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Some thoughts regarding prototype installation tests of gas-insulated HVDC systems

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SUMMARY

Based on service experience, gas-insulated HVAC systems feature a high degree of reliability and excellent long-term performance. This applies for gas-insulated switchgear (GIS) as well as for gas-insulated lines (GIL). Users intending to employ gas-insulated HVDC systems expect the same reliability and long-term performance. This leads to the question of the necessity of long-term tests on gas-insulated HVDC systems in general and to the formulation of relevant test procedures if applicable. The test mainly closes the lack of experience with the new HVDC technology under real service conditions. The test will be called “prototype installation test” to express the idea that this test should be carried out for collecting more experience with this kind of DC technology. The main part consists of a long-term test at DC voltage under high load conditions followed by a test with superimposed LI and SI voltage waveforms. A test duration in correspondence with practical load cycles of 30 days is suggested. The test at high load requires a current injection of the rated current into the HV circuit. AC as well as DC current heating is discussed. The test procedure for superimposed voltage testing in general and the testing with superimposed oscillating voltage in particular is presented. The oscillating impulse voltage is especially required in case of long test assemblies like GIL.

Based on these considerations a prototype installation test procedure is recommended, which can prove the long-term capability of gas-insulated HVDC systems. This proposal is also under discussion in JWG D1/B3.57.

KEYWORDS

Gas-insulated HVDC Systems, long-term test, testing procedure, superimposed voltage test, current heating

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1. Introduction

HVDC transmission systems are of special importance for long distance transmission. Besides DC overhead lines, underground lines are of interest, in particular when environmental concerns are relevant. Moreover, gas-insulated DC substations are applied at the converter stations due to their space saving features. Based on service experience, gas-insulated HVAC systems feature a high degree of reliability and an excellent long-term performance. This applies for gas-insulated switchgear (GIS) as well as for gas-insulated lines (GIL). The user who intends to apply gas-insulated HVDC systems does expect the same reliability and long-term performance.

Up to now, only some few gas-insulated HVDC systems are in operation worldwide [1]. In consequence, little service experience and few information about the long-term capability of this type of technology are available until now. This leads to the question of the necessity of long-term tests on gas-insulated HVDC systems in general. Especially GIL assemblies need a similar evidence for functionality as for other underground line systems like cables, where the prequalification test is usually performed [2, 3].

2. Motivation for prototype installation tests of gas-insulated HVDC systems

2.1. Necessity of long-term tests on gas-insulated HVDC systems

When considering the necessity of long-term tests on gas-insulated DC systems, in particular GIL, a lot of pro and con arguments can be cited.

Cons: DC GIL is applied as an alternative to DC cables. However, the DC GIL insulating system is different from that of a DC cable.
DC cables applied with modern VSC converter technology consist of polymer material whose ageing is well known, in particular at polarity reversal. GIL mainly contains SF_6 or N_2/SF_6 gas mixture as insulating medium. This medium does not show any known ageing phenomena [4].
The insulators are well proven and their long-term reliability is well known from long-term investigations. The lifetime of insulators amounts to more than 50 years. Furthermore, each insulating component is tested thoroughly in course of the quality assurance procedure.
Moreover, gas-insulated HVDC systems are type tested in a sophisticated and time consuming procedure considering all critical stresses to be expected during service, e. g. the charging process of the insulating components and stresses by superimposed voltages.

Pros: DC cables are subjected to a long-term test to prove the long-term capability. Comprehensive recommendations are presented in CIGRE Brochure 496 [2]. If DC GIL is considered to be an alternative to DC cables, the long-term capability of those systems has to be proven as well.
Furthermore, some critical phenomena in gas-insulated HVDC systems as the impact of manufacturing, mobile particles and surface charging of the insulators in combination with the stress by superimposed impulse voltages can only be studied in long-term tests.
Moreover, AC GIL was also subjected to extensive long-term tests before installing in the EHV system. Different tests on prototype installations are reported in literature, e. g. [5, 6]. Additionally information for long-term test on buried GIL is given in IEC 62271-204 Annex C [7].
The most convincing pro-argument is the lack of experience with this new technology. Therefore, it is urgently requested to collect more experience before the first installation of new DC gas-insulated

systems. If this technology would not behave as reliable as gas-insulated HVAC systems, the customer won't accept it.

2.2. Test parameters to prove long-term performance under real service conditions

The main intention of the long-term test for gas-insulated systems is to confirm the reliability of the system under real service conditions. Therefore, all different major modules of the gas-insulated systems should be tested, being installed by using the same installation procedure as for future customer projects. Tests on GIL systems will require a certain length giving the chance to neglect cooling effects at the test set-up's boundaries and to test the thermo-mechanical behaviour adequately. The test procedure is described in detail in chapter 4. For gas-insulated switchgear, the focus of the test is on the dielectric behaviour. Besides the dielectric stress, the maximum thermal and mechanical stress should be applied to the system (e.g. movements of sliding contact systems due to heating and cooling phases).

In the case of GIL, the system will typically be installed in tunnels or directly buried. The maximum thermo-mechanical stress arises for directly buried GIL. Additionally to the described test procedure, the sections of static and sliding friction of the tubes in the soil and the forces and movements on the angle modules should be determined by measurements for the special case of directly buried systems [8].

After the commissioning phase, DC voltage and current (preferable DC or equivalent AC current) are applied. A repetition of load cycles with high load and no load phases should be carried out. By this, thermal expansion of the modules, sliding contacts and compensators of GIS or GIL are initiated. Hence, thermal and mechanical stress is subject to this test procedure. Additional to voltage and current measurements, it is advisable to measure temperatures, mechanical forces and extensions during the test procedure. Regarding the reproduction of overvoltages, e.g. caused by lightning strikes, switching operations or converter failures, LI and SI voltage superimposed to DC voltage shall prove the dielectric strength of the system under real installation conditions.

3. Basic structure of prototype installation test

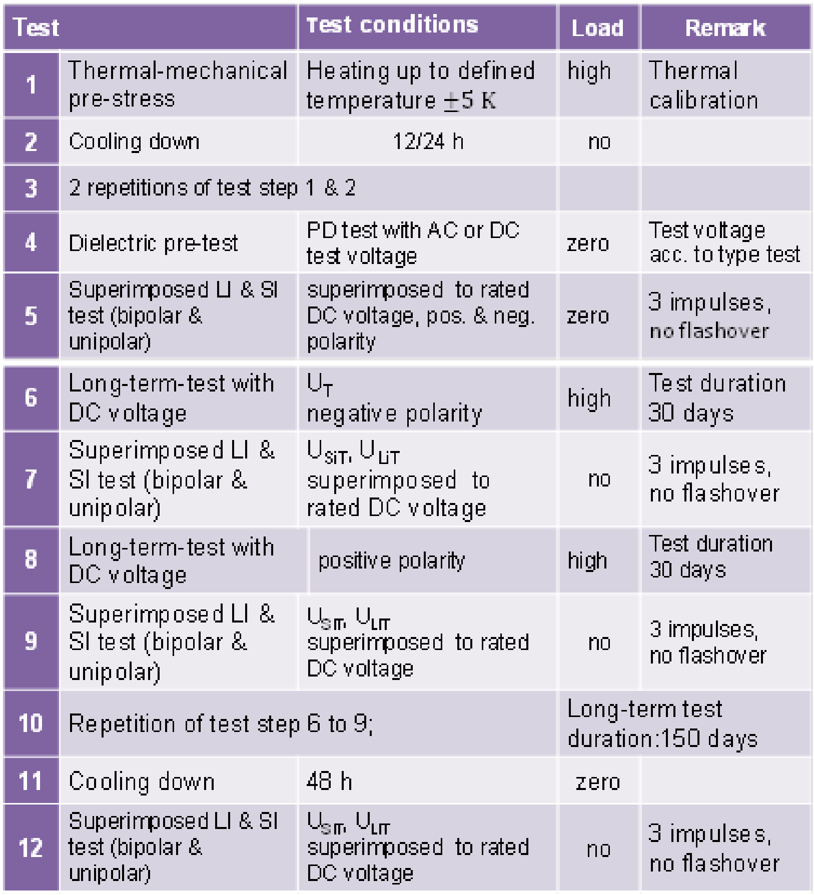
The basic structure of the prototype installation test for a gas-insulated DC system is presented in Table 1. If the DC installation consists of a gas-insulated part and a cable a combined test could be suggested as later discussed in Table 2.

Before dielectric testing thermo-mechanical pre-tests are carried out in step 1 to 3 to ensure the mechanical integrity and current carrying capability of the system.

The dielectric integrity of the installation is tested in step 4 and 5. In these steps the system is tested at ambient temperature and no-load conditions. The acceptance criteria of step 5 “no flashover” means that no flashover across the insulator surface is permitted. In consequence, in case of a flashover the test arrangement has to be checked and the flashover has to be localized.

The actual long-term test with DC voltage starts at step 6 or step 8, respectively. The test voltage level U_T will be discussed in chapter 4. The test duration of this first sequence is chosen to be 30 days. The superimposed switching and lightning voltage (step 7 or 9, respectively) shall be subjected to the test object not later than two hours and without earthing of the test object or switching off the DC source. The test level U_SiT and U_LiT will also be considered in chapter 4.

If this first test sequence is passed successfully, a second long duration test is carried out, lasting for 150 days each, followed by the superimposed voltage tests (step 10). After this test sequence, the test arrangement is cooled down for 48 h and subjected to superimposed voltage again, i. e. the test arrangement has reached ambient temperature, but the status of the insulating components are at least partly charged.



Test		Test conditions	Load	Remark
1	Thermal-mechanical pre-stress	Heating up to defined temperature ±5 K	high	Thermal calibration
2	Cooling down	12/24 h	no	
3	2 repetitions of test step 1 & 2			
4	Dielectric pre-test	PD test with AC or DC test voltage	zero	Test voltage acc. to type test
5	Superimposed LI & SI test (bipolar & unipolar)	superimposed to rated DC voltage, pos. & neg. polarity	zero	3 impulses, no flashover
6	Long-term-test with DC voltage	U_T negative polarity	high	Test duration 30 days
7	Superimposed LI & SI test (bipolar & unipolar)	U_{SIT}, U_{LIT} superimposed to rated DC voltage	no	3 impulses, no flashover
8	Long-term-test with DC voltage	positive polarity	high	Test duration 30 days
9	Superimposed LI & SI test (bipolar & unipolar)	U_{SIT}, U_{LIT} superimposed to rated DC voltage	no	3 impulses, no flashover
10	Repetition of test step 6 to 9;		Long-term test duration:150 days	
11	Cooling down	48 h	zero	
12	Superimposed LI & SI test (bipolar & unipolar)	U_{SIT}, U_{LIT} superimposed to rated DC voltage	no	3 impulses, no flashover

Table 1 : Prototype installation test for a pure gas-insulated DC system

If the gas-insulated HVDC system is connected to a DC cable the interface has also to cover the recommendations for testing of DC extruded cable systems [2, 3]. As the intention of the prototype installation test of a gas-insulated system is different from that of the prequalification test of a cable (verification of electrical lifetime), a test procedure is proposed to cover both.

Load	LC (or HL)	LC (or HL)	HL	ZL	HL	ZL	LC (or HL)	LC (or HL)	SIMP
Number of cycles or days	40	40	40	120	40	60	40	40	n.a.
Test voltage	+	-	-	-	+	+	+	-	Rated values
	U_T	U_T	U_T	U_T	U_T	U_T	U_T	U_T	

Table 2 : Test sequence – gas-insulated system, cable termination with cable for VSC

Basis is the test procedure for polymeric insulated cables, for example for VSC applications. To cover the special requirements of gas-insulated systems, the duration of the DC voltage stress has to be extended to consider the longer DC transition of solid insulating materials used in gas-insulated systems. The procedure shown in Table 2 is an example how to extend a pre-qualification test for cables. It has to be noted that the test voltage for cables and cable terminations is higher compared to gas insulated systems. This aspect has to be considered for the design of the interfaces between both types of equipment.

4. Test levels and test procedure

4.1. Steady state DC voltage and DC current

When a DC voltage is applied, the low effective DC conductivity of usually used epoxy composite solid insulation determines the rate of transition from a capacitive to a resistive field distribution in the system. The transition to a DC field distribution for epoxy insulators takes hours to months, depending on the permittivity and conductivity of the material and the temperature. Temperature gradients define primarily, via the temperature dependence of the DC conductivity, where field enhancement and space charge accumulation occurs in the solid, but also shapes the capture volume for ions near the solid-gas interface. Moreover, the surface electric field can reach its minimum or maximum value during the transition between voltage switch-on and DC steady state. This, associated to the variety of possible operation conditions, requires long-term DC insulation system tests [9]. Actually the test duration should correspond to the time to reach the DC steady state, minimum 90 % - transition from a capacitive to a resistive field distribution in the gas-insulated system. A test duration of 30 days for each DC step is an acceptable compromise to realize almost DC steady state conditions at high load and no load.

The long-term test is to be considered as an accelerated procedure. With this regard, a test at rated DC voltage U_{rdc} is not reasonable. Taking into account a lifetime exponent of N=12 for the gas-insulated system determined by the solid insulation a test voltage of 1.4 U_{rdc} seems adequate to confirm a lifetime of 50 years. On the other hand, a test voltage distinctly higher than the rated voltage could lead to a field strength at the insulators higher than in practice, probably affecting the charge accumulation at the insulator and the charging time. As the main purpose of the test is to confirm the capability of the system to withstand the charging processes and stresses due to the superimposed voltage, a test voltage of 1.2 U_{rdc} is a compromise which can largely prevent charging processes not occurring in practice.

The current causes a heating of the insulating system. This process has an essential impact on the production of charge carriers and on the charging process in general. Therefore, a heating comparable to practice by the rated current is reasonable. The heating method used shall be conductor heating. The heating shall be generated with equivalent DC or AC current. Gas-insulated systems can be subject to significant harmonic current content. Such harmonic current cannot be easily reproduced in laboratories. Equivalent DC and AC power frequency current (50 Hz or 60 Hz) shall then be used. The amplitude of the equivalent test current shall produce the same total watt losses calculated for the specified harmonic current spectrum. The calculation of the equivalent DC and AC current is given in IEC/IEEE 65700-19-03 [10].

4.2. Superimposed LI and SI voltage tests

The test object shall be subjected to superimposed impulse voltages. These tests shall simulate the overvoltage stresses during service. Overvoltages are caused by line to ground faults as well as converter faults – represented by switching impulse voltages – or by lightning strokes, represented by lightning impulse voltages. When fixing the amplitude of the superimposed impulse voltages some differences between the type test and the prototype installation test with regard to statistical as well as insulation coordination considerations have to be reflected.

Statistical considerations

The type test is conducted with rated voltage on a test arrangement consisting of about five insulators, and three impulses of each polarity are applied. The prototype installation test is carried out on a test object comprising about 200 insulators and subjected to 9 up to 15 impulses depending on the number of sequences. As the breakdown voltage is related to the number of insulators (volume effect) and to the number of impulses the amplitude has to be adopted.

The dependency of the breakdown voltage on the number of insulators can be determined as given in IEC 60071-2 [11]. According to the procedure described in detail in Annex 1of this paper the LI voltage should be reduced by about 4% and the SI voltage by about 8% related to the rated impulse voltages and assuming 200 insulators in parallel.

The dependency on the number of impulses can be derived from [12]. Figure A2 of Annex 1 shows the dependency on the number of impulses for LI and SI voltage. The difference of breakdown voltage on the number of impulses applied at type test and prototype installation test respectively, is less than 2%.

In consequence, from a statistical point of view the amplitude of the superimposed LI voltage would have to be reduced to 94% of the rated LI voltage.

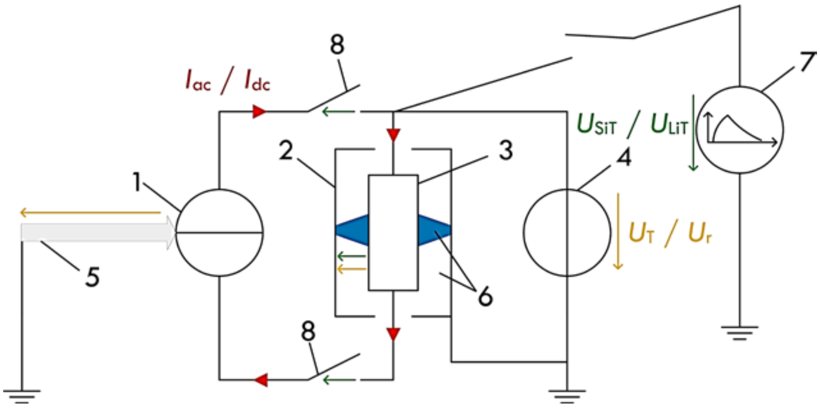
Insulation coordination considerations

If the installation is adequately designed according to the insulation coordination procedure in IEC 60071-1 [13], no overvoltage exceeding the coordination withstand voltage U_{cw} shall occur. Taking into account a safety factor k_{s} the required coordination withstand voltage, which is lower than or equal to the rated voltage, is determined. According to [11] a safety factor $k_{\mathrm{s}} = 1.15$ is recommended for internal (non-self-restoring) insulation. However, for gas-insulated systems a higher safety factor is reasonable. In practice, mostly a safety factor of 1.25 is applied [14]. As a result, to avoid stresses exceeding those in practice, the amplitude of the superimposed impulse voltage subjected to the test object during the prototype installation test shall be reduced to 80% of the rated LI and SI voltage.

5. Test circuit and test equipment

5.1. Basic Test circuit

A typical example of a test circuit for a prototype installation test of gas-insulated systems can be seen in Figure 1. The test arrangement consists of an enclosure (2), the insulation (6) and the inner conductor (3). The inner conductor forms a short circuit loop in order to inject high currents. The inner conductor of the test sample is supplied with continuous DC voltage U_{T} / U_{r}. Simultaneously a current source (1) is feeding the short circuit loop of the test sample with a current I_{ac} or I_{dc}. Furthermore, the test sample needs to be tested with superimposed impulse voltage. An impulse voltage source (7) is connected to the test sample for generating U_{SiT} or U_{LiT}. The impulse voltage is subjected the test object by a spark gap or a coupling capacitor, which is indicated by a switch (section 5.3). If necessary, optional switches (8) can be used for isolating the impulse voltage U_{SiT} or U_{LiT} during superimposed impulse voltage testing in order to protect the current source (1) and the transmission path (5) from damage.



1. Current source
2. Enclosure
3. Inner conductor
4. DC voltage source
5. Power transmission for 1.
6. Gas insulated system
7. Impulse voltage source
8. Switches (optional)

Figure 1 : Typical test circuit for prototype installation test of gas-insulated systems

5.2. Current sources for heating

Conventionally, current heating of current loops is performed by AC current transformers, which induce the AC current directly in the current loop. AC currents induced to the enclosure have to be avoided only, if the enclosure current affects the temperature gradient across the insulators significantly. Another option is to inject the DC current directly on HV potential. Furthermore, for a test object with a length of several hundred meters and a test current of several kilo-amperes, AC current testing would require high magnitudes of reactive power.

To overcome these drawbacks, an injection of a DC current at DC high voltage potential is possible. The main task is to transmit power and simultaneously isolate the voltage. Possible technical solutions to transmit the power are: hydraulic transmission via hydraulic oil, inductive transmission via isolating transformer [15], mechanical transmission via isolating shaft, inductive transmission via secondary short circuit loop [16] and capacitive transmission with high frequency [17].

A novel technical solution using capacitive power transmission is presented in Figure 2 [17] [1]. An AC/AC converter generates a kHz-frequency power signal at earth potential. The kHz-frequency power signal is converted with a transformer and transmitted by capacitors, while the DC voltage U_{dc} is blocked by the capacitors. Resistors parallel to the capacitors are applied to achieve a homogeneous potential distribution across the capacitors. To avoid reactive power flow in the circuit an inductance is integrated in the circuit. The resonant frequency of the circuit is the operating frequency of the AC/AC converter. At high voltage potential, the power is converted and rectified to the high current I_{dc}.

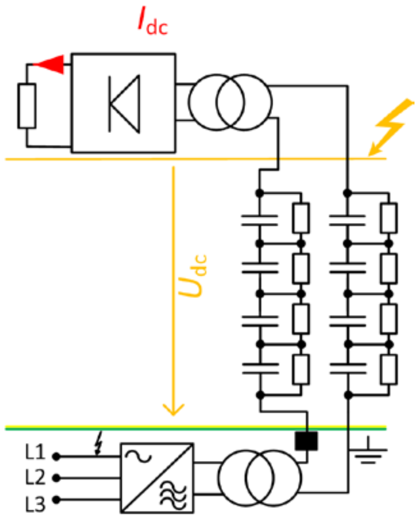


Figure 2 : Injection DC current I_{dc} at high DC voltage U_{dc} by capacitive transmission [17]

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[1] The support of this work by the IWB-EFRE-Program from Hesse, Germany (Funding Code 20002558) is gratefully acknowledged.

5.3. Blocking and coupling of superimposed LI and SI voltages

The test circuit according to IEC 60060-1 [18] is given in Figure 3. The superimposed test voltages or composite test voltages are generated by two voltage sources, a high voltage DC-source and an impulse voltage source, that are connected to each other via coupling and blocking elements at the HV terminal of the test object. To measure the voltage on the test object a DC-divider or composite voltage divider is recommended.

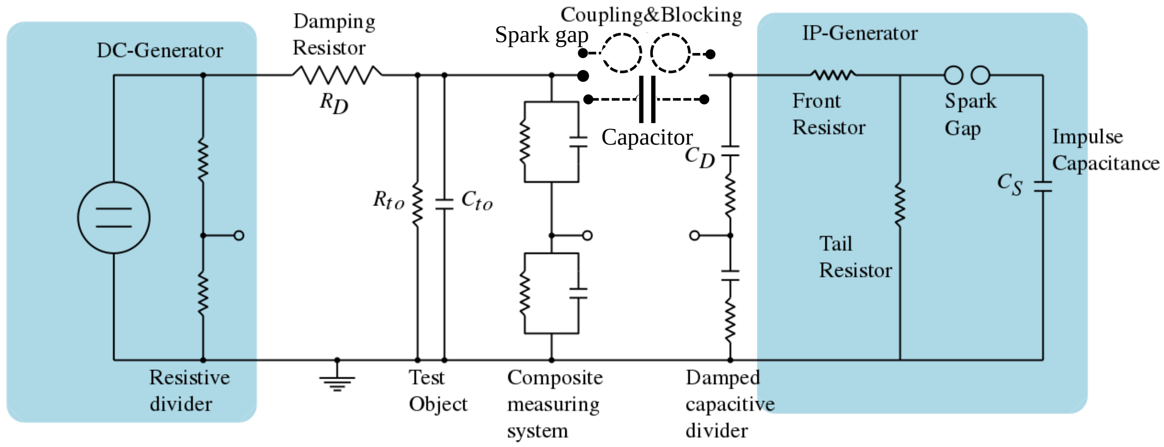

Figure 3 : Test circuit for testing with superimposed impulse voltages

The impulse capacitance of the IP Generator C_S needs to be at least twenty times higher than the load capacitance C_L. This includes the capacitance of the test object, of the divider C_D and all stray capacitances.

For blocking the DC voltage and coupling the impulse voltages, two options are applicable, spark gap or capacitor. Both coupling devices have some disadvantages, which have to be taken into account when applying the superimposed impulse voltage during the prototype installation test. Since the blocking capacitor and the test object capacitance form a voltage divider, it is recommended that the blocking capacitor is about ten times larger than the test object capacitance. Due to the extension of the test object its capacitance amounts at least to some 10 nF. This would require a coupling capacitor of 100 nF and more, which is hardly achievable under practical on-site conditions [19].

The spark gap exhibits varying ignition voltage depending on climatic conditions and is not able to extinguish its arc under DC voltage stress. Voltages across the test object and the impulse generator do not superpose as expected but they overlap leading to a steep voltage rise. The spark gap remains conducting as long as the test object is loaded. When the arc in the spark gap extinguishes the test object is completely discharged and the DC source has to charge it again [19]. It is assumed that this process has negligible impact on the surface charges of the insulators, but further investigations on this subject are necessary.

5.4. Superimposed impulse voltage testing with oscillating impulse voltage

Test assemblies such as GIL will require a certain length. This results in a high capacitance in the range of some 10 nF of the test object and in travelling wave effects of the impulse voltage, because the rise time of the impulse voltage is near the propagation time of an electromagnetic pulse through the GIL. To avoid related problems a different impulse voltage has to be used. Smaller generators and higher front times can be realized with standard oscillating impulse voltages according to IEC 60060-3 [20], which is typically applied for on-site testing after installation.

Superimposed oscillating impulse voltage has so far not been performed in practice. Actual HV laboratory results show the technical feasibility of such test, but some effects on the voltage shape due to the superposition have to be considered.

Figure 4 shows an oscillogram of a superimposed impulse voltage test with oscillating switching impulse voltage (OSI). Figure 4 demonstrates that due to the superposition of same polarity the amplitude of the test voltage decreases, which has to be taken into account in the test procedure.

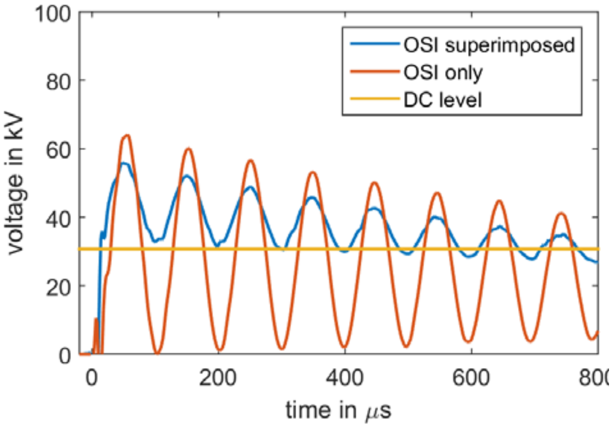

Figure 4 : OSI superimposed with DC voltage: laboratory result

6. Conclusion

The intention of the prototype installation test as well as the preliminary test procedure is presented. Furthermore, special consideration is made with respect to the injection of DC currents at high voltage DC potential and to the generation and superposition of the impulse voltages.

With the recommended long-term test for gas-insulated systems, the reliability of gas-insulated systems under real service conditions can be confirmed. In addition to type tests, the prototype installation test consisting of combined dielectric, thermal and mechanical stresses is particularly suited to prove the long-term capability and reliability of gas-insulated systems for HVDC and will increase the customer acceptance for these new technologies. This contribution is to support the actual discussion in Cigré JWG D1/B3.57 regarding the definition of a prototype installation test.

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ANNEX 1

Statistical considerations

Dependency on the number of insulators:

Number of insulators during type test: 5; number of insulators during prototype installation test: 200

Assuming that the rated test voltage corresponds to the 10% breakdown probability, the following values can be taken from diagram C1 in [11].

$$U_{10(5)} = U_{50} - 2.1\,Z$$

$$U_{10(200)} = U_{50} - 3.2\,Z$$

With $Z = 0{,}03\,U_{50}$ for lightning impulse voltage and $Z = 0{,}06\,U_{50}$ for switching impulse voltage it follows

$$U^{LI}_{10(5)} = U_{50} * 0.937$$

$$U^{LI}_{10(200)} = U_{50} * 0.904$$

$$U^{LI}_{10(200)} / U^{LI}_{10(5)} = 0.96$$

$$U^{SI}_{10(5)} = U_{50} * 0.874$$

$$U^{SI}_{10(5)} = U_{50} * 0.808$$

$$U^{SI}_{10(200)} / U^{SI}_{10(5)} = 0.92$$

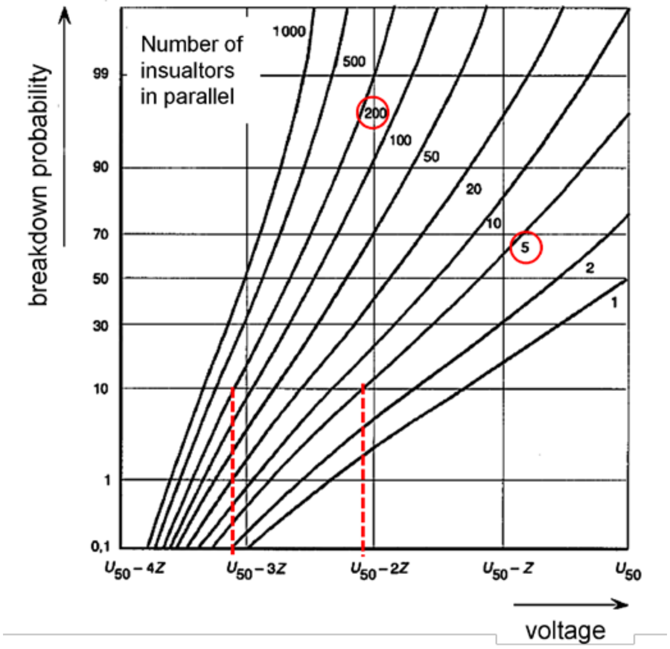

Figure A1: Dependency of the breakdown voltage on the number of insulators

- ➢ Due to the number of insulators, i. e. 200 insulators in parallel, LI voltage should be reduced for about 4% and the SI voltage for about 8% related to the rated impulse voltages.

Dependency on the number of impulses

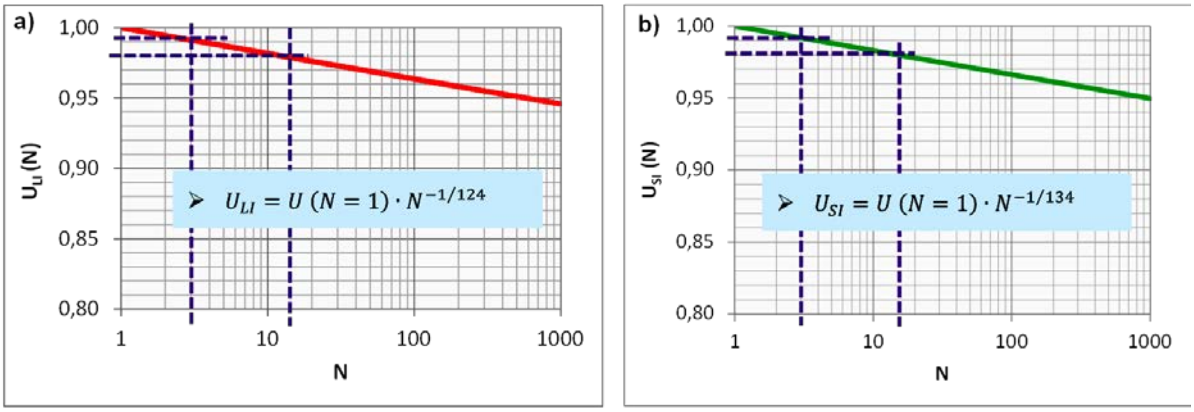

Figure A2: Dependency on the number of impulses for LI and SI voltages [12]

- ➢ Difference of breakdown voltage on the number of impulses applied at type test and prototype installation test respectively is less than 2%.