

D15.2 Document on test requirements, procedures and methods

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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NOMENCLATURE

ABBREVIATION	EXPLANATION
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
GIS	Gas Insulated Switchgear / System
VSC	Voltage Source Converter
LCC	Line Commutated Converter
IEC	International Electrotechnical Committee
WP	Work Package
D15.1	PROTOTioN WP 15 deliverables 15.1
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EXECUTIVE SUMMARY

HVDC GIS has been introduced as a promising technology where the benefits of the proven HVDC transmission and AC gas-insulated switchgear/systems can be combined. Up to the present time, no international standards describing the requirements, applicable tests and test procedures of HVDC gas insulated systems (GIS) have been developed. This document provides a general guideline for listing the tests that shall be applied to HVDC GIS to verify their designed performance. Focus is given to the dielectric test requirements due to the different nature of DC electric fields in GIS compared to AC fields. Additionally, due to lack of operational experience on HVDC GIS, a long-term test method to prove the dielectric performance of a prototype installation under in-service conditions is described. The described method will be applied to a prototype HVDC GIS which will be built by a GIS manufacturer (task 15.3 of PROMOTioN) based on the specifications and ratings that are defined in deliverable D15.1.

Chapter 1 introduces the theoretical benefits of HVDC GIS technology and the motivation for defining test procedures and requirements.

Chapter 2 deals with the special considerations of HVDC GIS. Focal point is the different type of electric field that can be generated in a GIS upon application of AC and DC voltage.

In chapter 3 terms and definitions related to HVDC GIS are introduced.

In chapter 4 the ratings of the HVDC GIS are presented. The ratings are based on international standards of AC GIS and CIGRE JWG D1/B3.57.

Chapter 5 lists all the required dielectric tests for proving the designed performance of the HVDC GIS. Likewise, the listed tests are based on AC GIS international standards and recommendations of CIGRE JWG D1/B3.57.

Chapter 6 focuses on the prototype installation test. This is a special test to demonstrate reliability of HVDC GIS technology under real service conditions. For this purpose, a long-term test procedure is fully defined. The recommended test procedure will be applied on an ABB HVDC GIS prototype.

Finally, chapter 7 summarizes the main conclusions of this document.

For the prototype installation test, the heating with AC current and the methods for the superimposed voltage test are discussed in annex A.

1 INTRODUCTION

1.1 MOTIVATION

Nowadays, HVDC systems have become a common solution for long distance power transmission. On the other hand, gas-insulated systems (GIS) is a proven technology in HVAC systems mostly driven by space saving and immunity to extreme weather conditions. These attributes have led to the investigation of a potential combination of the two technologies, resulting to HVDC gas-insulated systems (HVDC GIS). In the context of offshore meshed HVDC networks it is apparent that such a technology can find ground for development since space minimizing and tolerance to extreme weather are required.

Up to now, only few HVDC GIS are in operation worldwide. In consequence, little service experience and few information about the long-term capability of this type of technology are available. Additionally, there are no international standards established for specifying and testing such systems.

This context determines the objectives of this document which are to:

- List tests for verification of HVDC GIS based on international standards for AC GIS and CIGRE technical brochures on HVDC GIS.
- Define a long-term test procedure which will be applied on a specific HVDC GIS prototype installation built by a GIS manufacturer based on specifications/ratings defined in PROMOTiON deliverable D15.1.

1.2 RELATION TO PROMOTION

PROMOTiON is European Union project which seeks to develop meshed HVDC offshore grids on the basis of cost-effective and reliable technological innovation in combination with a sound political, financial and legal regulatory framework. PROMOTiON is divided to different work packages. Subsequently each work package consists of different tasks.

This document serves as the second deliverable D15.2 of work package WP15 “DC GIS technology demonstrator”. Furthermore, it falls under task 15.1 “Defining specifications and long term testing requirements” which is led by SHE (Scotland).

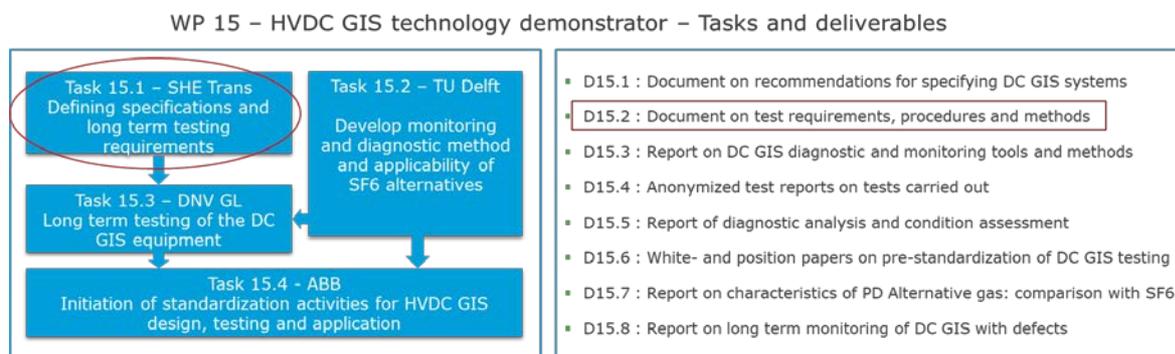


Figure 1: Layout of WP 15

In the first deliverable of WP15 i.e. D15.1, the HVDC GIS under consideration have been defined and ratings such as rated insulation levels, rated currents have been specified.

In the last section of this document a long-term testing method is defined for verifying the dielectric performance of a prototype installation under service conditions. The defined testing method will be used as input for testing a prototype HVDC GIS built by ABB (task 15.3) in accordance with specifications and ratings defined in deliverable D15.1.

1.3 APPLICABILITY

This document specifies test requirements for HVDC gas-insulated metal-enclosed system in which the insulation is obtained, at least partly, by an insulating gas other than air at atmospheric pressure, for DC rated voltages up to 550 kV. Focus is given to dielectric test requirements since the electric field within a DC GIS can be significantly different compared to the respective AC field.

This document covers the test requirements of gas-insulated metal-enclosed switchgear/systems, as these are specified in deliverable D15.1. Such a system consists of individual components (e.g. disconnectors, earthing switches, bushings, cable terminations, current/voltage transformers, surge arresters) which are intended to be directly connected together.

This document completes and amends, if necessary, the various relevant standards applying to the individual components constituting the HVDC GIS.

The defined long-term test procedure is intended to be applied for the specific ABB 320 kV HVDC GIS pole as this is described in chapter 6.

1.4 DOCUMENT STRUCTURE

The rest of the document is structured as follows: In chapter 2 special considerations of HVDC GIS are listed while in chapter 3 terms and conditions related to the HVDC GIS technology are introduced. Chapter 4 describes the ratings of HVDC GIS. Chapter 5 lists the required tests for HVDC GIS. Finally, in chapter 6 a prototype installation test procedure is defined for an ABB HVDC GIS pole rated in accordance with deliverable D15.1.

2 SPECIAL CONSIDERATIONS FOR HVDC GIS

Specifications and test requirements for AC GIS have been already standardized. Therefore, they can be used as a starting point for defining test requirements for DC GIS too. However, there are differences between the two technologies which shall be taken into account. The most distinctive difference is the different electric field that is generated within GIS upon application of AC and DC voltages:

2.1 DC VS AC ELECTRIC FIELD IN GIS

The distinctive difference between AC and DC systems is the nature of the generated electric field across the insulating materials. A DC electric field can be substantially different to an AC electric field within a GIS. This is briefly explained in the following paragraphs.

In a GIS, the insulation between the conductive parts and the enclosures consists of solid insulation such as partitions, support insulators or insulating drive rods as well as gas insulation i.e. pressurized SF₆.

The dielectric behaviour of insulating materials under DC stress is different compared to the behaviour under AC or impulse voltage stress.

As, under AC conditions, the displacement current is much larger than the current due to conductivity, the electric fields are determined capacitively in case of AC operation. The rearrangement of the fields due to electric conductivity can be disregarded. This situation changes completely in case of DC stress, where the fields are determined over the electric conductivities, at least after accordingly long periods of operation at DC, i.e. several months. Further, in the case of transients (such as overvoltages and polarity reversals) during DC operation, the electric fields are determined by a mixture of conduction and polarization. Therefore, the attention has to be paid to the fact that DC fields are determined by conductivities, while in transients, such as overvoltages or polarity reversals, the fields are determined capacitively [1] [2].

While AC fields are, capacitive and governed by the permittivity of the insulating materials, DC fields are resistive and governed by the electric field and temperature-dependent conductivity of the insulating materials. Upon application of an AC voltage a capacitive field is formed between the primary conductor and the enclosure; maximum field is located close to the surface of the primary conductor and minimum on the surface of the enclosure. On the other hand, the DC electric field distribution on insulator surfaces does not follow the same pattern in any case. Notably, for high temperature gradients between the enclosure and the conductor the maximum electric field might be shifted towards the enclosure radius [3]. Another significant factor is the fact that AC field is formed directly upon application of voltage, whereas DC field requires a transition period to reach its steady state. This is explained below.

2.2 TRANSITION FROM CAPACITIVE TO STEADY STATE RESISITIVE FIELD

Upon application of a DC voltage on a GIS, the formed capacitive field is gradually transformed to resistive field. The transition from capacitive to resistive field is a dynamic process requiring periods ranging from few hours up to months depending on the permittivity and the electric field- and temperature-dependent conductivity of the insulating materials. More specifically, starting from a capacitive field distribution at the moment of energization, electrical stress distribution is continuously evolving with time, depending on the surface and bulk currents in the solid insulation defined by the volume conductivity, as well as on the ionic currents in the gas. This results in interface charging, particularly of the solid-gas surface and space charge accumulation in the solid insulation until the resistive steady state is reached [4]. Via the temperature dependence of the conductivity, temperature gradients define primarily the duration of the transition time as well as where field enhancement and space charge accumulation occur in the solid. In Figure 2, the influence of temperature gradient across the partition on the transition time is depicted. It is shown that during current conduction, for higher ambient temperatures shorter transition periods are foreseen. On the other hand, for lower ambient temperatures the transition periods can be significantly prolonged. Furthermore, according to the graph, the dielectric field transition time differs between the different locations on the spacer.

It is therefore required for dielectric testing to have an estimation of the required transition time for the electric field to reach its steady state [5].

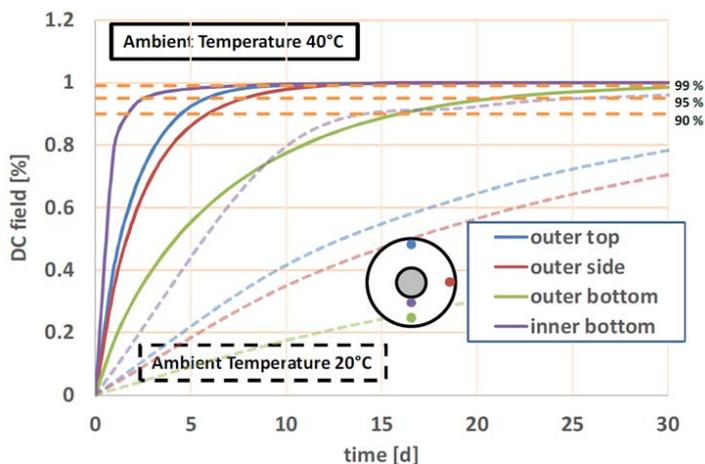


Figure 2: Transition time for the insulator, depending on the location and ambient temperature, simulation results for full rated current of 4000 A [6]

2.3 CHARGE ACCUMULATION

When a DC voltage is applied to an insulator, charge moves and accumulates locally. According to [4] the charge accumulation is attributed to the following mechanisms:

- a) Conduction in insulator volume
- b) Conduction on insulator surface
- c) Drift of charge carriers

According to reference [4], the accumulated charge which is formed during DC-stress can hinder the breakdown withstand of the insulation during a polarity reversal or a superimposed impulse voltage. Based on tests performed on epoxy spacers it was shown that when charge accumulation occurs, the breakdown voltage for lightning and switching impulse can decrease. The polarity reversal test is applicable for LCC applications only. Because of faster voltage rise, bipolar superimposed impulse voltages are more critical compared to polarity reversal test. It is therefore required that superimposed impulse tests are performed to guarantee the dielectric performance of a HVDC GIS under these stresses.

3 TERMS AND DEFINITIONS

Additionally to the terms and definitions of IEC 62271-203 [7], the following terms and definitions are related to HVDC GIS and are based on [3].

3.1 HIGH LOAD (HL)

High load consists of a continuous heating period at rated current up to the thermal steady state (duration d_9). The heating method used shall be conductor heating. The heating shall be generated with DC or equivalent AC current. The duration d_9 is the time sufficient for the temperature rise to reach a stable value.

The test shall be made over a period of time sufficient for the temperature rise to reach a stable value. This condition is deemed to be obtained when the increase of temperature rise does not exceed 1 K in 1 h. This criterion will normally be met after a test duration of five times the thermal time constant of the tested device. Duration d_9 for gas insulated components is typically in the range of some hours. The term is used in the long-term testing procedure of HVDC GIS.

3.2 ZERO LOAD (ZL)

No heating is applied on the tested HVDC GIS object. The term is used in the long-term testing procedure of HVDC GIS.

3.3 LOAD CYCLES (LC)

A typical "24 hours" load cycles consists of high loads (HL) and zero loads (ZL) periods. The term could be used in the long-term testing procedure of HVDC GIS. In D15.1 a realistic load profile for off-shore HVDC stations is given and will be used to define the LC test parameter.

3.4 DC STEADY STATE ELECTRIC FIELD

The state where 90% of the transition from a capacitive to a resistive field distribution at each location of the insulator surface within a DC gas-insulated system has been obtained. Depending on the temperature of the insulation material, the transition to a DC field distribution takes months or hours.

3.5 DURATION OF TRANSITION FROM CAPACITIVE TO CONDUCTIVE ELECTRIC FIELD

The required time from the moment of application of DC voltage until DC steady state electric field is reached d_{DC} . The duration depends on the temperature distribution in the insulation system and can vary over several orders of magnitude (comp. Figure 2). In case the DC steady state is unknown and the time to reach the DC steady state d_{DC} could not directly be determined, the duration can be approximated with the following methods:

- 1) Worst case approximation of dielectric time constant $\tau_m = \epsilon_0 \epsilon_r / \sigma$ (taking the longest value over the whole insulation, i.e. typically the location with lowest conductivities). For the estimation of the dielectric

time constant it is necessary to measure permittivity and electrical conductivity of the insulating material (bulk).

- 2) DC electrical field simulation. A simulation verified by experiments (at least by means of model-arrangements) has to be used. The scalability of the model has to be demonstrated.
- 3) Measurement of the DC potential field on the actual insulator surface in energized state on different locations along the insulator radius. d_{bc} is considered to be fulfilled, if the rate of change of the measured potential field is lower than 10% of the initial rate (initial time delays shall be ignored).

Furthermore, the surface conductivity of the insulating material shall be measured. If the charge transport in the solid insulation is dominated by the bulk conductivity compared to the charge transport caused by a surface conductivity only the bulk material has to be regarded for calculation of the dielectric time constant (in case of dominant bulk conductivity).

3.6 EQUIVALENT 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 Annex A or in reference IEC/IEEE 65700-19-03.

4 RATINGS

Based on [3], the following ratings are defined for HVDC GIS: This chapter defines HVDC GIS specific ratings, general HVAC GIS ratings still apply in accordance with [7].

4.1 NORMAL SERVICE CONDITIONS

For the normal service conditions, clause 2 of IEC 62271-203 [8] is applicable. The following reference table [8] lists the normal and special service conditions for GIS.

Item	Normal		Special	
	Indoor	Outdoor	Indoor	Outdoor
Ambient air temperature:				
Minimum (°C)	-5 or -25	-25 or -40	-25	-50
Maximum (°C)	+40	+40	+50	+50
Solar radiation (W/m ²)	Not applicable	1 000	Not applicable	>1 000
Altitude (m)	1 000	1 000	>1 000	>1 000
Site pollution severity ^a	Not applicable	c	c, d or e	d or e
Ice coating (mm)	Not applicable	1, 10 or 20	Not applicable	>20
Wind (m/s)	Not applicable	34	Not applicable	>34
Humidity (%)	95	100	98	100
Condensation or precipitation	Occasional	Yes	Yes	Yes
Vibration class	Not applicable	Not applicable	IEC 62271-207 IEC/TR 62271-300	IEC 62271-207 IEC/TR 62271-300
NOTE The user's specification may use any combination of normal or special service conditions above.				
^a Site pollution severity c, d or e according to IEC/TS 60815-1:2008, 8.3.				

Table 1: Reference table of service conditions relevant to GIS

4.2 NOMINAL DC VOLTAGE

Nominal DC Voltage (U_n) is the mean value of the direct voltage required to transmit nominal power at nominal current [7].

4.3 RATED DC VOLTAGE

In line with the definition of IEC/IEEE 65700-19-03 Ed. 1 [8], the rated DC voltage (U_r) is equal to the maximum continuous DC voltage for which the equipment is designed to operate.

4.4 RATED DC WITHSTAND VOLTAGE

The rated DC withstand phase-to-earth voltage (U_w) indicates the maximum DC voltage that the HVDC GIS can withstand for a specified period. Based on [3] a value of $1.5 \times U_r$ is recommended.

4.5 RATED LIGHTNING IMPULSE WITHSTAND VOLTAGE

The rated lightning impulse withstand voltage (U_p) indicates the peak value of a standard lightning impulse in accordance with IEC 60060-1 [9] that the HVDC GIS can withstand.

4.6 RATED SWITCHING IMPULSE WITHSTAND VOLTAGE

The rated switching impulse withstand voltage (U_s) indicates the peak value of a standard switching impulse in accordance with IEC 60060-1 [9] that the HVDC GIS can withstand.

4.7 RATED SUPERIMPOSED LIGHTNING IMPULSE WITHSTAND VOLTAGE

The term superimposed impulse voltage means a superposition of DC-voltage and impulse voltage. The rated superimposed lightning impulse withstand ($U_r + U_p$) voltage indicates the superposition of rated voltage (U_r) and rated lightning impulse withstand voltage (U_p) [3].

4.8 RATED SUPERIMPOSED SWITCHING IMPULSE WITHSTAND VOLTAGE

The term superimposed impulse voltage means a superposition of DC-voltage and impulse voltage. The rated superimposed switching impulse withstand voltage indicates the superposition of rated voltage (U_r) and rated switching impulse withstand voltage (U_s) [3].

4.9 RATED DC CURRENT

In accordance with IEC 62271-1 [10], the rated normal DC current (I_r) is the value of the current which the HVDC GIS shall be able to carry continuously under normal outdoor service conditions as these are specified in [7].

4.10 EQUIVALENT AC CURRENT

AC current (I_{eqac}) is the applied fundamental frequency AC current during the type tests and long performance test.

4.11 RATED SHORT-TIME WITHSTAND CURRENT

The rated short-time withstand current (I_k) which the HVDC GIS can carry during a specified short time under prescribed conditions of use and behaviour. Based on the shape and time duration of the current, several current-time combinations can be specified. The peak value of the rated short-time withstand value is defined as the rated peak withstand current.

Note: Short-circuit waveforms in HVDC systems may vary significantly from AC systems. For practical reasons, testing will be performed with AC current (see annex A.1). To compare application requirements with withstand ratings it is recommended to compare:

- thermal load: waveform of $\int i^2(t) dt$ (Joule integral)
- mechanical load: instantaneous peak value

5 TYPE TEST REQUIREMENTS AND METHODS

For HVDC GIS no tests have been yet standardized. In this section tests are recommended for HVDC GIS based on international standards and [3]. This section completes and amends, if necessary, the various relevant standards applying to the individual DC components such as disconnectors, earthing switches, bushings, current/voltage transformers, surge arresters constituting the HVDC GIS.

Since the nature of the generated dielectric field across insulating materials is the distinguishing difference between HVAC and HVDC GIS, the listed tests are classified to dielectric and non-dielectric tests.

The recommended dielectric tests are based on [3] where tests are recommended for HVDC GIS for rated voltages up to 550 kV. For other than dielectric tests, the IEC 62271-203 for HVAC GIS can be generally applicable.

Test	Category (Type, Routine, On-Site, optional, Special)
DC withstand voltage test	Type
Lightning impulse voltage test	(Type) not mandatory
Switching impulse voltage test	(Type) not mandatory
Superimposed lightning impulse voltage test	Type
Superimposed switching impulse voltage test	Type
Polarity reversal test	(Type) not mandatory
Partial discharge test	Type/Routine/On-site
DC insulation system test	Type
Prototype installation (long term) test	Special

Table 2: Recommended dielectric tests for HVDC GIS upto 550 kV according to JWG D1/B3.57

6 TEST PROCEDURE OF PROTOTYPE INSTALLATION TEST

6.1 MOTIVATION

The prototype installation test is a proposed test to indicate the long-term performance of the complete HVDC GIS and should normally be performed after the type tests have been carried out.

Due to the lack of experience in operation of HVDC GIS, WP15 of PROMOTioN has initiated the idea of performing a prototype installation test on a HVDC GIS. The purpose of this test is to verify the reliable dielectric performance of an HVDC GIS under real service conditions. Due to long periods that might be required for obtaining steady state dielectric field and charge accumulation phenomena, a long duration test is recommended for a reliable representation of in-service dielectric stresses.

The recommended test will be performed on a complete HVDC GIS which will be built and assembled by the manufacturer. The test will take place at the KEMA HVDC laboratory of DNV GL in Arnhem. A duration of approximately one year is foreseen for the performance of such a test.

6.2 PROTOTYPE INSTALLATION TEST

6.2.1 SCOPE OF PROTOTYPE INSTALLATION TEST

The successful performance of the long-term test demonstrates the performance of the manufacturer as a supplier of a HVDC gas-insulated system of a certain rated voltage U_r provided that the following conditions are fulfilled:

- The rated voltage U_r of the tested gas-insulated system is not surpassed.
- The limiting temperature of the various parts is not higher than that of the tested gas-insulated system.

A list of prototype installation test is given in Table 3, which gives a summary and references for prototype installation testing of DC GIS.

The scope of the HVDC GIS prototype installation test is different compared to the scope of the HVDC cable prequalification test [11], because

- The test voltage factors of the cable system are determined to prove the total lifetime (V-t characteristic).
- The cable system reaches the DC steady-state faster than a GIS.
- The load cycles are necessary to cover the thermo-mechanical aspects of the cable system.
- At the end of a prequalification test a superimposed voltage test must be performed. The reason for this test is to verify that no major thermo-mechanical changes have taken place in the cable system during the long-term testing.

Furthermore, DC cables are also subjected to a long-term test to prove the long-term capability. The DC cable prequalification test is also applicable for cable terminations and has to be performed separately. Thus, DC cable terminations are not covered by this HVDC GIS prototype installation test.

For HVDC GIS, a verification of the electrical lifetime is insignificant because

- The electrical lifetime (V-t characteristic) of solid insulating material used in GIS/GIL is equal or even better under DC voltage stress compared to AC at typical service stress [4].
- Experiences with AC GIS show that all parts of the insulation system do not reveal any ageing mechanisms which cause critical ageing; assuming manufacturing in sound condition according to the quality requirements. Therefore, the entire insulation system should not exhibit an increase of the failure rate with time. After 30 years of operation, there is no general ageing which significantly affects the long-term performance. The lifetime can be estimated to be much higher than 30 years. This is in line with the findings based on considerations about the critical physical phenomena and investigations of the statistical long-term performance [12].

Item	Test	Clause	Note
a	Scope of prototype installation test	6.2.1	including applicability, range of approval
b	Test parameters	6.2.2	required test values
c	Test arrangement	6.2.3	required information
d	Pre-dielectric tests	6.2.4	additional tests for PROMOTioN
e	Heating cycle voltage test	6.2.5	mandatory test
f	Superimposed impulse voltage test	6.2.5	mandatory test (part of heating cycle voltage test)
g	Subsequent dielectric tests	6.2.6	additional tests for PROMOTioN
h	Examination	6.2.7	mandatory observation

Table 3: prototype installation test on DC GIS

The prototype installation test shall comprise the electrical tests on the complete HVDC GIS.

For this demonstrator, HVDC GIS consists of approximately 40 m of GIS circuit including GIS components (at least one of each type), such as bushing, various busducts and connecting elements (straight, L, T, X elements, dismantling unit), partition and support insulators, DC voltage transformer (RC-divider), DC current transformer (zero-flux current sensor), disconnecter and earthing switch, fast-acting earthing switch and heating current transformers.

For this demonstrator, the test objects are busducts, insulators, spacers, disconnecter and earthing switch, fast-acting earthing switch, bushing, DC voltage transformer (RC-divider), DC current transformer (zero-flux current sensor), which means that if one of these objects fails dielectrically, then the HVDC GIS failed.

The non-test objects are heating current transformers and all monitoring systems which means that if one of these components fails, they can be replaced and continue with the remaining test program.

6.2.2 TEST PARAMETERS

The definitions of rated voltages of HVDC GIS are based on chapter 4. The following technical data is based on the test object of this PROMOTioN demonstrator. The type of this 320 kV ABB HVDC GIS. The following Table 4 gives the technical data of ABB HVDC GIS. Table 5 shows the test parameters for this prototype installation test.

Rating	Value	Unit
Nominal DC voltage U_n	± 320	kV_{dc}
Rated DC voltage U_r	$\pm 350 (1.1 \times U_n)$	kV_{dc}
Rated LI withstand voltage U_P	± 1050	kV
Rated superimposed LI withstand voltage U_P / U_r	Lightning impulse voltage DC voltage	kV kV_{dc}
	± 1050 ± 350	
Rated SI withstand voltage U_S	± 950	kV
Rated superimposed SI withstand voltage U_S / U_r	Switching impulse voltage DC voltage	kV kV_{dc}
	± 950 ± 350	
Rated DC withstand voltage to earth U_w	± 610	kV_{dc}
Rated normal current I_r	2000 / 2600 / 4000	A_{dc}
Rated peak withstand current	160	kA
Rated short-time withstand current	64	kA
Rated duration of short-circuit	1	s
Insulating medium	SF ₆	
Rated filling pressure	0.53	MPa abs @ 20 °C
Minimal functional pressure	0.45	MPa abs @ 20 °C
Installation	indoor / outdoor	
Maximum ambient temperature	40	°C
Minimum ambient temperature	-30 / -5*	°C
	*Minimum temperature for low voltage components placed in GIS local cabinet	

Table 4: Technical data of test object ABB HVDC GIS

Test parameters	Value	Unit
Test DC voltage U_T	\pm min. 385 (min. $1.1U_r$)	kV_{dc}
DC PD pre-stress (1 min) test voltage U_{dcpre}	± 525 ($1.5 U_r$)	kV_{dc}
DC PD test voltage (2 h) U_{dcpd}	± 420 ($1.2 U_r$)	kV_{dc}
AC PD pre-stress (1 min) test voltage U_{acpre}	372 ($((1.5 \times U_r)/\sqrt{2})$)	kV_{rms}
AC PD (1 min) test voltage U_{acpd}	297 ($((1.2 \times U_r)/\sqrt{2})$)	kV_{rms}
Test LI withstand voltage U_{TP}	± 840 ($0.8 \times U_P$)* ± 940 (PROMOTioN)**	kV_{peak}
Test superimposed LI withstand voltage U_{TP} / U_r	$\pm 840^* / \pm 350$ $\pm 940 / \pm 350$ (PROMOTioN)**	kV/kV_{dc}
Test SI withstand voltage U_{TS}	± 760 ($0.8 \times U_S$)*	kV_{peak}
Test superimposed SI withstand voltage U_{TS} / U_r	$\pm 760^* / \pm 350$	kV/kV_{dc}
Test AC heating current I_{eqac}	4000	A_{rms}
*: 80 % impulse voltages site tests of IEC 62271-203 [7]; **: higher PROMOTioN values, related to an LI rating of 1175 kV ($0.8 \times 1175 = 940$).		

Table 5: Overview of test parameters of test object for prototype installation test

For convenience of testing, LC and HL conditions may be achieved by heating the equipment with AC current. Differences in AC vs. DC heating are discussed in annex A. For the PROMOTioN HVDC GIS demonstrator, the AC test current is chosen same as rated DC current.

6.2.3 TEST ARRANGEMENT

HVDC GIS shall be assembled in the manner specified by the manufacturer's instructions, with the grade and quantity of materials supplied.

Unless otherwise specified in the details for the particular test, tests shall be carried out at an ambient temperature of -5 to $+40$ °C (normal indoor conditions, see Table 1).

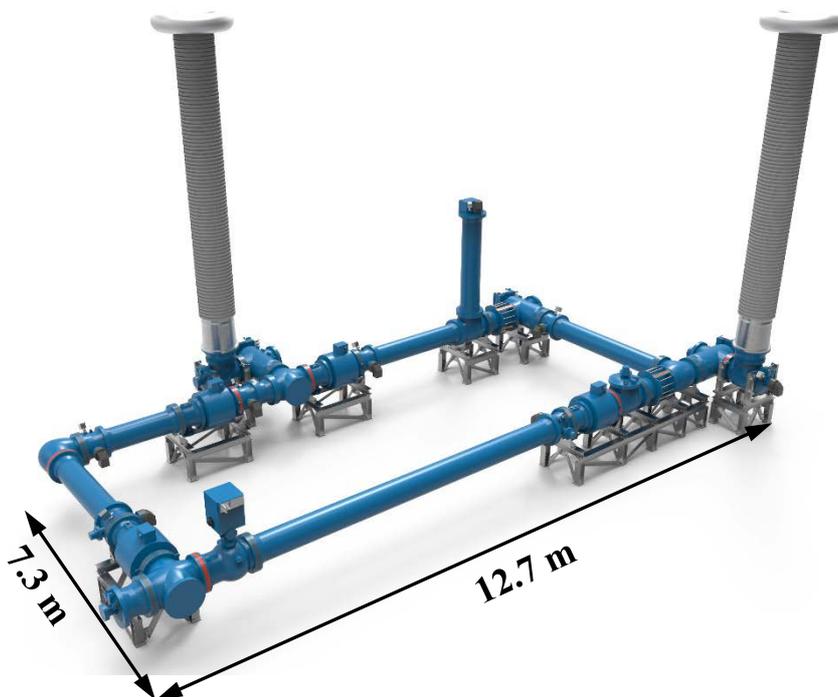


Figure 3: Installation setup of ABB HVDC GIS

6.2.3.1 MONITORING SYSTEMS

During the test, test voltage and current, temperature (ambient and enclosure), PD, arc detection, gas pressure/density shall be monitored and the measured data shall be recorded.

For this demonstrator, the following monitoring systems are included.

No.	Monitoring	Method	essential for operation of test
1.	DC voltage	external DC divider	yes
		GIS RC-divider	no
2.	AC heating current	GIS measuring CT1 output	yes
		GIS measuring CT2/CT3 output	no
		GIS AC/DC current sensor	no
3.	Enclosure and ambient temperature	Thermo-couples (Type T)	yes
4.	Partial discharge	Omicron measuring record	yes
		UHF	no
		Optical system	no
		TU Delft online monitoring system	no
5.	Arc detection	Optical system	no
7.	Gas density	Density	no

Table 6: Monitoring systems from Promotion demonstrator

6.2.4 PRE-TESTS

For the pre-conditioning of DC GIS, calibrating relevant values and checking the test set-up, a pre-test program can be performed. Table 7 gives a test procedure of pre-tests prior to prototype installation test.

Step	Test	Conditions	Load	Requirement
1.	Thermal cycle pre-test	Heating up to steady state with I_{eqac} or I_r	LC / HL	<ul style="list-style-type: none"> To check d_9; LC (see Figure 4: load pattern refers to D 15.1, clause 5.2.4) HL (loaded with various currents as D 15.1 specified) Record enclosure temperature Record ambient temperature
2.	AC PD measurement	Pre-stress at U_{acpre} ; PD measurement at U_{acpd} .	ZL	<ul style="list-style-type: none"> 1 min pre-stress 15 min PD measurement For coupling capacitor traditional method: maximum permissible PD ≤ 5 PC (max. permissible PD discharge depends on the feasibility of site noise level and only be defined if AC coupling capacitor is available on-site) For PD internal sensors method: no PD pattern changes comparing with reference noise level pattern
3.	DC PD measurement	Pre-stress at $\pm U_{dcpre}$; PD measurement with $\pm U_{dcpd}$.	ZL	<ul style="list-style-type: none"> 1 min pre-stress 2 h each polarity PD measurement record PD pattern as reference
4.	Lightning impulse test	LI voltage U_{TP}	ZL	<ul style="list-style-type: none"> Start LI with opposite previous DC polarity 3 impulses each polarity No flashover is allowed
5.	Switching impulse test	SI voltage U_{TS}	ZL	<ul style="list-style-type: none"> 3 impulses each polarity No flashover is allowed
6.	Superimposed LI test	Positive and negative rated DC voltage U_r and U_{TP}	ZL	<ul style="list-style-type: none"> 3 impulses for bipolar and unipolar No flashover is allowed
7.	Superimposed SI test	Positive and negative rated DC voltage U_r and U_{TS}	ZL	<ul style="list-style-type: none"> 3 impulses for bipolar and unipolar No flashover is allowed
8.	Polarity reversal test	Polarity reversal $\pm U_T$	ZL / HL	<ul style="list-style-type: none"> 120 min negative U_T 120 min positive U_T 45 min negative U_T Time duration for polarity reversal is within 2 minutes Optional: the duration of each polarity can be longer periods (up to 30 days, depending on the lab availability) depending on the d_{DC}.

Table 7: Test procedure of pre-tests

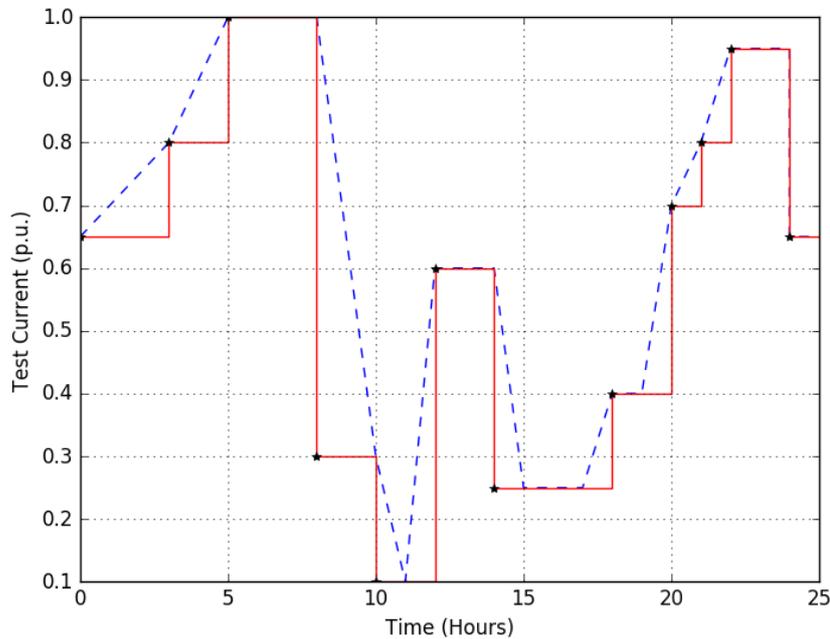


Figure 4: Load cycle (1 p.u.= 4000 A)

6.2.5 LONG-TERM VOLTAGE TEST

General conditions are as follows.

- a) Minimum duration is 360 days.
- b) Equivalent AC current shall be constantly applied in order to guarantee the same ΔT caused by rated DC current (see Annex A, clause A.1).

The sequence of tests is shown in Table 8.

Note: for this PROMOTiON demonstrator, it is recommended to insert a SIM (see Table 10) after each of cycle step to verify the GIS's ability to handle the combination of long term DC stress and impulse-overvoltages.

No breakdown of the insulation shall occur.

If a breakdown occurs, causing an interruption to the ongoing testing of connected test objects, the test may be resumed after the failed component is removed and replaced.

The actual heating cycle or impulse during which the failure occurred shall be repeated for the remaining test objects.

If a breakdown occurs during a constant heat period, then the time elapsed without applied voltage shall be added behind the originally planned end date of that period.

This means, the overall number of days with voltage remains the same as specified in the test requirements.

After any interruption of voltage and current, for example an interruption caused by external factors the test may be resumed. The detail procedure, after an interruption occurs, is shown in Table 8.

	ZL	ZL	HL	HL	ZL	ZL	HL	HL	HL	HL	HL	HL	LC	ZL	LC	ZL
Number of days	60	1	60	1	60	1	60	1	60	1	60	1	15	1	15	1
Test voltage	-		-		+		+		-		+		+		-	
	U _T	SIM	U _T	SIM	U _T	SIM	U _T	SIM/ACPD	U _T	SIM	U _T	SIM	U _T	SIM	U _T	SIM/ACPD

ZL = zero load (zero heating), HL = high load (continuous heating), LC = load cycle (24 hours per cycle consisting of HL and ZL periods).

SIM = Superimposed switching and lighting impulse voltage test (see clause 6.2.5.1 Table 10).

SIM/ACPD = AC partial discharge measurement at U_{ac} followed by SIM test.

- a) the given duration for each cycle step is a minimum and can be freely extended for scheduling reasons.
- b) if an interruption of voltage and/or current is less than 30 min, each cycle step of ZL/HL shall be resumed, at the point of the cycle, when the interruption occurred and is still valid. If the interruption is longer than 30 min and less than 3 days, then specific time elapsed without applied voltage and current shall be added behind the originally planned end date of that period. It shall be ensured that a period of uninterrupted voltage and/or current of at least three times the interruption time follows after the interruption. It may be necessary to prolong test period to achieve these criteria (see examples in Table 9 below).
- c) if the interruption occurs is longer than 3 days each cycle step shall be repeated.
- d) if an interruption of voltage and current is less than 30 min, the specific heating cycle of LC shall be resumed, at the point of the cycle, when the interruption occurred and is still valid. If the interruption is longer than 30 min and less than 3 days, then the specific heating cycle of LC shall be repeated. If the interruption occurs is longer than 3 days, each cycle step of LC shall be repeated.
- e) after each cycle step, there is no rest period allowed.
- f) after each SIM, a break of unlimited time is allowed.
- g) each SIM has to be carried out directly after the previous cycle step.
- h) each SIM is followed by 10 no-load disconnecter and earthing switch switching operations to simulate regular switching device operation (no-load means no voltage and no current during switching)
- i) Test DC voltage (U_T) is higher than the rated DC voltage (U_r), which could lead to a field strength at the insulators higher than in practice, thus affecting the charge accumulation at the insulator and the charging time. As the main purpose of the test is confirm the capability of the system to withstand the charging process and stress due to the superimposed voltage, a test DC voltage of min 1.1 U_r is a compromise which can largely prevent charging processed not occurring in practice.

Table 8: Sequence of heating cycle voltage test for prototype installation test



Example no.	Interruption of voltage at	Tests resume at	Duration of interruption	Required time without interruption	Total step time of 60 days reached	Time without interruption reached	Test complete at
1	day 15	day 18	3 days	9 days (3 x 3)	day 63 (60 + 3)	day 27 (18 + 9)	day 63
2 (worst case)	day 60	day 63	3 day	9 days (3 x 3)	day 63 (60 + 3)	day 72 (63 + 9)	day 72

Table 9: Two examples for reaction to test interruptions within a 60 days long term test step (start at day 0)

6.2.5.1 SUPERIMPOSED IMPULSE VOLTAGE TEST

Some critical phenomena in HVDC GIS 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 [2].

The aim for the superimposed impulse test at end of every cycle serial (definition refer to Table 8) of the prototype installation test is to check the integrity of the HVDC GIS.

The definitions of the different levels of voltage are given in chapter 4. Additional information is given in annex A.2.

The tests shall be performed as given in Table 8.

The time interval two successive impulses shall not be shorter than one minute.

The test objects shall withstand without failure whole sequence.

The test waveform shall be according to IEC 60060-1 and IEC 60230 (2018).

No breakdown of the insulation or flashover along DC GIS shall occur.

Superimposed impulse test	SI	SI	LI	LI
Number	3	3	3	3
Polarity of impulse voltage	-	+	-	+
Impulse test voltage	U_{TS}	U_{TS}	U_{TP}	U_{TP}
Polarity of DC test voltage	same as previous ZL/HL step			
DC test voltage	U_r	U_r	U_r	U_r

Table 10: Sequence of superimposed switching and lightning impulse test (SIM)

6.2.6 SUBSEQUENT TESTS

After completing long-term voltage test, the following subsequent dielectric tests are recommended.

Table 11 gives a test procedure of subsequent dielectric tests after the completion of the long-term voltage test.

Step	Test	Conditions	Load	Requirement
1.	DC PD measurement	Pre-stress at $\pm U_{dcpre}$; PD measurement with $\pm U_{dcpd}$.	ZL	<ul style="list-style-type: none"> • 1 min pre-stress • 2 h each polarity PD measurement • record PD pattern for reference
2.	Lightning impulse test	LI voltage U_{TP}	ZL	<ul style="list-style-type: none"> • 3 impulses each polarity • No flashover is allowed
3.	Switching impulse test	SI voltage U_{TS}	ZL	<ul style="list-style-type: none"> • 3 impulses each polarity • No flashover is allowed
4.	AC PD measurement	Pre-stress at U_{acpre} ; PD measurement at U_{acpd} .	ZL	<ul style="list-style-type: none"> • 1 min pre-stress • 15 min PD measurement • For coupling capacitor traditional method: maximum permissible PD ≤ 5 PC (max. permissible PD discharge depends on the feasibility of site noise level and only be defined if AC coupling capacitor is available on-site) • For PD internal sensors method: no PD pattern changes comparing with reference noise level pattern

Table 11: Test procedure of subsequent dielectric tests

6.2.7 INSPECTION AFTER TEST

After completion of the prototype installation test, the HVDC GIS shall be examined by visual inspection of the test object and comparison with a drawing folder. Visual inspection shall be done with normal or corrected vision without magnification, and the objects shall reveal no signs of deterioration which could affect the system in service operation.

Note: For PROMOTioN project, there could be possible further tests requested. The examination will be referred after complete all tests.

7 CONCLUSIONS

As of today, no tests have been yet standardized for HVDC GIS. On the other hand, for HVAC GIS detailed test requirements have been established. In order to define tests for HVDC GIS, the distinguishing characteristics of HVDC-GIS have been identified. In fact, a DC electric field is totally different to an AC field within a GIS. While in AC systems a capacitive field is formed directly upon voltage application, in HVDC systems long transition periods are required to reach a steady state field whilst charge accumulation phenomena can occur in the insulating materials and their surfaces.

The different type of electric field between HVAC and HVDC GIS determines the context for defining dielectric test requirements of HVDC GIS. Based on the CIGRE's JWG D1/B3.57 work, dielectric tests have been specified for HVDC GIS. For other than dielectric tests, the test requirements of HVAC GIS can be generally used.

On another note, there is very few operational experience with HVDC GIS. This fact in combination with the long periods required to reach steady state DC electric fields and charge accumulation phenomena, prompts the performance of a long-term test. Such a test shall verify the dielectric performance of a HVDC GIS under in-service conditions.

In fact, a long-test procedure is defined which will be applied to a 320 kV HVDC-GIS pole manufactured by ABB. The HVDC GIS pole consists of passive components, Disconnecter/Earthing Switch, Compensation Unit, Fast acting earthing switch, heating transformers, Bushings, Instrument transformers and will be tested at DNV GL KEMA HVDC laboratory.



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ANNEX A: SPECIFICS OF PROTOTYPE INSTALLATION TEST PROCEDURES

A.1 AC TEST CURRENT VS. DC OPERATING CURRENT

Heating with an AC test current instead of a DC current which will be the in-service condition implies differences in regards of temperature rise:

- The skin effect will cause additional power losses and temperature rise in the inner conductor. Those additional power losses constitute a higher thermal stress than the rated DC current. Based on [6], the skin effect factor k of GIS equipment hollow inner conductors typically is in the range $1.02 < k < 1.1$. Therefore, the AC current reduction factor comparing to DC current is approximately $I_{ac} \approx I_{dc} \times 1/\sqrt{k}$.
- If the enclosure of the test setup forms a closed current path (current flows through conductor and return from the enclosure), then the magnitude of the enclosure current is almost as high as the conductor current and thus a significant temperature rise is caused. Notes: this method may be used for temperature rise test of HVDC GIS, which is not a scope of this document.
- If the enclosure does not form a closed current path, eddy current might flow through the enclosure. Two situations were included in a simulation study as with eddy current and without eddy current. If eddy current exists, its magnitude is typically significantly smaller than the conductor current. The impact of eddy current in terms of temperature-rise is typically a few K. Because the temperature difference ΔT is important for HVDC application, the ΔT is compared by three conditions: heating by DC current ($\Delta T = 1$), heating by AC current with eddy current and heating by AC current without eddy current. The results show in Figure 5. It shows that ΔT is practically not a function of eddy currents. Only negligible impact of the eddy currents on the ΔT are discovered. Though generally marginal in absolute quantities, the effect on ΔT is more pronounced for thin enclosure wall thickness as for cast enclosures.
- When HVDC GIS is under in-service situation, the rated DC current shall also cover most situation where harmonic currents cause additional temperature-rise to the rated current, which relative harmonic currents for typical LCC and VSC converter stations are studied (see [6]), the conclusion is given that additional current of 0.5 % to account of 1% of additional losses due to harmonic currents (Figure 6) [3].
- Besides a rather simple test set-up with AC current heating method, the influence of AC voltage of the heating current sources is also considered. Because the test voltage is several ten thousand times higher than the AC voltage that drives the heating current. Thus, the ripple of the DC voltage is caused by the AC voltage of the heating current source is negligible.
- For tests of HVDC GIS equipment under in-service condition, stresses due to DC voltages of both polarities, polarity reversals, superimposed impulse voltages and various load conditions have to be combined. The dielectric influence of load conditions is characterized by the temperature difference ΔT between the inner conductor and the enclosure. For this ΔT , the harmonic current content shall be

accounted for. It is suggested to feed an AC heating current. The skin effect due to AC will result in higher ΔT , a rule of compensation is given. The increase in enclosure temperature does not affect the resulting ΔT considerably. Thus, no further compensation is required.

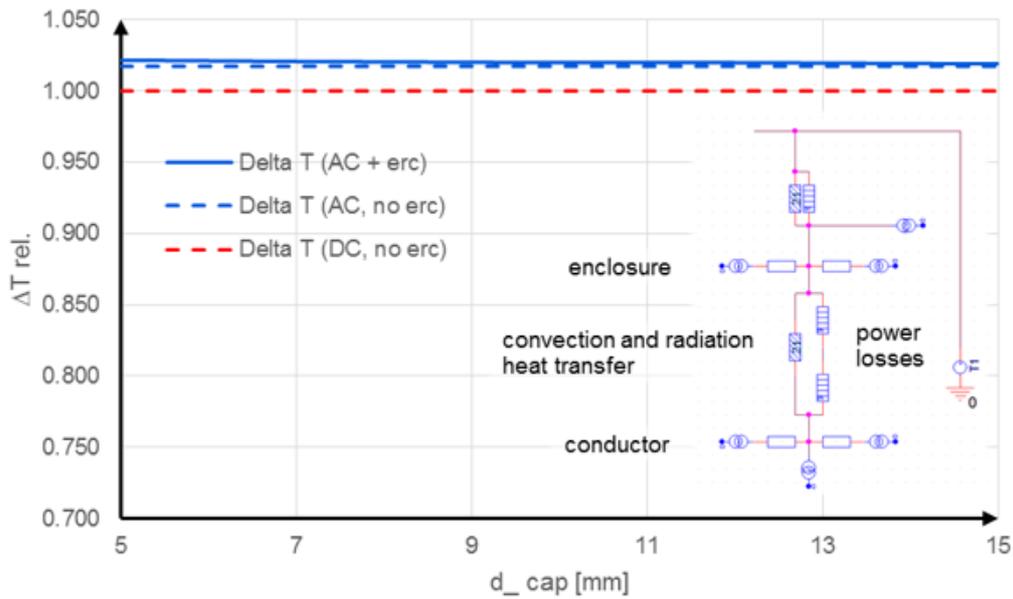


Figure 5: Temperature difference between conductor and enclosure according to [6]

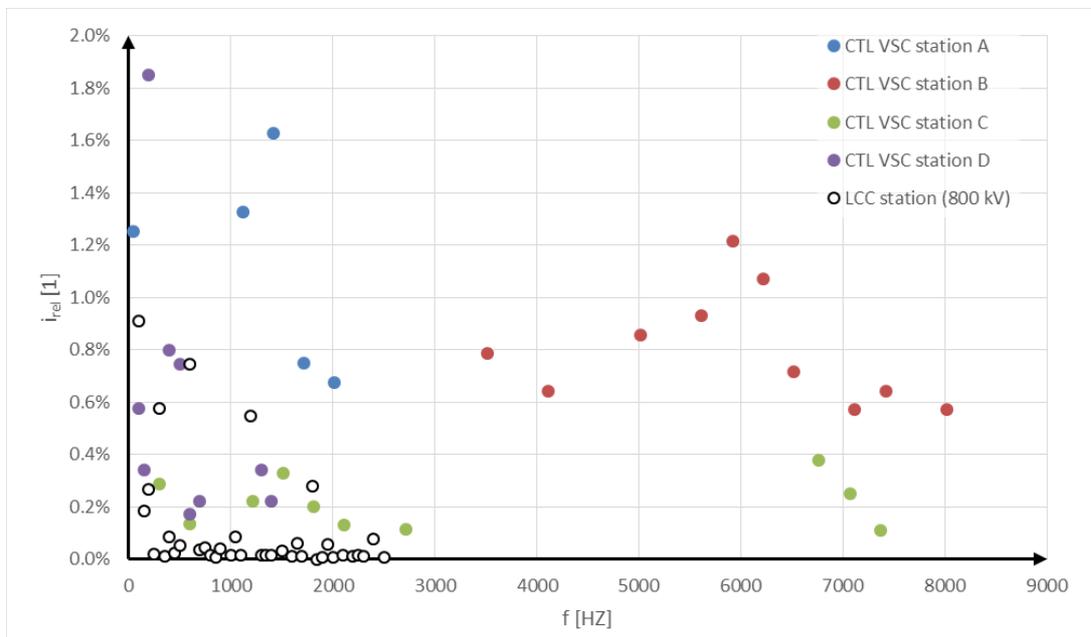


Figure 6: Typical levels of harmonics, data source for VSC stations [13] for LCC station [14] and rated current of 4000 A

A.2 TESTING WITH SUPERIMPOSED VOLTAGES

The superposition of an impulse wave on a DC voltage is obtained by using a blocking capacitor or a sphere gap and a current limiting resistor. For both methods, it is suggested to use a damping resistor between test object and DC-Source. The damping resistor is needed to decouple the DC-source from the impulse voltage and protect it in the case of failure from the Very Fast Transients (VFT) evoked by the breakdown. To measure exactly the superimposed voltage, it is necessary the use a mixed divider closed to the test object, as the voltage drop over the blocking capacitor or sphere gap and its influence of the impulse waveform shape shouldn't be neglected. To minimize the voltage drop on the blocking capacitor the capacity should be by about a factor of 10 higher compared to the capacity of the test object.

Regarding the shape of the generated composite voltages the following are applicable depending on the method of connection between the two voltage sources.

Method 1: Sphere gap

In the case of sphere gaps, the front time of the lightning impulse and the time to peak of switching impulse cannot be defined according IEC 60060, as the ignition of the sphere gap is a random process and the transient voltage after ignition of the sphere gap does not meet the IEC's voltage waveforms. It should be targeted that the sphere gap always ignites between 50% – 90% voltage difference between impulse and direct voltage. The time to halve-value for LI and SI is defined according IEC 60060-1.

Method 2: Blocking Capacitor

In the case blocking capacitors are used the definitions for lightning impulse and switching impulse according IEC 60060-1 have to be met completely.

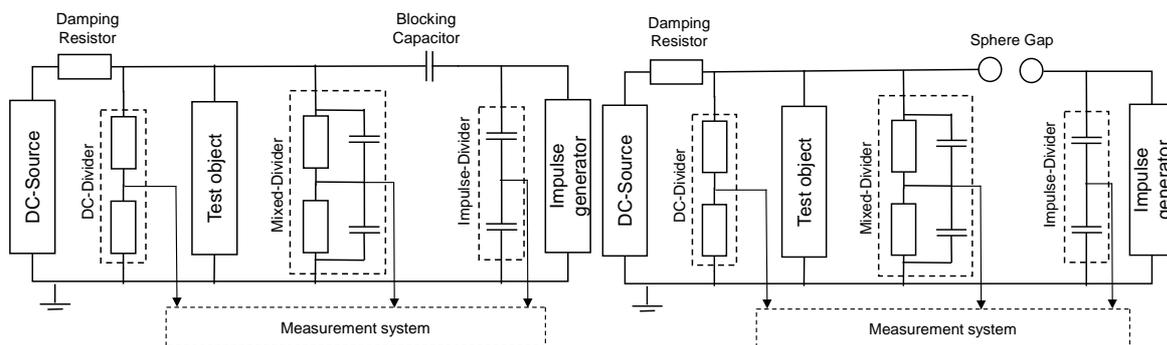


Figure 7: Test circuits for superimposed impulse voltage test. Blocking capacitor (up) and sphere gap (down) [15]

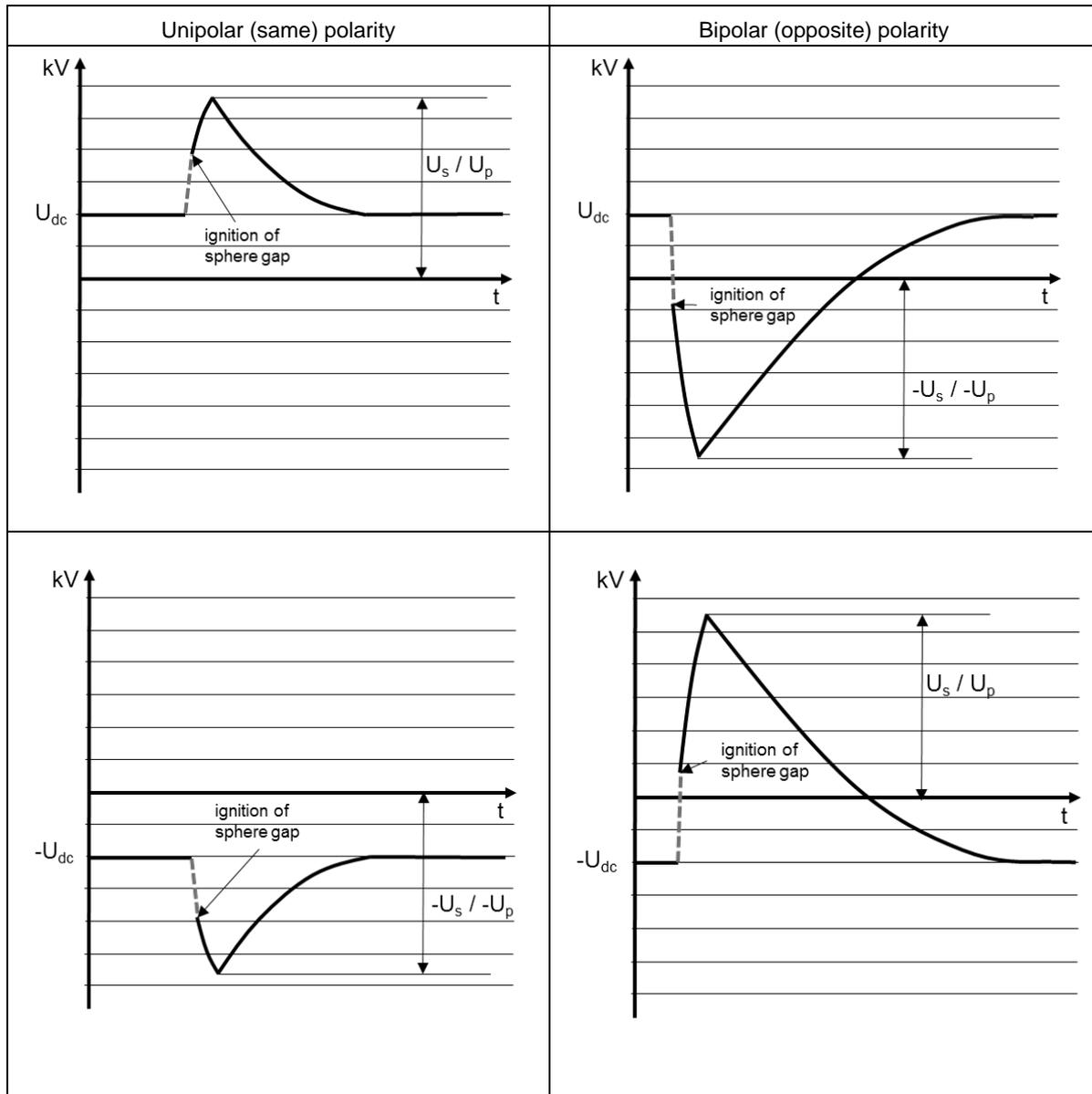


Figure 8: Unipolar and bipolar superimposed impulse voltage

Generally, it is suggested to use the method with blocking capacitor for the superimposed voltage tests due to the better quality of the impulse waveforms maintained by it. However, depending on the availability of a blocking capacitor and/or limitations of testing equipment, carrying out superimposed voltage tests with a sphere gap is acceptable according to [16] and IEC 60230(2018).