D1: Material and Emerging test techniques

General overview of AC and DC current injection on high voltage potential for HVDC long-term tests

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Summary

HVDC transmission systems like cables or gas insulated systems are of great interest for future grid expansions. They are usually type tested in one-year long-term tests, to ensure lifetimes up to 40 years and more. HVDC equipment always has to be tested with voltage and current at the same time to investigate temperature dependent space charge effects inside the insulation material. Even though the HVDC equipment in the grid is operated with DC current and DC voltage, laboratory tests often have to be performed with AC current heating due to laboratory limitations. The following report shows the technical limits of AC current injection and presents solutions for DC current injection on high voltage potential. The solutions are described and compared to each other. Furthermore, the report shows the status of actual research and prototyping for this new generator type.

1. Introduction

The design of HVDC equipment like cables or gas insulated systems always has to take space-charge distributions in the insulation material into account. Because of accumulating charges on insulator surfaces and the material, the electrical field distribution changes depending on the temperature and the duration of the voltage stress. High local electrical field stress can occur due to growing space charge accumulation. These effects depend on the electrical resistance of the insulating material and thus also on the temperature. Therefore, adequate testing of HVDC equipment can only be achieved with thermal and electrical stress at the same time [1]. The heating of the test object is usually implemented by current injection to the inner conductor to simulate actual operating conditions. This can be performed by various methods, which are described and compared in this report.

2. Long-term testing of HVDC equipment

One year long-term tests are specified for HVDC transmission systems like gas insulated systems or cable systems. For HVDC cables, they are specified in IEC 62895 [2] as prequalification tests, whereas long-term tests on gas-insulated HVDC systems are discussed in Cigré JWG D1/B3.57 [1] as prototype installation tests. The test procedures are different. During prequalification tests of cable systems, the design limits of the conductor temperature and the maximum temperature difference across the insulation shall be reached, so that the technical limits and the aging of the equipment is tested. Therefore, the cable system is heated by a current, which may differ from the nominal current rating [2]. Since only the temperature and the temperature gradient are of interest, long-term tests are usually performed with AC current injection to the inner conductor according to Figure 1. Furthermore, IEC 62895 [2] requires a dummy loop of several meters, without any high voltage applied. The dummy loop is used to determine the temperature at the inner conductor. The advantage of AC current

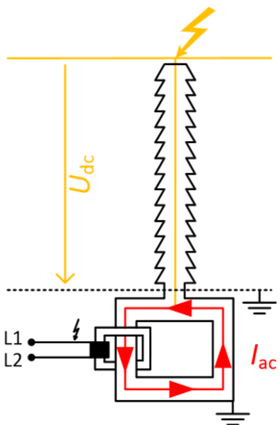

Figure 1: AC current injection

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KEYWORDS

High voltage testing techniques, HVDC testing, current injection, prototype installation test, prequalification test

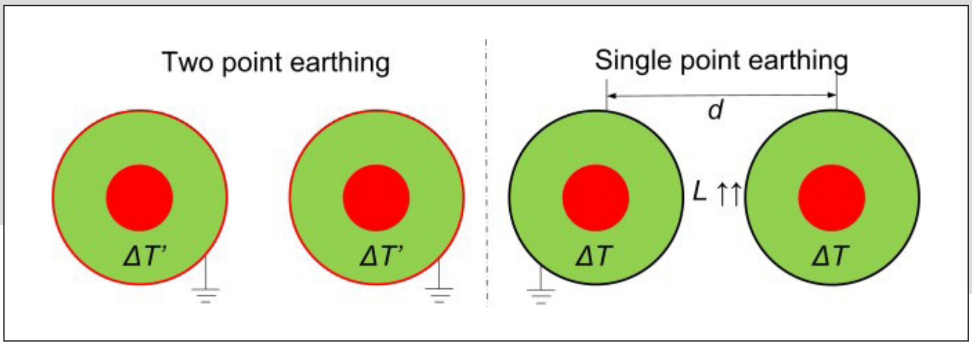


Figure 2: Heating of components during AC current testing with two-points and single-point earthing (red = heated) [4]

injection is that the same current generator type can easily be used for the dummy loop [7].

The prototype installation test for gas insulated systems has a different purpose and, therefore, follows a different test procedure. Gas insulated systems like switchgear or lines form a more complex arrangement with several contact surfaces. These are usually the most critical components during the heating process. Therefore, temperature rise tests on gas insulated systems are performed with the nominal current. The temperature rise at the contact surfaces and the overall assembly is observed and has to be within the limits according to IEC 62271-203 [3]. The same procedure is specified for gas insulated HVDC equipment [1]. Due to test equipment limitations, usually AC current heating according to Figure 1 is also used for gas insulated systems.

2.1. Technical limits of ac current testing

AC current heating has some technical limitations. Especially larger HVDC test objects of large cross sections have a higher reactive power demand due to their high inductance and high nominal current of the test object. Considering a typical current loop, the overall inductance of the assembly will be in the range of 1 μH/m [4]. With a testing current of 5000 A at 50 Hz, the required reactive power would be in the range of 7,85 kVA/m and the active power in the range of only 0,3 kW/m. Assuming a 300 m testing loop, the reactive power would be 2.4 MVA, while the active power would be in the range of only 90 kW. The need of reactive power to feed the test loop results in larger AC current sources and power supplies. The high inductance during AC current heating of HVDC equipment results from the single point earthing of the outer sheath or enclosure, respectively. Single point earthing is necessary to avoid induced currents on the sheath/enclosure, which would not occur during real service operation of the DC equipment. Such sheath/enclosure currents would change the temperature difference across the insulation from ΔT to ΔT'. Figure 2 shows the differences between two-points and single-point earthing [4].

2.2. Customer arguments against ac current heating

For special arrangements, AC current heating may also be stretched to its limits. Especially submarine cables with iron armoring will have eddy currents and hysteresis losses in the armoring, which influences the temperature distribution. The armoring might be removed, but the customer needs to accept the change in the test object. Gas insulated systems with iron enclosures would have the same limits, so that special agreements with the customers of the HVDC equipment would have to be made [7].

Gas insulated systems shall be tested with rated current. This can be achieved with rated DC current, with a representative AC current or the injection of the rated DC current value as AC current. Testing with rated DC current is only possible with the use of DC current injection.

A representative AC current during the tests has to be determined by pre-tests. The customer might assume a different temperature distribution in case of AC current heating instead of DC current heating, which might distort the test results. The same or higher temperatures for the representative AC current compared to the rated DC current have to be ensured and proven to the customer. To ensure the performance for higher temperatures during testing the manufacturer of HVDC equipment has to oversize the equipment. This results in higher material investment for the design. The customer might also assume induced currents in the overall test assembly, which might change the temperature distribution. For example, zero load and high load test circuits in parallel will always result in induced currents in the zero load test loop [7]. To solve all these issues, special agreements for testing are necessary.

The injection of the rated DC current value as AC current will result in much higher temperatures at the whole test object. Therefore, the manufacturer has to oversize the total design to pass the test.

3. DC current injection

To summarize, tests on HVDC equipment have to ensure reliable operation during the total lifetime in the HVDC application [1]. Usually power system operators desire a test procedure as close as possible to practice, which would become possible by DC current injection (section 2.2). Furthermore, the technical limits of AC current heating described in section 2.1 would be solved. Even heating of AC cables by DC current could be of interest for high voltage laboratories in order to reduce the reactive power demand and to be able to test longer loops of higher cross sections. On the other hand, the dummy loop during prequalification tests of cables mentioned in chapter 2 has to be considered for DC current injection. In this case, a separate DC current source or other technical solutions have to be considered for the dummy loop [7].

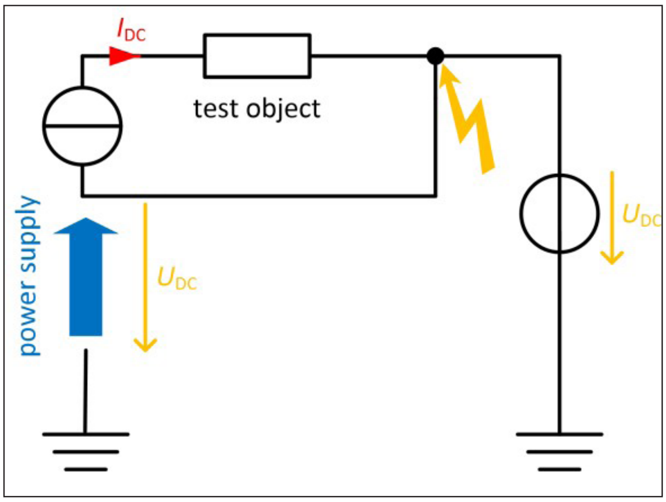


Figure 4: Basic sketch for DC current injection on high voltage potential [4]

A basic sketch of a DC current injection I_{DC} on high voltage potential U_{DC} is shown in Figure 4 [4]. The test object can be represented by a resistor. The current source must generate the high DC current on high voltage potential. The power supply of the current source has to fulfill two tasks. First, it has to transmit the power for the current source. Secondly, it has to insulate the high voltage of the test object against ground.

3.1. Technical implementations

To solve the task sketched in Figure 4, several technical solutions are possible. Concepts to inject DC current on high voltage potential are shown in Figure 5. All concepts comprise a rectifier operating on high voltage potential. For this rectifier cooling devices suitable for high voltage applications are necessary. The capacitive current injection (1) uses capacitors in order to insulate the high DC voltage and to simultaneously transmit the power. An AC/AC converter operated at several kHz feeds the capacitors, which results in a high frequency current through the capacitors. The high frequency current is transformed and rectified on high voltage potential. The overall circuit operates in resonance. The resonant frequency of the circuit can be met by adjusting the AC/AC-converter [4].

The hydraulic current injection (2) uses a hydraulic motor-generator-combination, while the hydraulic oil pipes insulate the high voltage. The hydraulic engines are combined with electrical motor/generator engines to receive electrical power, which can be transformed and rectified on high voltage potential. The hydraulic oil is pumped through a closed loop from ground to high voltage potential.

The inductive DC current injection (3) uses conventional AC current transformers to generate a high AC current in a shorter loop, which can directly be rectified on high voltage potential in order to feed the larger testing loop [5].

The DC current injection by an isolating shaft and electrical engines (4) uses a motor- generator-combination to transmit the power mechanically. The isolating shaft insulates the high DC voltage. The mechanical power is converted to electrical power on high voltage potential, then transformed and finally rectified.

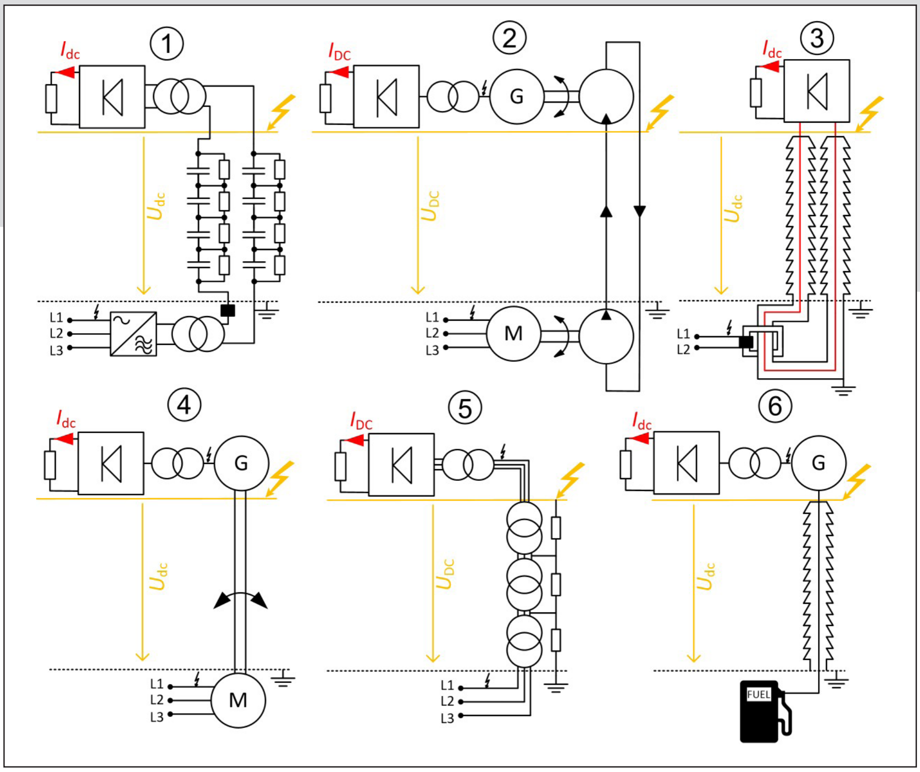
The current injection by isolating transformers (5) in series insulates the voltage and transmits the power simultaneously. A resistive voltage divider ensures a homogenous voltage distribution among the isolating transformers. On high voltage potential, the current is transformed and rectified [6].

The current injection with a fuel-power-system (6) uses a fuel generator on high voltage potential to generate the electrical power. Since the generator can be operated only for a couple of hours with one tank filling, an insulated fuel-feeding has to be designed.

3.2. Comparison of technical implementations

A generator for DC current injection has to fulfil several tasks during long-term tests. Most importantly, the following points have to be considered during the testing, operation and design:

1. **Testing**
   1.1 DC voltage long-term performance (DC-perform.)



1. Capacitive current injection [4]
2. Hydraulic current injection
3. Inductive DC current injection [5]
4. Isolating shaft and electrical engines
5. Isolating transformers [6]
6. Fuel-power-system

Figure 5: Concepts for DC current injection on high voltage potential

1.2 Polarity reversal test performance (polarity rev.)
1.3 DC current ripple
1.4 Electro-magnetic compatibility (EMC)
1.5. Possibility of superimposed impulse voltage tests (SIMP)
1.6. Influence on partial discharge measurements (PD)

2. Laboratory Operation

2.1 Handling and maintenance of the test generator
2.2 Controlling of the generator
2.3. Influences on parallel working areas
2.4. Space requirements

3. Design and erection of the generator

3.1 Overall costs of the generator
3.2 Use of commercial standard parts without redesign (stand. parts)
3.3 Weight of the overall assembly
3.4 Upscaling / downscaling of the concept for different voltage, current and power. All concepts of Figure 5 are compared in Table 1. Each point is evaluated separately for each concept and is marked with "+" if an advantage is estimated, "0" if neutral and "-" in case of a disadvantage.

		1. Testing						**2. Laboratory**				**3. Design**			
		1. DC-perform.	2. polarity rev.	3. ripple	4. EMC	5. SIMP	6. PD	1. maintenance	2. controlling	3. Influences	4.space	1. costs	2. stand. parts	3. weight	4. upscaling
concept	**1. capacitive**	+	0	+	-	-	-	+	+	0	+	+	+	+	+
	2. hydraulic	+	+	0	+	+	+	-	0	-	0	+	+	0	0
	3. inductive	0	0	+	+	0	+	+	+	+	-	-	0	+	-
	4. mech. shaft	0	+	0	+	+	+	-	0	-	0	0	-	0	0
	5. transformer	0	0	+	+	+	+	+	+	+	-	-	0	-	+
	6. fuel-engine	-	-	0	-	-	0	-	0	-	+	+	+	+	0

Table 1: Comparison of the concepts in Figure 5 ("+" = advantage, "0" = neutral, "-" = disadvantage)

The capacitive current injection (1) uses the total distance between high voltage and ground to insulate the DC voltage. Furthermore, the RC-characteristics result in a very homogeneous voltage distribution. For polarity reversal, the overall capacitance of the RC transmission path has to be regarded, such that polarity reversal is possible in the specified time. Since inductances are included in the transmission path, the current source has to be switched off during superimposed voltage tests. Special overvoltage protection during superimposed impulse voltage testing might be possible, but has to be developed. In this case still the capacitance of the current source has to be taken into account, since the high capacitance may influence the voltage shape. The high frequency generator has the advantage of a very low current ripple and a very compact design, with low space requirements. Furthermore a very flexible controlling, without maintenance requirements will be possible. On the other hand, the high frequency may influence PD measurement systems, which are operated in the kHz range. Also currents at the grounding wire due to the AC/AC converter have to be considered, which might influence other laboratory segments. Due to the extensive use of electronics the generator can be designed very cost efficient. In addition, mainly standardised components can be used. Therefore, a strictly modular concept is possible that can easily be scaled to higher voltage ratings. On the other hand, electronics are sensitive to electro-magnetic interferences especially during flashovers, which has to be considered during the generator design.

The hydraulic concept (2) has a robust insulation across the total insulating distance provided by insulating oil. It is not affected by impulse voltage stress. Therefore, the insulation will be able to easily manage the electrical stress. Furthermore, the impulse voltage shape is not influenced by the transmission path, since its total capacitance will be very low. As long as the total assembly itself is free of partial discharges, no influence during PD measurement is to be expected. Since electrical drives with 50/60 Hz will be used, the current ripple and the space requirements will be higher compared to other concepts. In addition, the drives will require higher maintenance efforts and produce more audible noise in the laboratory compared to non-rotating concepts. The generator control will be less flexible compared to other concepts. For example more time for switching off the generator will be required compared to other concepts, since the rotation needs to be slowed down. For the design of the generator, many commercial standard parts can be used, which results in a very cost efficient design. Since hydraulic drives usually only operate in lower power regions, the technical limits of hydraulic drives set a limit to technical ratings, such as maximum test loop geometry and maximum current.

The functionality of the inductive current injection is highly dependent on the system used in the transmission path. The concept will be most efficient, when the shorter transmission path loop and the test object consist of the same material and type. Therefore, both would have the same current and voltage ratings. Considering an AC current trough the cable/gas insulated system in the transmission path, the temperature at the transmission path will be higher than the same assembly at the test object stressed with DC current. This results in a poor insulation performance. Therefore, the risk of failure inside the transmission path will be higher than the risk of failure for the test object. In conclusion, the current and voltage rating of the cable/gas insulated system for the transmission path has to be higher than the ratings of the test object. If special designs for the transmission path or two parallel systems are used, the costs increase. The necessary space for current loop and terminations will also be higher than in other concepts [7]. Superimposed voltage tests will be possible, but the overall capacitance of the transmission path has to be considered.

The performance of the current injection with isolating shaft (4) strongly depends on the performance of the shaft. Since the shaft has to withstand permanent mechanical and electrical stresses, comprehensive knowledge about the material and its long-term behavior under multi-physical stress is required. Since electrical drives are used in this concept, similar disadvantages as in concept 2 are assumed. Compared to other concepts, costs are higher, because special parts and assemblies and, therefore, engineering effort is required. For higher voltage levels and higher rated power the isolating shaft has to be extended, with consequently ever higher mechanical requirements.

A major disadvantage of the current injection with isolating transformers (5) is that only a small distance inside the transformer can be used to insulate the voltage. Therefore, the system can be very sensitive to DC effects

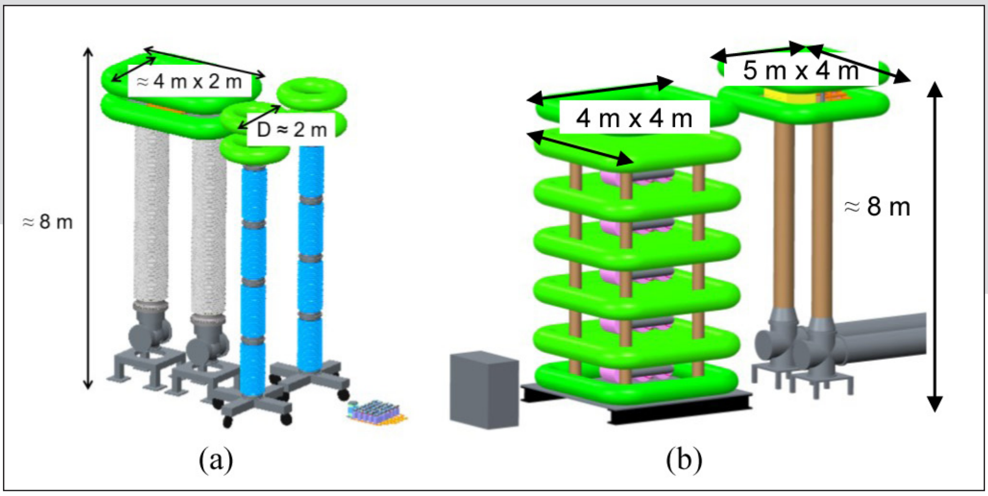


Figure 6: (a) Capacitive current transmission [4] / (b) Inductive current transmission with isolating transformers

during long-term DC and polarity reversal stress. Thus, a certain number of transformers have to be used in series, which increases costs and the weight of the overall assembly. If these disadvantages can be managed, the concept will have a very stable operating behavior since no rotating machines are used. The concept can easily be scaled up by adding further isolating transformers. But each transformer has to carry the rated power and thus to be dimensioned with the required cross-section of the copper windings. Overall material invest and weight and thus the costs of the design will be higher compared to other concepts.

The current injection with a fuel-power-system is a very simple and cheap solution to fulfill the task. But the high risk of fuel explosion in combination with electrical arcs and the constant fuel feeding are crucial points for the designer and the operator of such generator. The influence on PD measurement is uncertain [7].

3.3. Prototype experience

Part of the concepts described in Figure 5 have already been prototyped or are actually in discussion to overcome the limitations of AC current injection. Known publications also show the progress in research for this new generator type. Figure 6 shows CAD prototypes of different generator concepts.

A capacitive current injection generator is being built up in the high voltage laboratories at Technische Universitaet Darmstadt. First experiences with smaller prototypes were positive and showed good performance. The construction of a larger generator for 5000 A and 660 kV voltage is currently in progress. It consists of a feeding unit on ground potential, two capacitor columns similar to voltage dividers and the rectifier on high voltage potential. Due to the high frequency of approximately 50 kHz the assemblies on high voltage potential can be designed very compact.

The current injection with isolating transformers had been investigated before, but was discarded during the development. The feeding unit could be designed very simple. Only a standard regulating transformer was required. Transformers with solid insulations were considered and investigated during the design process. Since the DC voltage has to be insulated between primary and secondary winding, only a small insulating distance is possible. Thus, insulation breakdowns occurred during the prototyping process. This proves that insulation faults are more likely compared to other concepts. Figure 6 (b) shows a possible implementation of the overall assembly. It turns out that this option is far less compact than the capacitive solution (Figure 6 (a)).

4. Conclusion

DC current injection on high voltage potential offers new technical possibilities for laboratory tests. Technical limits of AC current testing can be overcome. Especially the high reactive power consumption by AC heating of HVDC equipment of high current ratings can be avoided. Also all customer requirements for adequate testing with the real technical ratings can be fulfilled. Even DC current heating during long-term tests of AC cable systems is of interest to achieve higher current ratings and larger cross sections. Several technical solutions can be developed to inject DC current on high voltage potential. Each technical solution has its advantages and disadvantages. Running prototyping projects for the generator concepts are shown. Especially the capacitive current injection seems very promising and is currently followed.

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