited for identification of protrusions in HVDC systems [31].

Floating electrodes are described to be well detectable with AC PD measurement. DC PD detection of floating electrodes seems in principle possible, but might require the interpretation of discontinuous signals.

C. Test method recommendations for FAT and SAT

Based on the experience with the DC GIL arrangement in section III-A during the commissioning tests and the conclusions from section III-B, test recommendations are derived for existing methods for DC GIL factory acceptance tests (FAT) and site

TABLE V

RECOMMENDATIONS FOR EXISTING DC GIL TEST METHODS

Test description	**FAT**	**SAT**
AC PD	X	X
DC PD	X	X
HL	(X)	(X)
ZL	(X)	(X)
OLI/OSI		(X)
SIMP	(X)	(X)
"X" = recommended / "(X)" = less recommended		

acceptance tests (SAT), which are given in Table V. Some considerations for type tests (TT) are discussed in section III-D.

Factory Acceptance Test (FAT)

The FAT shall prove the correct manufacturing and assembling. The detection of all types of defects shown in Table IV during FAT has to be discussed, e.g. for pre-assembled DC GIL assemblies. Void defects (Table IV – 1.1) must be excluded by appropriate quality assurance testing in the factory. Therefore, an AC PD measurement in factory is reasonable. The question arises, if it is reasonable to exclusively rely on AC tests for the HVDC equipment and by that disregard typical phenomena under DC voltage stress, especially when considering the risk of flashovers during operation. The commissioning experience in section III-A has shown that particles of low PD magnitude and frequency in AC PD tests (Fig. 4) resulted in higher PD magnitudes under DC voltage stress (Fig. 5). This behavior confirms that AC voltage tests are important but can discover DC relevant particles only in limited scope, since the overall particle movement at DC voltage is different. Therefore, all PD signals of particle type during AC PD measurement should not be neglected. This also confirms that besides AC PD tests, PD tests at DC voltage are reasonable in general, in order to detect particles remaining in the gas gap by an adequate DC test method. AC as well as DC PD measurements should therefore be integrated in the FAT of pre-assembled DC GIL to adequately detect defects 1.1 and 3.1–3.3 listed in Table IV. In general, particles in gas-insulated HVDC systems (Table IV – 3.1) should be taken seriously and should be considered as a reason to open and clean the gas compartment. Especially continuous and reproducible PD-signals indicating particles may become, as observed, crucial and such particles should be removed. The PD measurements at AC and DC voltage (Fig. 4 and Fig. 5), indicating some particles in the gas compartment, and the later particle-initiated flashover at SIMP testing during the GIL commissioning prove this statement. The test time necessary to detect free particles under DC voltage was observed to be rather short (section III-A). For a DC PD test a standardized procedure and an acceptance criterion needs to be defined. Basic considerations to this topic are given in section III-D.

In general, it would be beneficial, to detect insulator surface defects (Table IV – 2.1-2.4) with additional test methods during FAT. Such defects may happen in the manufacturing and assembling process and would potentially not be covered by a PD measurement. E.g., a particle on insulator defect during commissioning (section III-A) was found with a ZL test, wherefore long-term ZL and HL tests would also be theoretically a possible test option for defect identification (section III-B). However, HL and ZL tests in factory result in unreasonable efforts. Therefore, the application of longer lasting HL and ZL seems more reasonable during TT or a prototype installation test. Proposals on future test methods to improve the prevention and detection of surface defects are discussed in section III-D.

Site Acceptance Test (SAT)

Generally, the SAT should focus on defects resulting from transportation and erection of the equipment. In principle, all types of defects listed in Table IV have to be discussed here again, except void defects, which should be detected during FAT. Cracks of insulators may still be a possible defect after inappropriate transportation and handling (Table IV – 1.2). Following the statements for PD measurement at FAT, AC and DC PD measurements are reasonable for SAT. Non-metallic insulator surface defects can often be neglected if no work on the insulators is performed on-site. This applies for pre-assembled FAT tested components, which means that insulator surface defects and by that HL and ZL tests on-site are not of high interest as long as such defects were excluded in factory.

The SAT for GIL assemblies fully erected on-site is more complex. The SAT therefore should cover the potential defects listed in Table IV, except of void defects (Table IV – 1.1), which should again be detected in factory. Cracks (Table IV – 1.2) of insulators have to be considered on-site again, since inappropriate handling cannot be excluded in all cases. As performed during commissioning of the prototype installation test in section III-A, it would be beneficial to perform all possible tests before starting the operation. However, such procedure will not be possible for DC GIL grid installations, especially when considering large installations of several kilometers. Such installations result in high capacitance, wherefore AC, OLI/OSI and SIMP tests are difficult to perform. Due to high conductor resistance and inductance, HL tests are difficult to perform also. Measures to prevent insulator surface defects (Table IV – 2.1–2.4) should be considered, too. Such defects could be detected with ZL or HL testing, but can be avoided by appropriate measures prior to the SAT. These are discussed in section III-D. In any case, it is reasonable to apply AC PD and DC PD measurements as discussed for FAT and SAT on pre-assembled DC GIL assemblies.

Further test methods

OLI/OSI tests in factory are not reasonable, because protrusion defects (Table IV – 3.2) can usually be well found by AC and DC PD measurement due to the high PD sensitivity in factory. How far protrusion defects can be detected by a PD measurement during SAT was already a matter of discussion for gas-insulated AC systems because a comparable high PD sensitivity is required [24]. The latter may become hard to realize during on-site testing. However as for AC, the necessity of an impulse voltage test with OLI/OSI on-site should be decided by the user based on the size of the installation, expected protrusions during erection, the expected PD measuring sensitivity and the test expenses.

SIMP tests (with DC pre-stress) for mobile particle detection (Table IV – 3.1) during SAT and FAT are not reasonable, since moving particles (Table IV – 3.1) are well detectable with AC PD or DC PD measurement. This results from the fact, that the particle motion of critical and detectable particles in the gas gap has to be triggered by a DC voltage before the SIMP test (see section III-B). The experience collected during DC GIL commissioning (section III-A) prove, that particles critical at transient stresses were adequately identified before a SIMP test. SIMP tests during FAT and SAT are theoretically a possible option to exclude surface defects, especially particles on insulators (Table IV – 2.4). But relying on standard SIMP tests on-site in order to exclude such defects seems unreasonable, since a SIMP test on-site results in incomprehensible high efforts. The development of new measures discussed in section III-D seems more suited to cover surface defects. However, it might be an option to perform such tests, e.g. to minimize the risk of particles on insulator surfaces (Table IV – 2.4) after on-site erection. As described in section III-B, SIMP tests would be more suited to identify such defects compared to impulse voltage tests without DC voltage. In such case, a suitable DC voltage pre-stress time before SIMP tests should be considered. As observed in section III-A, the detection of free moving particles (Table IV – 3.1) was possible in a rather short DC pre-charging time of only 2 h. Surface defects may be difficult to detect with such short DC pre-charging time. Effects on insulators may need substantially longer charging times.

As observed in section III-A, polarity reversal tests did not lead to different results than a DC PD measurement at both polarities. Therefore, polarity reversal tests should stay "not mandatory" as proposed in [1].

D. Proposal for Future Test Methods

According to [1] it is generally preferred to carry out PD measurement with AC voltage, because of the lack of experience with DC PD testing. However, the results given in section III-A and IV-B show, that if PD under DC is measured in a GIL arrangement with sufficient UHF PD sensitivity, it may be clearly separatable from interferences by basic DC PD measurement in the time domain (see section II-D). If required, noise reduction in the test setup could be further improved by gating or other measures. As observed (Fig. 4 and Fig. 5) and discussed in section III-C, AC and DC PD measurements may also lead to different results. To cover DC related effects, DC PD measurement should be considered to be included in TT, as already discussed for FAT and SAT. Similar to AC PD measurements an acceptance criterion and a standardized procedure for DC PD measurement need to be defined. DC PD measurement as well as acceptance criteria still need further discussion. As applied in Fig. 5, a possible criterion for UHF DC PD measurement might be, that PDs have to be lower than the 5 pC equivalent from step 2. Periodical, as well as continuous PDs should be considered in an acceptance criterion, but no single pulses. Besides that, further details as well as standardization of DC PD measurement should be discussed in technical committees. DC PD measurement would become a more powerful tool, if defects may be identified like with PRPD patterns at AC. The collected experience indicate, that PSA methods may be used for defect identification at DC voltage. So far, such methods are used in research applications only.

The installed particle trap of the DC GIL prototype given in this paper was investigated in detail in pre-studies and during the design phase [4][35]. The efficiency of the particle trap in the gas gap is proven well during operation (refer to section IV-B). However, further detailed design optimizations of particle trap measures are required based on the prototype installation test results given in section III-A. This confirms that the particle trap design tests were important, but improvement of the test methodology is still possible. Therefore, the introduction of a design relevant "efficiency test of particle mitigation measures" at a representative GIL assembly would be beneficial to prove the overall performance of particle mitigation measures. Such test can prove the efficiency of capturing or deactivating particles in the gas gap, particles near to insulators, as well as avoiding particle motion effects towards insulators at DC and transient stresses. By that, the efficiency of the implemented particle mitigation measures to capture or deactivate a "standardized" number of particles would be proven, which is an important design feature for DC GIL, as they are assembled on-site. An one time performed "efficiency test of particle mitigation measures" would also be advantageous, because each FAT and SAT test than would only have to check the occurrence of high amounts of particles, which are not captured and are more easily to detect in general. With such standardized test, the defects 2.4 and 3.1 in Table IV would also become less critical. Other tests like HL, ZL or SIMP tests on-site to check the existence of such critical particles in every FAT and SAT would thereby be of minor importance since the design is proven to be able to handle "normal amounts" of particles when they are present in the DC GIL. A standardized test procedure for a "efficiency test of particle mitigation measures" should be discussed in detail in technical committees.

Table IV shows, that insulator surface defects (2.1–2.4) may be critical defects in a gas insulated HVDC system. With existing test methods (Table V) unreasonable efforts are required to identify such defects. With a "efficiency test of particle mitigation measures" the risk of metallic particles on insulators would be minimized. It remains a risk of non-metallic insulator surface defects (Table IV – 2.1–2.3), which may change the surface conductivity and thereby the surface potential distribution, which may result in critical stresses. Such defect mostly will result due to quality issues during manufacturing and erection. Future GIL research and development could investigate new measures to identify potential insulator surface defects. E.g. new test methods may include leakage current measurements, measurements of the insulator surface conductivity, measurement of the potential distribution or new test methods over all.

As described in section III-C, the application of test methods on large GIL assemblies erected on-site demand unreasonable efforts. However as described in section II, the probability of possible defects increases with increasing GIL length. Future DC GIL research and development may incorporate this fact by e.g., development of GIL sub-assemblies which may be pre-tested. By that, the discussed additional test methods and quality measures in this chapter could be integrated in large assemblies as well.

IV. Service Experience

The ±550 kV DC GIL passed the most critical half of the prototype installation test successfully (refer to Table II), which means that all possible HL and ZL combinations were tested with a SIMP OLI test at the end of 30 days cycles (the other half had to be omitted due to limited test site availability). The solid insulation showed a reliable long-term performance. The condition of the DUT is therefore rated good. It is estimated that the DUT would have been able to pass the second half of the test as well. Service experience with the DC GIL prototype was collected during these cycles, especially regarding its outdoor installation, its PD behavior and the effectiveness of the particle trap.

A. High Load and Zero Load Operation

The temperature gradient across the insulation has a major impact on the resistive electric field distribution [1]. The DC GIL is installed outdoor, which is why weather changes will influence the temperatures and thereby the resistive field distribution. Table VI shows typical temperature gradients ΔT across the gaseous insulation measured in summer and winter at the temperature sections T_1 and T_2 at HL and ZL cycles (Fig. 1). As expected, ZL cycles develop on average no temperature gradient across the insulation. HL cycles apply the desired temperature gradient ΔT. The maximum temperatures were in the range of 60 °C at the enclosure and 80 °C at the inner conductor. Because of sun radiation and rain, temperature deviations are possible despite the ZL and HL condition. Detailed time dependent temperature curves are discussed in [8].

It is assumed that the electric field distribution is described in average by the mean ΔT given in Table VI. The temperature deviations during day and night given in Table VI will only slightly be able to change the field distribution around the mean value, because DC field transition effects need much longer application times to develop. The daily average ΔT only changed by approximately ±3 K within a 30 days cycle. The day to night temperature changes are thereby estimated to have low influence on the stationary resistive field distribution, because they appear within a few hours, while the DC charging time of the insulators from capacitive to resistive field distribution is in the range of three to seven days [3]. The temperature deviations are therefore considered uncritical to the result of the prototype installation test. The ZL cycle at the outdoor-installed DUT still adequately simulates low load conditions, and the HL cycle nominal load conditions in the grid.

TABLE VI
TYPICAL TEMPERATURE GRADIENTS ΔT MEASURED AT THE DC GIL PROTOTYPE

ΔT in K	HL		ZL	
	Summer	Winter	Summer	Winter
Mean	14.6	11.2	1.6	0.1
Max	36.0	21.1	18.8	3.2
Min	0.3	3.3	-5.0	-7.4
"ΔT " = Temperature gradient between conductor and enclosure in the middle of a GIL segment				

B. Partial Discharges during Service

The PDs observed during long-term testing could often be allocated to interferences (refer to section II-D). At sensors CH4 and CH6 (Fig. 3) some PD signals for few minutes only were measured after the commissioning and at the beginning of the prototype installation test, at negative ZL and HL after some days. Fig. 6 shows an example. Evaluating the attenuation profile of these signals according to [16], the PD is lower than the 5 pC equivalent and near to CH4. The continuity of the signal, the spontaneous start and stop as well as the experience from commissioning at the affected area (refer section III-A) suggest metal particles, which are not yet fully captured by the particle traps, as the origin of the signal. Particles near to insulators in the affected gas compartment were removed carefully during commissioning (section III-A). Therefore, only particles in the less accessible gas gap are possible, wherefore they are estimated to be the origin of the signals. In conclusion it is assumed that the metal particles in the gas gap were finally successfully captured in the

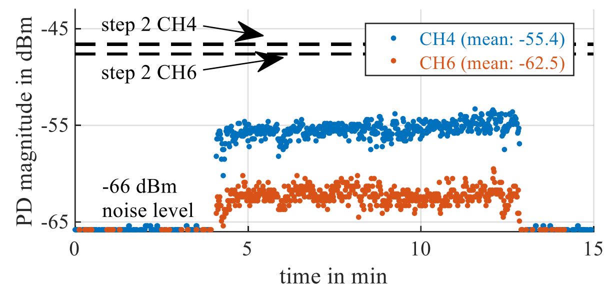

Fig. 6. Example of a DC PD signal at CH4 and CH6 during long-term testing (approx. 10 min).

particle traps at the UHF PD signal stop during long-term operation, because they did not cause any further signals after the first two test cycles. The SIMP tests at the end of each PD affected cycle were successfully passed. This proves a good performance of the installed particle traps inside the gas gap of the DC GIL prototype, because particles could reliably be trapped during operation, so that even spontaneous transient stresses did not reactivate them.

V. CONCLUSION

The overall experience with the prototype installation test has proven that long-term testing of newly developed DC GIL equipment will give important insights for the later grid installation, which would have not been found with type testing and common FAT and SAT testing only. An important tool was the installed UHF PD monitoring system, enabling the detection of free moving particles during test conduction, for which reason it is recommended to consider applying such systems in future installations. Typical DC defects were identified by use of an extended commissioning procedure. Based on the collected commissioning experience, recommendations are derived for further optimization of current test requirements for DC GIL. As known from various publications, it was observed that free moving particles may become critical for operation of DC GIL systems, wherefore particles should be taken seriously. Commissioning showed that such particles behave differently under AC and DC voltage. Therefore, the conduction of DC PD measurement at FAT and SAT supports a reliable detection of particles. DC PD testing is a potential measure to improve TT also, since the experience prove the general feasibility of DC PD measurement. Further work is required to enable defect identification based on DC PD measurement techniques in an industrial scale. As a future test method for DC GIL, a design relevant "efficiency test of particle mitigation measures" is proposed, so that their efficiency is proven for common particle defects in the design phase. By that particle defects would also become less critical at SAT and FAT. During commissioning, a particle on an insulator could not adequately be detected with PD measurement. In general, insulator surface defects should therefore get special consideration in future test methods or by quality measures in factory and on-site.

After overcoming the phenomena during commissioning, the tested DC GIL has shown a good long-term performance during the performed cycles of the prototype installation test with respect to its design, solid insulation and particle performance in the gas gap. Occasionally occurring PDs during the long-term test can mainly be assigned to external interferences. Some UHF PD inside the GIL installation below the equivalent 5 pC value occurred at the beginning of the test. Metallic particles in the gas gap are assumed to be the origin of these PD signals. Their extinction during service has proven the suitability of the installed particle traps in the gas gap not affected by insulators. In addition, the commissioning part of the test provided valuable information on how to optimize the particle traps close to insulators.

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M. Hallas (IEEE Member) received the Diploma degree from the Technical University of Darmstadt, Germany, in 2012. His diploma thesis was in the field of metal oxide surge arrestors and received the IEEE Power Engineering Society German Chapter Best Diploma Thesis Award 2013. From 2012 to 2015 he worked as R&D engineer for GIS up to 170 kV at ABB AG Germany. Since 2015, he has been working at the high voltage laboratories of the Technical University of Darmstadt with the aim of a "Dr.-Ing." degree. His research interest includes gas-insulated HVDC systems, their testing and commissioning. Aside from his research he was a "young expert" of the CIGRE JWG D1/B3.57 "Dielectric testing of gas-insulated HVDC systems". Martin Hallas is member in IEEE, CIGRE and VDE/ETG.

Claus Neumann received the Dipl.-Ing. degree in electrical engineering from the Technical University of Aachen and his Dr. Ing. degree from the Technical University of Darmstadt. After seven years engagement in the HV lab of a switchgear manufacturer. he was active from 1979 till 2010 in different positions in the field of HV equipment and systems at RWE, finally, at the TSO Amprion as head of Operative Asset-management. Since April 2010 he has been working as a freelance Senior Consultant

In 2001 he became Honorary Professor at the Technical University of Darmstadt, where he gives a lecture in HV switchgear and substations since 1994. He is a member of CIGRE and has been active in various Working Groups. Among others, he was the convenor of the JWG D1/B3.57 "Dielectric testing of gas-insulated HVDC systems".

Volker Hinrichsen received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from the Technical University of Berlin (TU Berlin), Germany. In 1989, he joined the Siemens AG, Berlin, Germany. In 2001 he became a Full Professor at the High Voltage Laboratories of TU Darmstadt, Germany, from where he retired in 2020. Prof. Hinrichsen is chairman and member, respectively, of several national and international scientific and standardization committees on surge arresters, insulation systems, insulation coordination, vacuum circuit breakers, and testing within IEC, IEEE, CIGRE, and VDE/DKE.

Detlev Gross (IEEE Senior Member) received the Dipl.-Ing. degree in el. engineering from Aachen University of Applied Sciences and the Dr. techn. degree in el. engineering from Graz Technical University (TU Graz). In 1986, he founded DG Instruments and in 1992 Power Diagnostix in Aachen. Detlev Gross is/was chair and member, resp., of several national and international standardization committees mostly on partial discharge in various high voltage equipment within IEC, IEEE, CIGRE, and VDE/DKE.