

D15.6 White- and position papers on pre-standardization of DC GIS testing

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
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EXECUTIVE SUMMARY

As a result of significant developments and space-saving benefits in switchgear systems for HVDC applications, the EU funded project “Progress on Meshed HVDC Offshore Transmission Networks” (PROMOTioN) with its aim to increase the Technology Readiness Level (TRL) of HVDC GIS for a meshed offshore grid. Due to the limit of operating experience to 250 kV, the Work Package (WP) 15 of PROMOTioN set up to demonstrate the long-term performance of a complete HVDC gas-insulated metal-enclosed system. Due to the lack of standardisation of HVDC GIS, this paper aims to summarise the experience and knowledge gained from all participants of WP 15, which includes prototype installation test, novel approaches of partial discharge (PD) measurements and eco-efficient SF6 alternatives for HVDC GIS, while to contribute to standardise testing DC GIS for power transmission at a rated voltage of 550 kV and higher.

This prototype installation test covers three types of load conditions with both DC voltage polarities. The 320 kV DC GIS test pole consists of different forms of busbars, disconnectors, earthing switches, bushing and build-in instrument transformers. The tests involve continuous DC stress (20% above rated value), impulse voltage tests, polarity reversal tests, superimposed impulse voltage tests, DC and AC PD measurement and a full rated current thermal stress. The detailed test program, test requirement and test procedure published in PROMOTioN WP deliverable D 15.2. Eventually, DC GIS demonstrates the technology will be well suitable for commercial HVDC station application.

This paper focuses on inputs from all participants of WP 15, including specification of HVDC GIS from TSO point of view, prototype installation test, novel approaches of partial discharge (PD) measurements and eco-efficient SF6 alternatives for HVDC GIS. The structure of this paper is described below.

After a brief introduction of chapter 1 about the importance of product standardization. Chapter 2 explains the current status of HVDC GIS standardization activities. Chapter 3 focuses on the inputs for standardization from PROMOTioN WP15 work. It covers the specification of HVDC GIS, prototype installation test, monitoring and diagnostics of HVDC GIS, measurement and behaviour of partial discharge for SF6 substitute gases and special considerations for pre-standardization of DC GIS. Chapter 4 concludes the main contributions and recommendations to the progress of the standardisation of HVDC GIS. Chapter 5 gives all the references.



1 INTRODUCTION

Standardization is essential to provide a common base for users to specify and operate, manufacturers to design and laboratories to test HVDC GIS equipment. Additionally, results from basic research at universities and institutes provide the technical foundation for standardization. Thus, contributions from all four areas are important to create a meaningful, effective specification.

The importance of HVDC GIS is increasing based on its advantages for contribution to DC transmission network. The operational experience and standardised qualification testing program are not ready yet. Therefore CIGRE JWG D1/B3.57 (Joint Working Group) has been working for collecting practical experience, research contributions and manufacturer's design testing and development testing carried out in independent laboratories and academic institutes. This working group made sufficient progress and contributions [1]. Especially, EU project PROMOTioN stepped into this topic and organised WP 15 to focus on the long term performance to HVDC GIS, including to develop novel approaches for PD measurement and investigate SF₆ and its alternative gases to interactions with standardisation work. PROMOTioN WP15 partners include TSOs, GIS manufacturer, an independent lab, research institute as well as university. The participants from WP 15 of PROMOTioN contribute to increasing the Technology Readiness Level (TRL) of HVDC GIS and deliver a significant contribution towards standardisation.

The main topics of deliverables of WP 15 are listed below:

- D15.1 Recommendations for Specifying DC GIS Systems [2]
- D15.2 Document on test requirements, procedures and methods [3]
- D15.3 Report on DC GIS diagnostic and monitoring tools and methods [4]
- D15.4 Test report of prototype installation test on HVDC GIS [5]
- D15.5 Report on diagnostic analysis and condition assessment [6]
- D15.6 White- and position papers on pre-standardization of DC GIS testing (the present document)
- D15.7 Report on PD characteristics of SF₆ alternative gases: comparison with SF₆ [7]
- D15.8 Report on long term monitoring of DC GIS with defects [8]

The present deliverable D15.6 aims at evaluating the key results of all WP15 deliverable and deriving inputs for standardisation of HVDC GIS.



2 CURRENT STATUS OF HVDC GIS STANDARDIZATION ACTIVITIES

With the beginning of R&D on a new compact generation of HVDC GIS in the early 2010s, basic work into standardization begun [9]. As of now (March 2020), within IEC first steps are planned to integrate DC-specific standards into existing AC switchgear standardization. In parallel to PROMOTioN WP15 activities, CIGRE working groups are active to draft Technical Brochures (TB) to build a technical foundation for future standardization.

2.1 INTEGRATION/ADDITION OF DC SPECIFIC STANDARDIZATION INTO EXISTING AC GIS STANDARDIZATION

- **Results from IEC SC 17 C – AHG37:**
- It is recommended to establish a new DC GIS standard
 - IEC 62271-317 DC GIS “DC gas-insulated switchgear assemblies.”
 - First NWIP draft rejected due to lack of participation, the second proposal with more participation
 - Start expected 2020, Uwe Riechert possible convener
- It is recommended to establish a new DC GIL standard
 - **IEC 62271-3XX DC GIL**
 - start later
- It is recommended to establish a new DC Common Specification standard
 - **IEC 62271-5 DC Common Specification for direct current switchgear**
 - This document shall cover all requirements which are common to DC GIS and DC GIL as well as air-insulated DC switchgear
 - Start 2020
 - Convener Motoharu Shiiki (Toshiba)

2.2 PARALLEL HVDC GIS STANDARDIZATION ACTIVITIES

- **CIGRE JWG B1/B3/D1.79:** new working group created “Recommendations for dielectric testing of HVDC gas insulated system cable sealing ends.”
 - Cornelis Plet will be a convener
 - Kick-off in February 2020, final report 2022
 - Members from WP15 from DNV GL, KEMA Labs, ABB, SGI, TenneT
 - Further members wanted
- **CIGRE JWG D1/B3.57:** Technical Brochure TB expected for publication in Summer 2020, currently in an internal review
 - D15.2 references CIGRE TB for type tests



- CIGRE TB contains a description of the prototype installation test
- Feedback gained from execution of PROMOTioN WP15 prototype installation test at KEMA Labs Arnhem was introduced into the CIGRE JWG

Comparison of PROMOTioN prototype installation test (D15.2 and test experiences) with definitions in TB (Table 1 and

- Table 2): The prototype installation test performed as part of PROMOTioN WP15 is valid for HVDC GIS also according to CIGRE JWG, during test execution, care has to be taken with regard to interruptions time that can easily occur during lab handling

Table 1: Similarities in Definition of Prototype Installation Test in upcoming CIGRE JWG D1/B3.57 and PROMOTioN D15.2

Similarities
Non-mandatory test to gain operational experience
Aging can not be proven by the long-term test
Min one year total test time
All major modules to be included
Include thermal and mechanical stresses
Pretests and subsequent condition check
Test voltage levels (1.2 rated DC & 0.8 rated impulse withstand with superimposed on 1.0 rated DC), 3 impulses per polarity and test
AC and DC heating current allowed
One ZL and two HL cycles for each polarity
Max interruption time 3 days
Make sure that interruptions are followed by triple the interruption time for recharging (early in interruptions prolong the test only by the $1 \times t_{off}$)

Table 2: Differences in Definition of Prototype Installation Test in upcoming CIGRE JWG D1/B3.57 and PROMOTioN D15.2

Differences	
CIGRE JWG D1/B3.57	PROMOTioN D15.2
GIL also covered	-
Oscillation impulse voltage with higher time tolerances allowed	would also be possible to test as an additional test but not included in D15.2
Separation of superimposed LI and SI possible (split of 60-day cycles in two 30 day cycles)	-
-	Load cycles with varying load current levels included
-	Mechanical operations of switching devices included
Interruption: each interruption must be compensated by min 2 h (exceptions for voltage dips during superimposed testing with spark gap)	No min. compensation time defined but considered in test execution

3 INPUTS FOR STANDARDIZATION FROM PROMOTION WP15 WORK

3.1 SPECIFICATION OF HVDC GIS

3.1.1 INTRODUCTION

Within this chapter recommendation for specifying HVDC GIS systems shall be given. The main differences to the specification of AC GIS are related to the specific insulating systems, voltage stresses, monitoring and testing. Therefore this chapter focus on these topics. An example specification of an HVDC GIS for three-terminal HVDC hub is given in [2].

The HVDC GIS shall comprise of at least the following equipment: bus-bars/bus-ducts, disconnectors, earthing switches, DC current transformers, DC voltage transformers, bushings, cable connection and appropriate insulation medium and enclosure. Note that circuit breakers will not be included in the DC GIS. On-load interruption of DC current is not possible without specialized DC circuit breakers which are until now not includable in DC GIS.

Besides, connections and sensors should be provided to facilitate the monitoring and testing of partial discharges.

3.1.2 RATED VOLTAGES AND CURRENTS

There are presently no standard transmission voltages for VSC-HVDC. Voltages ranging from ± 150 kV DC to ± 525 kV DC have been used recently and in projects under commissioning [10]. The DC voltage used is mostly determined by the amount of power required to be transferred through the link and is limited by the available voltage rating of the cable technology.

The current rating of the HVDC link is usually limited by the IGBT devices used. Typically, existing devices are rated up to 2000 A, but this is usually de-rated to achieve a safe operating area.

However, several HVDC converters may be connected in parallel onto a common HVDC transmission grid. Hence, the HVDC grid and its associated switchgear would be rated for currently more than 2000 A.

3.1.3 LIGHTNING AND SWITCHING IMPULSE WITHSTAND VOLTAGES

Lightning and switching phenomena determine the maximum transient voltages and currents experienced by the switchgear. Required Lightning Withstand Level (LIWL) and Switching Withstand Level (SIWL) vary depending on insulation coordination study. Standard withstand levels provided in IEC 60071 for AC systems, may be used as a reference for HVDC systems. Appropriate insulation withstands level should be ensured through insulation coordination and transient overvoltage studies. SIWL and LIWL levels selected should maintain a margin to the maximum calculated Switching Impulse Protection Level (SIPL) and Lightning Impulse Protection Level (LIPL) respectively. Typically, a margin of 15% to 30% is applied.



3.1.4 TEST REQUIREMENTS

Unlike AC, the accumulation of charge over surfaces for DC can take a long time. It is highly dependent on the atmospheric conditions, temperature, physical design and construction: shape and material used. The accumulation of charge can range from a few minutes to months, which makes testing extremely challenging. There is currently no standard for testing of HVDC GIS. However, sections of IEC 62271-1 and IEC 62271-203 for testing of AC gas-insulated metal-enclosed switchgear for rated voltages above 52 kV could be used as a reference for HVDC.

3.1.4.1 ROUTINE TESTS

Routine tests shall be carried out on all items of the HVDC GIS. They prove that the performance of the components being tested agrees with the base design for which type tests have been performed. They serve to eliminate defects introduced by the manufacturing process, which may fail operation. As such, AC GIS routine test standards for this purpose are sufficient [11]. Routine tests shall be conducted in accordance to IEC62271-1 Clause 8, and IEC 62271-203 Clause 7 with the exception that the dielectric tests on the main circuit either power frequency voltage or DC voltage and partial discharge tests shall be used.

3.1.4.2 TYPE TESTS

Most of the type tests listed in IEC 62271-1, and IEC 62271-203 are suitable to be performed for HVDC GIS as stated. However, additional tests to prove to withstand DC stresses should also be performed. Type tests suitable to be performed for HVDC GIS are as follows:

- Tests to verify the insulation level of the equipment and dielectric tests on auxiliary circuits.
- Tests to prove the radio interference voltage (RIV) level (This test applies only to bushings.)
- Tests to prove the temperature rise of any part of the equipment and measure the resistance of the main circuit.
- Tests to prove the rated peak and the rated short-time withstand current
- Verification of protection (IP/IK coding)
- Gas tightness tests
- Electromagnetic compatibility test
- Tests to prove the satisfactory operation of the included switching devices
- Insulator tests

3.1.4.3 ADDITIONAL TYPE TESTS

Most of the type tests listed in IEC 62271-1, and IEC 62271-203 are suitable to be performed for HVDC GIS as already stated.

DIELECTRIC TEST WITH DC PRE-STRESS APPLIED

DC voltage leads to an accumulation of surface charges on insulators. It may take a long time for the charge to accumulate fully. The period could even take several months. This accumulation of charge tends to lower the switching impulse and lightning impulse flashover voltage. Typically, the DC voltage must be applied for a

longer period [12]. However, appropriate charging time must be derived and verified through a multi-physics simulation with consideration to the GIS geometries and prevailing environmental conditions. A higher voltage or higher temperatures may be used in the test to shorten the period of charge accumulation after it is first demonstrated through appropriate simulation. Lightning impulse and switching impulse tests under 3.1.3 may then be carried out.

Superimposed DC voltage and lightning/switching impulse tests should also be conducted to test such conditions which are likely during operation of the HVDC GIS.

The insulator/gas interface superimposed tests shall be performed at high load conditions. The tests shall be performed, as shown in Table 3.

	Description	Test Voltage	Duration
Type tests Gas insulation	DC voltage withstand test	$1.5 \times U_n$	1 min
	Lightning impulse (LI) voltage test	IEC 60071-1/-5	15 impulses.
	Switching impulse (SI) voltage test	IEC 60071-1/-5	15 impulses
	Superimposed voltage test	$1.0 \times U_n + \text{rated LI/SI voltage}$	15 impulses
	Polarity reversal test ^{*1}	$1.25 \times U_n$	30 minutes
Insulator/gas interface	Insulation system test: DC voltage test	$1.0 \times U_n$	90% charging time
	Superimposed voltage tests (worst case conditions)	$U_r + \text{rated LI/SI voltage}$	3 impulses
*1 The polarity reversal test is applicable for LCC systems only. The dielectric stresses are covered by more critical tests like superimposed voltage tests. Therefore, polarity reversal tests are optional tests and not mandatory.			

Table 3: Dielectric testing [2]

LONG DURATION TESTS

For HVDC gas-insulated systems, a verification of the electrical lifetime (V-t characteristic) is of insignificant importance. Because the electrical lifetime of solid insulating material used in GIS/GIL is equal or even better under DC voltage stress compared to AC at typical service stress.

Experiences with AC gas-insulated systems show that all parts of the insulation system, assuming sound manufacturing quality requirements, do not reveal any ageing mechanisms which cause critical ageing. Therefore, overall the entire sound insulation system should not exhibit an increase in the failure rate with time. After 30 years of operation, there is no general ageing which recognizably 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 long-term statistical performance. Additional mechanical stresses caused by load cycles similar to those in cables are of minor interest for GIS/GIL applications. They are covered by thermal cycles performance tests of each insulator design, according to IEC 62271-203 (6.106). Additional tests are not necessary. Nevertheless, a combination with the insulation system tests under high load conditions could be performed.

3.2 PROTOTYPE INSTALLATION TEST

HVDC GIS has the standard parameters as HVAC GIS such as solid insulation, gas insulation and interface gas-solid. Still, it also has different electrical field distribution determined by the temperature, conductivity of the insulating materials and particular phenomena of the accumulation of space- and surface charges. Zooming into the history of operation of HVDC GIS worldwide, there is little service experience and no persuasive long-term reliability to ensure the technology readiness level for real service conditions. Therefore, this prototype installation test is valuable for evaluation of this technology and providing the evidence of long-term performance capability under simulated the closest service condition. This prototype installation test under the task of WP 15 especially meets the needs of such necessity.

3.2.1 TEST PROGRAM

Prototype installation test especially applies for the first installation of a new gas-insulated system for a long-term test period. This long-term test requires the overall assembling process represents the real application in the real grid and the size and components of the test arrangement match with all critical components of the real customer projects.

Figure 1 shows the brief test program and test procedure of the prototype installation test; the detailed information refers to [3].

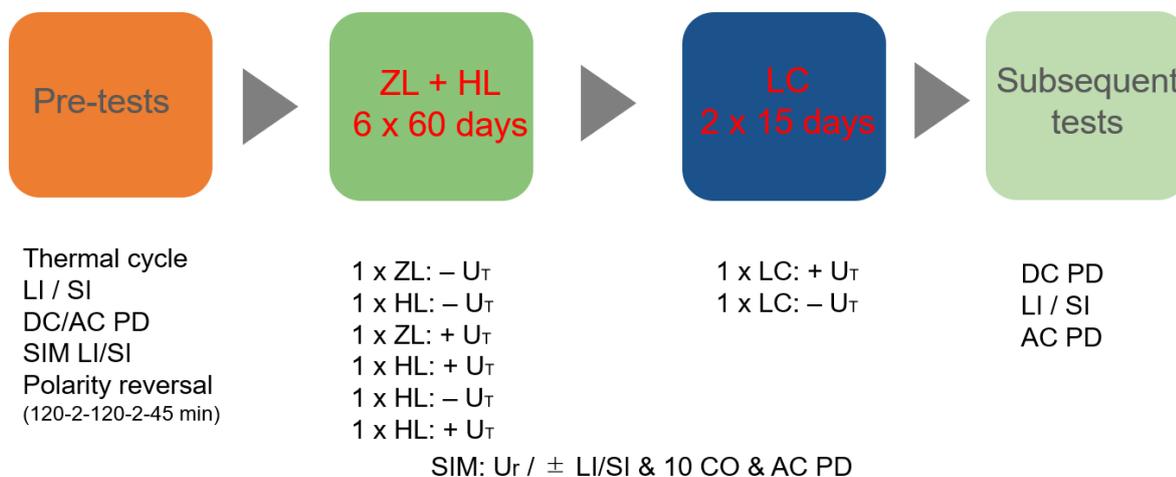


Figure 1: Test program and test procedure of the prototype installation test

The test program includes pre-tests, long-term voltage test (ZL, HL and LC loads) and subsequent tests. After each test block (ZL/HL/LC), superimposed impulse tests needs to be performed. Additionally, to simulate the real grid operation covers the mechanical operations of the switching devices under no-load condition, which might create particles or other unforeseen defects during the mechanical open and close switching operations.

3.2.2 TEST OBJECT

The test object is a 320 kV DC GIS complete system and has the nominal DC voltage of 320 (U_{ndc}) kV and the rated continuous DC voltage of 350 (U_{rdc}) kV. This test loop consists of approximately 40 m of the DC GIS circuit, see Figure 2.

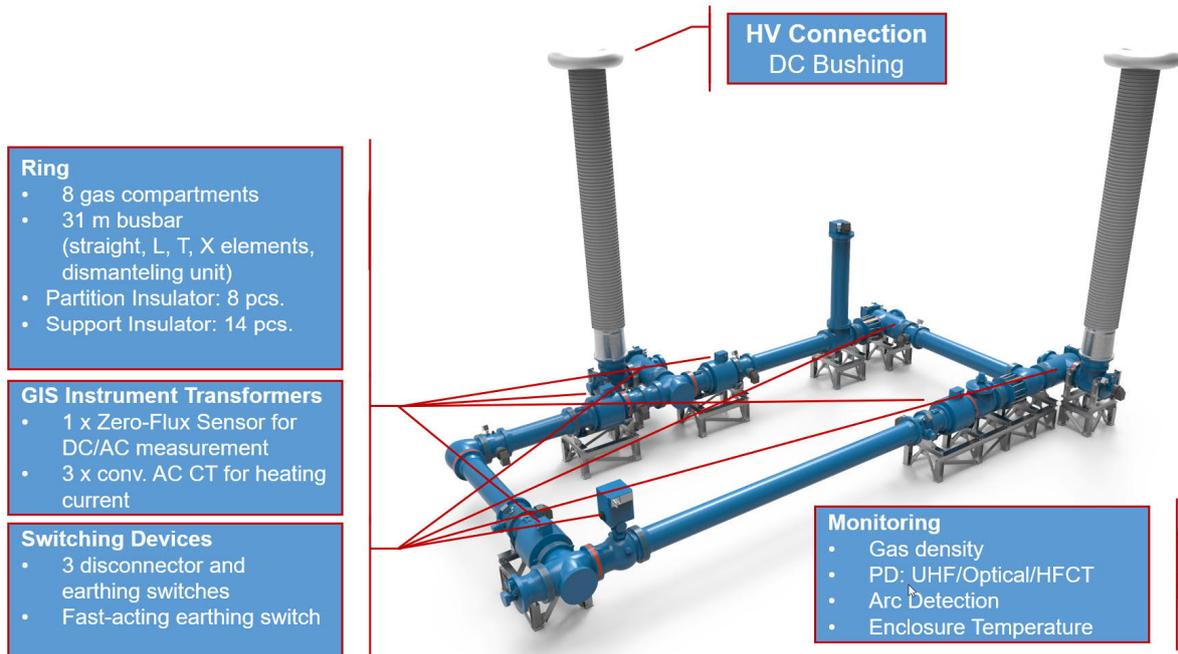


Figure 2: 320 kV HVDC GIS prototype test

The test object equipped with voltage, current, temperature, gas, arc detection, and PD monitoring system, see Figure 3. There are three ambient thermocouples located in different location of the test object because this is a relatively large test loop (7.3 x 12.7 m). The test experience is that multiple locations of the ambient temperature recording system are necessary, especially for larger test loop, to get proper test environment information. Furthermore, the surface temperature of each section of DC GIS should be recorded as well.

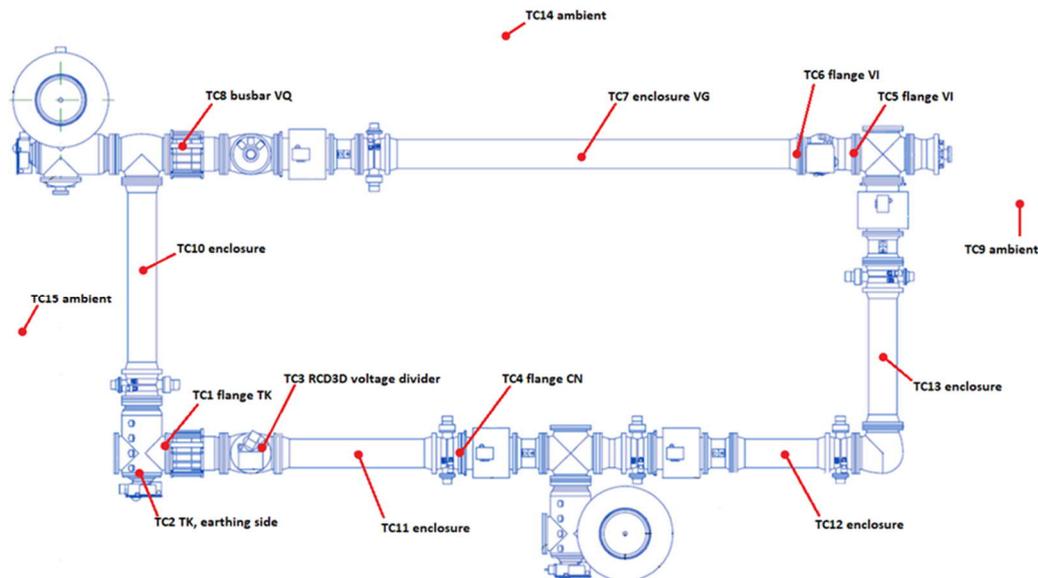


Figure 3: The overview of the test arrangement

3.2.3 TEST LOAD CONDITIONS

There are three types of load conditions: zero load (ZL), high load (HL) and load cycle (LC) see Figure 4, Figure 5 and Figure 6, respectively. During HL and LC load cases, to achieve the corresponding temperature differences on the solid insulation in the GIS, a heating transformer needs to produce the current following the busbar (conductor) as the main current path. This current is possible with DC as well as with thermally equivalent AC. For the PROMOTiON test, three conventional AC CTs to induce the equivalent AC, which is often easier to achieve in a lab environment.

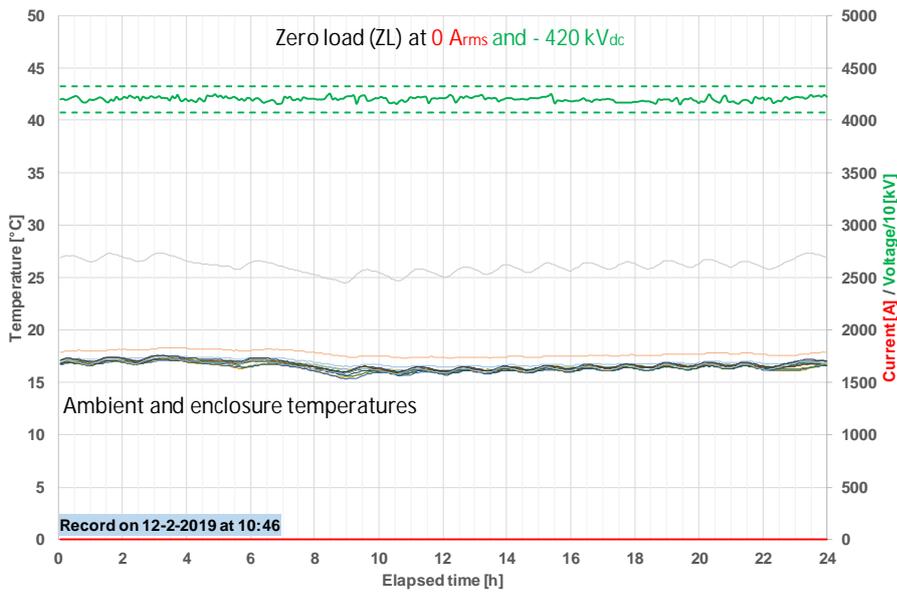


Figure 4: The real zero load graph

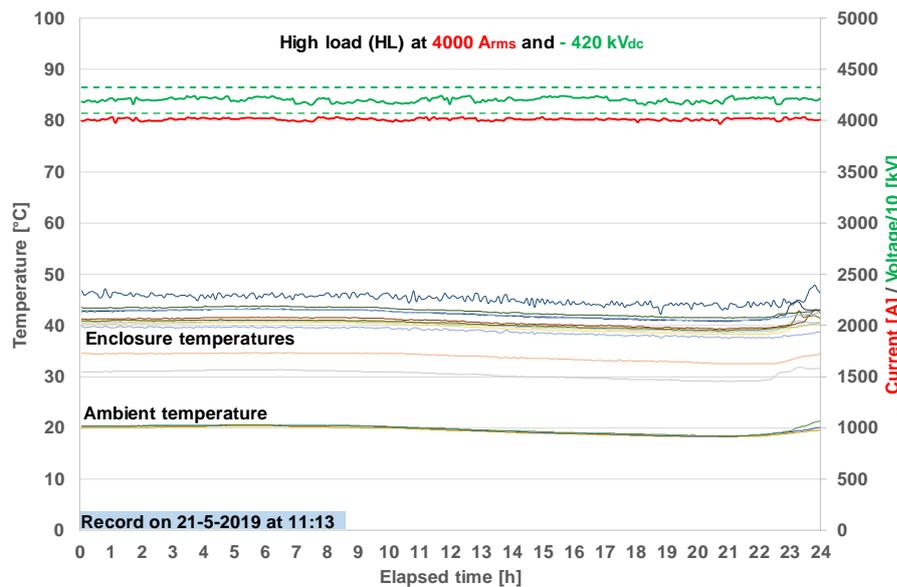


Figure 5: The real high load graph

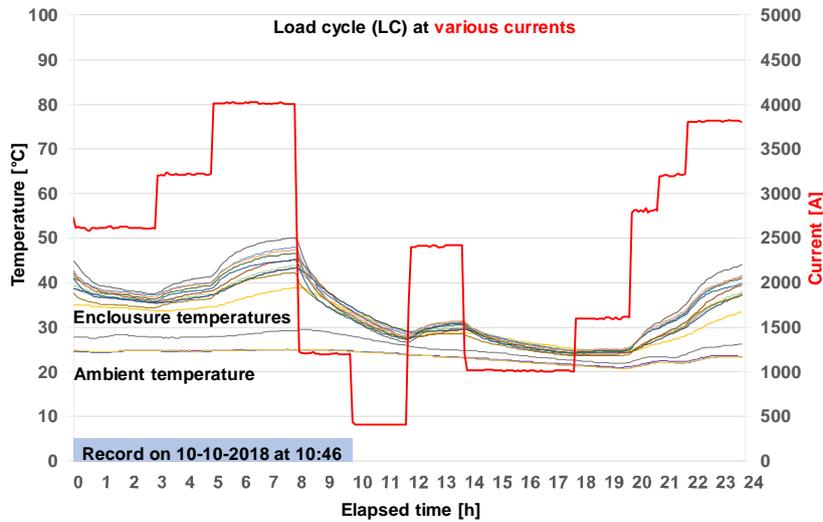


Figure 6: The real load cycle graph during pre-conditioning test

Based on all temperature recording data of HL, the temperature difference between enclosure and ambient (ΔT) is 20 ± 1 K during thermal steady state. In this project, after 6 hours, the temperature of the test object reaches the thermal steady state at HL load conditions.

*: $\Delta T = T$ average surface of enclosure – T average of ambient.

The prototype installation test simulates long-term interruption-free operation at DC voltage with regular impulse overvoltage due to switching operations or lightning strikes. However, in practice, there can occur unforeseen interruption, including lab power-downs, equipment handling or other unforeseen (voltage, current, temperature) interruptions. The compensation requirement is defined as detailed in [3]. Compensation times are only for short-term (max. three days) interruption. Otherwise, each cycle block needs to be resumed.

3.2.4 SUPERIMPOSED LIGHTNING AND SWITCHING IMPULSE TEST

The superimposed impulse voltage test is a unique requirement for HVDC components, including HVDC cable and HVDC GIS. There are two methods (Spark gap and blocking capacitor) introduced in IEC 60230:2018. A spark gap method is applied to generate the superimposed DC and impulse voltages in this project, the actual test circuit and real test set-up see Figure 7.

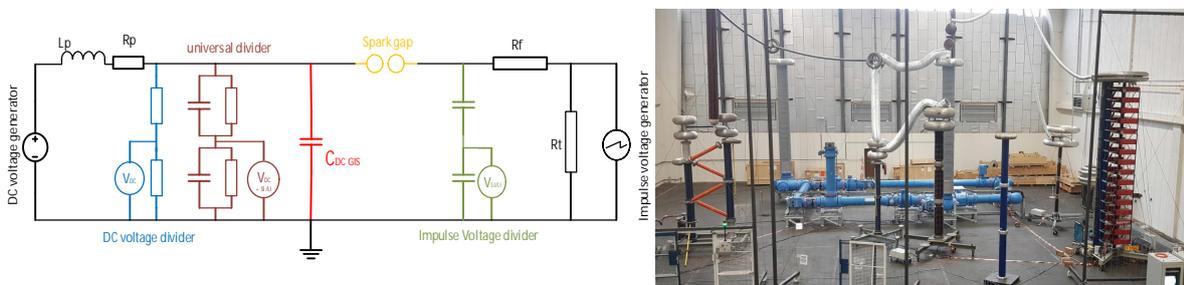


Figure 7: Superimposed impulse test diagram and real test set-up

Moreover, the typical superimposed LI and SI test graphs are present in Figure 8.

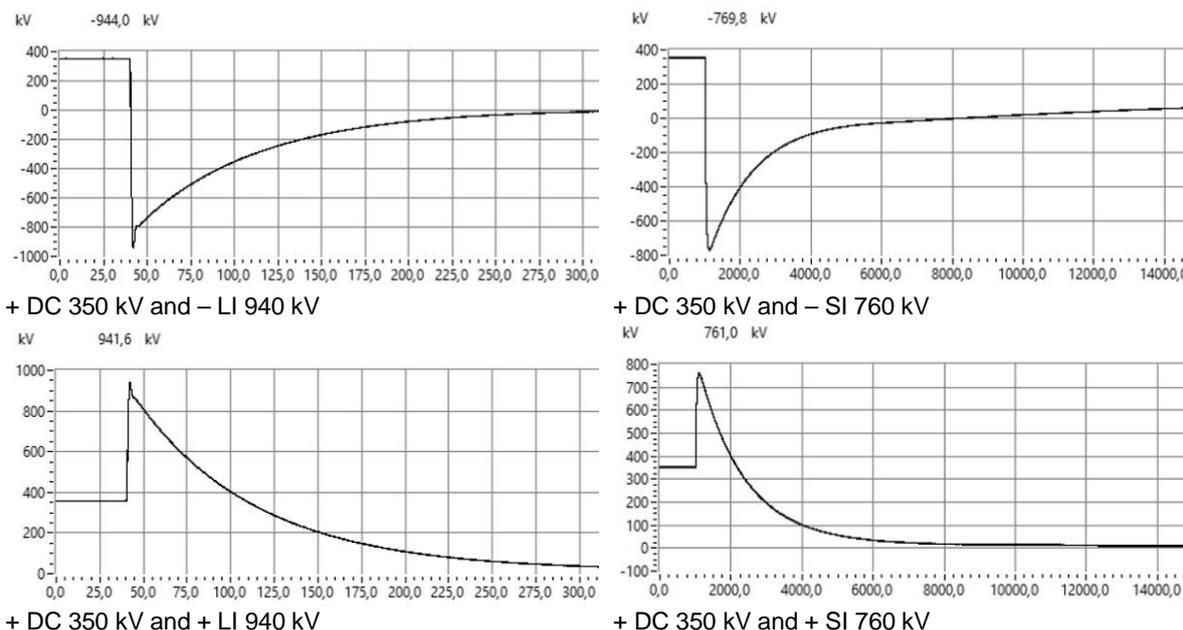


Figure 8: Typical superimposed LI and SI test graphs, all combinations with positive DC voltage shown, four further combinations with negative DC analogously.

Based on the practice experience, the pros and cons of both methods are summarized below, see Table 4 and Table 5.

Table 4: **The spark gap method:**

Pros	Cons
Smaller impulse generator required; A spark gap is cheap; Space-saving; Easy to implement; Cost-effective for a laboratory.	Energy dissipation to the test object with extra discharging and recharging process; The breakdown of a spark gap influenced by the ambient conditions of a laboratory (air pressure, humidity, temperature); Distance control of spark gap is critical to avoid the impulse extinguish and re-ignition;

Table 5: **The blocking capacitor method:**

Pros	Cons
Energy dissipation to the test object without extra discharging and recharging process; Less influenced by ambient conditions of a laboratory.	Large impulse generator required; Expensive capacitive coupling capacitor; Large testing space required; Un-easy to implement; Costly.

The spark gap method is an effective solution, but if there are no equipped trigger units can have extinction and reignition effects (see Figure 9).

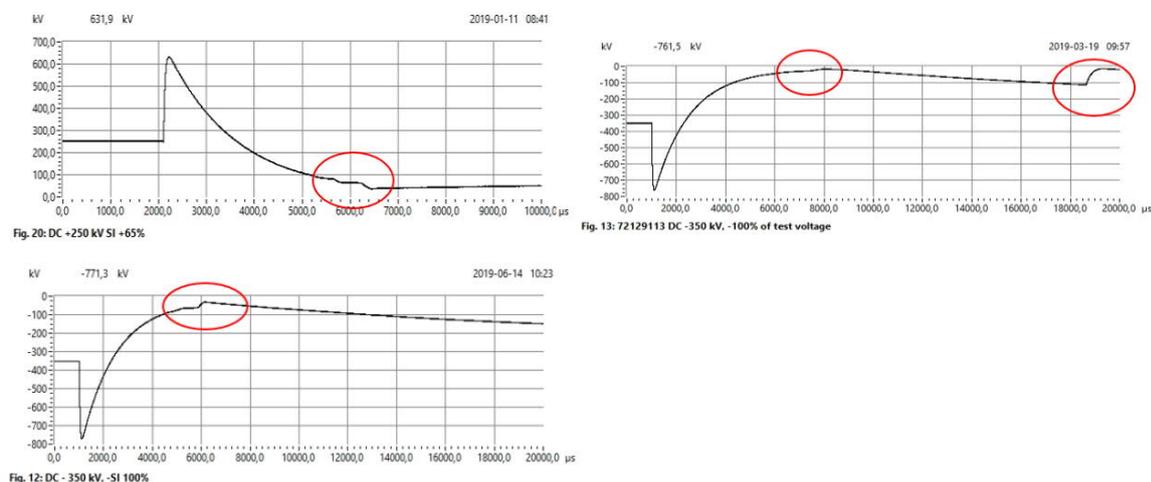


Figure 9: a few samples of extinction and reignition effects of spark gap method

3.3 MONITORING AND DIAGNOSTICS OF HVDC GIS

3.3.1 GENERAL

Partial discharge measurements can be carried out in HVDC GIS following the traditional UHF method as described in [13]. However, the UHF method is not able to properly estimate the apparent charge due to the frequency bandwidth of the sensors and the propagation modes in the UHF range in the GIS. Moreover, at high frequency, the attenuation of the signals in the UHF is prominent, which in practice means that the distance between antennas has to be carefully considered to ensure a good sensitivity in the whole GIS. The signal attenuation is due to the GIS components, like spacers [14], disconnecting elements [15], T-branches [16], L-branches [17] and in general due to any installed element that either creates a geometrical or material discontinuity in the GIS with respect to the GIS tube.

To overcome these limitations, a new method based on magnetic antennas has been developed at the Delft University of Technology. The foundations of the method have been presented in [18]. The magnetic antennas consist of two shielded loops that can be installed in the conventional dielectric windows where the UHF antennas are connected when a partial discharge propagates through the GIS the induced currents in the GIS enclosure have to diverge as they encounter the opening of the dielectric window. The charge in the direction of the currents surrounding the dielectric window induces a magnetic field that is picked up by two shielded coils. The shielded coils are arranged in such a way that one coil measures the flux created in the upper part of the opening and the other coil measures the flux in the lower part, both with respect to the propagation direction of the partial discharge. Since the induced partial discharge currents flowing in the GIS are homogeneously distributed, both antennas measure opposite polarity signals of similar magnitude. This fact helps in recognition of the partial discharges since external coupled noise normally doesn't induce symmetric voltage in the antennas.

Due to their constructive aspects, the magnetic loop antennas work in the HF and low VHF range, [19]. In practice, due to the geometry and dimensions of typical HVDC GIS, this means that the antennas measure the portion of the partial discharge signal that propagates in the transverse electromagnetic mode (TEM). In this frequency range, the signal attenuation is smaller than in the UHF range. In laboratory experiments, the sensitivity of the magnetic loop antennas is in the order of magnitude of 1 pC at 3.3 m distance for a free moving particle in SF₆. Moreover, it has been experimentally measured that after propagating 20 m in the GIS, including switchgear, a disconnecter switch, a T-branch and several L-branches, the peak value of the measured partial discharge signals is normally attenuated by around 50%.

Since the measuring system uses the HF and VHF range, a normal partial discharge calibrator can be used to perform the sensitivity check and the charge calibration. Since the antennas are based on magnetic detection, it is advisable not to mount the antennas close to GIS ends or terminations; otherwise, the reflected currents due to the impedance mismatching will reduce the sensitivity of the antenna. In that regard, a minimum distance around 1.5 m to the GIS terminations or ends is recommended for the magnetic antenna location.

The charge calibration of the magnetic antenna can be done by using a mathematical method that performs the double-time integral of the measured signals affected by a calibration factor. This calibration factor can be experimentally determined using a calibration rig. At the Delft University of Technology, a testbench has been built to perform the calibration. The testbench is a calibration rig that uses a small GIS compartment reproduction in which the inner conductor has been adapted to mount a high-frequency current transformer [19]. Using the high-frequency current transformer and applying the double-time integral of the measured signal, the calibration constant is experimentally determined. The calibration should inject a PD pulse with a broader frequency content than the magnetic loop antenna, which in practice means that a partial discharge calibrator for cable testing is suitable. The calibration factor heavily depends upon the GIS dimensions; therefore, it can only be used in partial discharge GIS measurements that use GIS tubes or the same dimensions. The experimentally determined calibration constant has been checked in laboratory experiments using real GIS and test cells equipped with current measurements for charge reference, [19]. The experiments show small deviations between the antennas and between them and the test cell reference, in the order of 30% maximum differences. This deviation is attributed to small differences in the orientation and position of the antennas in the real GIS dielectric window with respect to the calibration rig.

3.3.2 EXAMPLE OF DIFFERENT PD MEASURING METHODS

Within the WP15 of PROMOTioN project, PD measurements are carried out with different measurement systems. Figure 10 shows an example of the evolution of PD signal recorded by the conventional system, light emission and UHF methods under negative DC voltage for a protrusion of 2 cm in 5 bar abs SF₆.

As illustrated in Figure 10, the recorded signals remain below the background noise level until the PD inception voltage (PDIV) is reached (about 60 kV). The current, image of the emitted light and the apparent charge follow the same tendency when the voltage increases above the PDIV. The sensitivity of both systems is similar as they



lead to the same PDIV whatever the type of gas. For UHF measuring system, when the PDIV is exceeded, the frequency spectrum amplitude changes due to the presence of electromagnetic waves inside test setup generated by PD (Figure 10(c) at -40kV and -60kV).

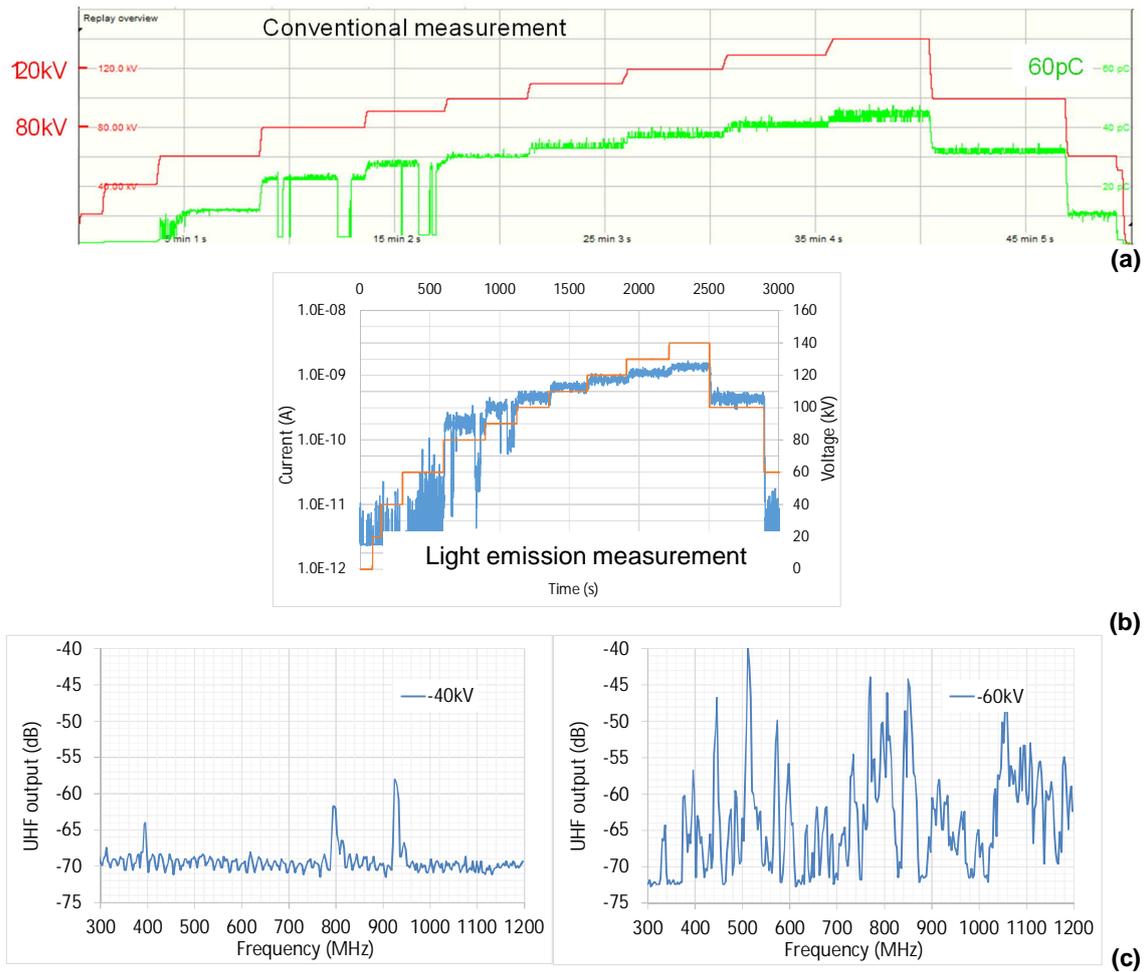


Figure 10: PD signal recorded by a different measuring system under a negative DC voltage with a protrusion defect of 2 cm. (a) Conventional method: the red curve is the applied voltage, and the green curve is the PD amplitude (b) Light emission: the orange curve is the applied voltage, and the blue curve is the measured current image of light emission quantity and (c) UHF antenna with a spectrum analyzer for SF₆ 5 bar abs (background noise at 40 kV and PD activity at 60 kV).

An example of a PD signal generated by a protrusion defect of 10 mm and recorded by the magnetic antenna, provided by TU Delft University can be found in Figure 11b. When PD inception voltage is exceeded, and the PD amplitude is sufficiently high (>3 pC), the magnetic antenna is able to detect a PD pulse. Moreover, there is a good correlation between different measuring systems (Figure 11c).

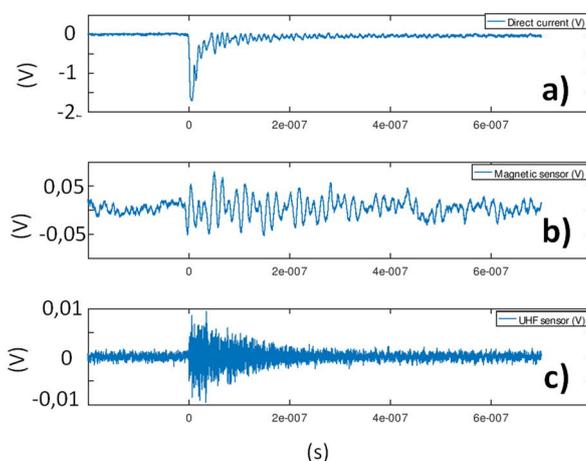


Figure 11: Example of PD pulse (a) generated by a protrusion of 10 mm and measured by a magnetic antenna (b) and a UHF antenna (c), the apparent charge measured by the conventional method is ≈ 7 pC.

3.4 MEASUREMENT AND BEHAVIOR OF PARTIAL DISCHARGE FOR SF₆ SUBSTITUTE GASES

Nowadays, SF₆ is commonly used as insulation gas for high voltage equipment. However, it is classified in the Kyoto protocol list as one of the gas with high GWP. In the past few years, researches have been conducted to find alternatives to SF₆ with a lower GWP. Among different solutions, the two fluorinated gases: (CF₃)₂CFCN – Novec™ 4710 (FN) and CF₃C(O)CF(CF₃)₂ – Novec™ 5110 (FK) are selected as promising candidates as they present very high dielectric strength, non-flammability, and low GWP. Unfortunately, they present a high boiling point, and they must be mixed with buffer gases to be suitable for low-temperature applications. Different gas mixtures combining FN/FK and CO₂/air are thus investigated to replace SF₆ in GIS/GIL. With the SF₆ replacement tendency, the performance of SF₆ alternatives HVDC GIS might need to be verified for future applications. In this context, the Workpackage 15 (WP15) of the EU funded project “Progress on Meshed HVDC Offshore Transmission Networks” (PROMOTioN) deals with the technology demonstration of HVDC GIS and investigation of partial discharge (PD) monitoring systems with SF₆ alternative gases.

There are CIGRE Working groups with regards to DC PD measurement:

D1.63 2015 Partial Discharge Detection under DC voltage stress [20]

As well as towards eco-efficient SF₆ alternatives, mainly for AC applications:

D1.67 2016 Dielectric performance of new non-SF₆ gases and gas mixtures for gas-insulated systems Christian Franck (CH)

Within PROMOTioN, the PD behaviour of eco-efficient SF₆ alternatives applied in HVDC GIS is investigated [7] and [8]. The results can deliver significant results for future standardisation.

A PD measurement is the most effective method for defect detection and identification inside the apparatus. Unfortunately, the methods for measurement and detection of PD under DC voltage are less developed and might be less effective than that under AC voltage. There is, therefore, still a lack of knowledge on PD measurement

under DC and especially if SF₆ alternative gases will be used as insulation gas in HVDC GIS/GIL. In the perspective of future HVDC meshed networks, it is thus necessary to anticipate the possibility to install SF₆ free DC GIS and to develop dielectric monitoring system based on PD measurement to reach the same reliability level as it is on AC GIS.

In order to overcome these gaps, studies on the PD behaviour of defect in potential SF₆ alternative gases, FN and FK mixtures under DC voltage in comparison with SF₆ have been realized in the WP15 of PROMOTioN project. The main results are summarized below. For more detail of this work, please refer to [7] and [8].

Investigated gases & defect

Various alternative gases with different SF₆ equivalent dielectric strength were investigated. They are listed in Table 6, Table 7 and Table 8. Note that the equivalent dielectric strength is determined under a uniform electric field.

Gas	Pressure (bar abs)
SF₆	5 (reference)
Novec™ 5110/Dry Air Mixture (6.6 % Novec™ 5110)	7.5
Novec™ 5110 (pure)	0.5
Dry Air (pure)	7
Novec™ 4710/CO₂ Mixture (10 % Novec™ 4710)	6.5
Novec™ 4710 (pure)	0.65
CO ₂ (pure)	5.85
Novec™ 4710/CO₂ Mixture (4% Novec™ 4710)	8.0
Novec™ 4710 (pure)	0.32
CO ₂ (pure)	7.68

Table 6: Investigated gases with the same dielectric strength like SF₆ at 5 bar abs

Gas	Pressure (bar abs)
SF₆	6 (reference)
Novec™ 5110/Dry Air Mixture (5.3% Novec™ 5110)	9.4
Novec™ 5110 (pure)	0.5
Dry Air (pure)	8.9

Table 7: Investigated gases with the same equivalent dielectric strength like SF₆ at 6 bar abs

Gas	Pressure (bar abs)
SF₆	6.8 (reference)
Novec™ 5110/Dry Air Mixture (4.5% Novec™ 5110)	11
Novec™ 5110 (pure)	0.5
Dry Air (pure)	10.5

Table 8: Investigated gases with the same equivalent dielectric strength like SF₆ at 6.8 bar abs

In the framework of Workpackage 15 - PROMOTioN project, PD behaviour of defect in SF₆ and SF₆ alternative gases is investigated in a GIS test compartment as illustrated in Figure 12. The test compartment is part of a real-size GIS to be closer to industrial applications. The studied defect is a tungsten needle with a diameter of 0.5 mm, a tip radius of 50 µm and a length exceeding the high voltage conductor of 1 cm or 2 cm. Different measuring systems, including conventional and non-conventional methods, are used to detect and analyse PD signals [4], [5], [7] and [8].

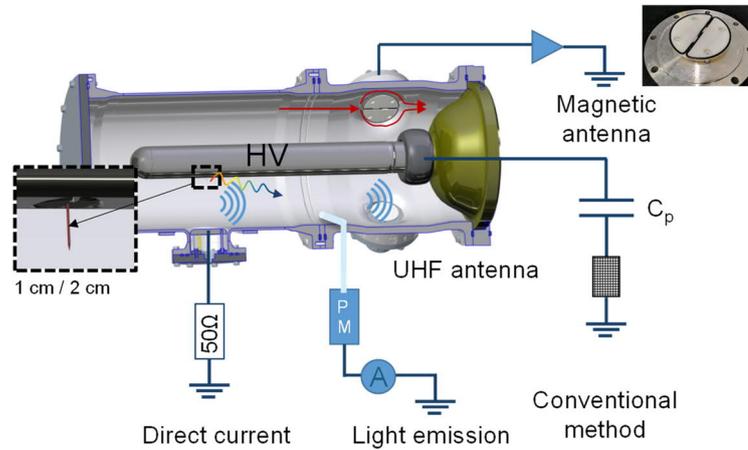


Figure 12: Test compartment used to study the PD with a protrusion on high voltage conductor and different PD measuring systems.

3.4.1 INCEPTION VOLTAGE

The inception voltages for the tested gases under negative and positive DC voltage are reported in Figure 13. Almost the same order of PDIV was observed for SF₆ and FN-CO₂ mixtures while a slightly lower PDIV was obtained for FK-Air mixtures compared to SF₆, i.e., about 20 - 30% depending on the equivalent SF₆ dielectric strength pressure. Moreover, slightly higher inception voltage is observed for all gases with positive polarity. The difference in term of PDIV might be due to the difference of dielectric strength between gas mixtures and SF₆ under an inhomogeneous electric field.

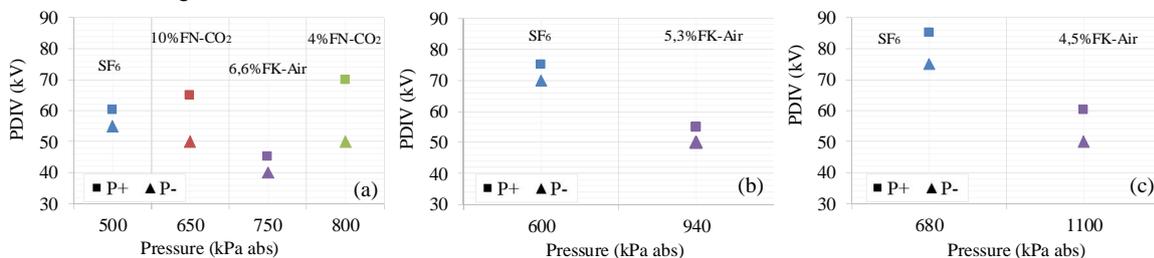


Figure 13: Partial discharge inception voltage for a 20mm protrusion. (a) 5 bar SF₆ equivalent dielectric strength, (b) 6 bar SF₆ equivalent dielectric strength and (c) 6.8bar SF₆ equivalent dielectric strength

3.4.2 PD BEHAVIOR

Figure 14 reports the evolution of PD amplitude and the average PD repetition frequency (average number of discharges per second) in the function of applied voltage for different investigated gases at 5 bar SF₆ equivalent dielectric strength.

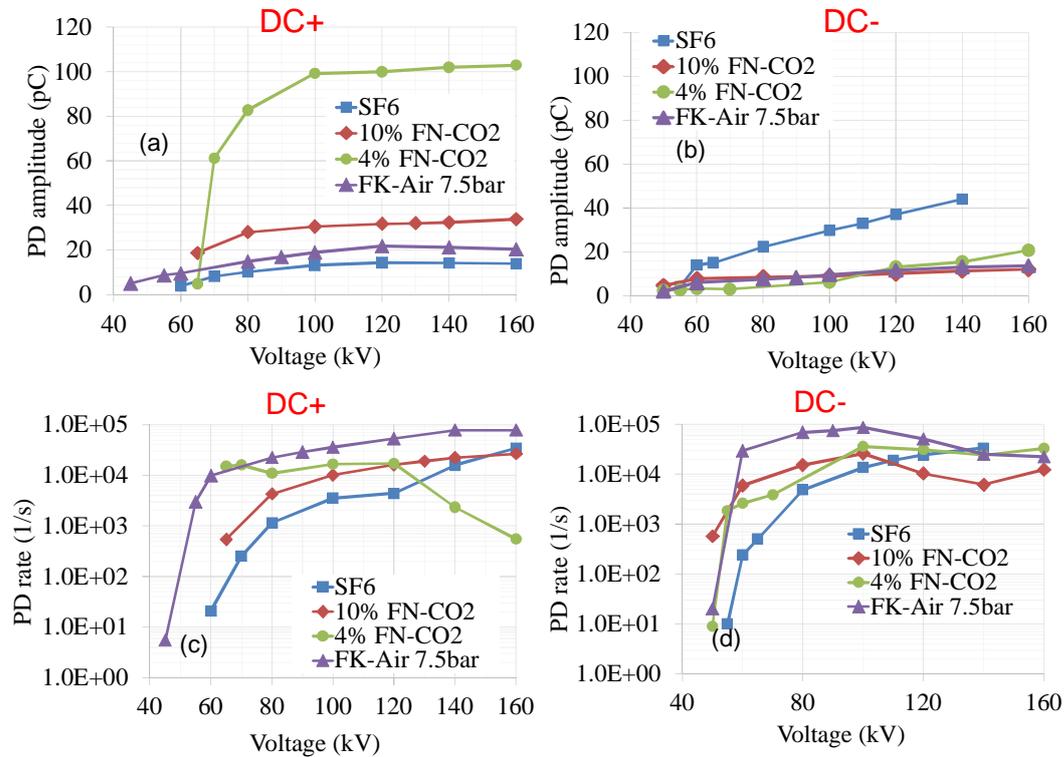


Figure 14: Evolution of PD behaviour in function of voltage for a 20 mm protrusion. (a), (c) Positive polarity, (b), (d) Negative polarity.

One can note that the PD amplitude and the PD repetition frequency increase generally with the increase of applied DC voltage. However, the gas nature influences PD behaviour significantly. For example, at the voltage of 100 kV, the PD amplitude is 13.2, 30.5, 99.3 and 18.9 pC for SF6 at 5 bar abs, 10% FN-CO2, 4% FN-CO2 and 6.6% FK-Air, respectively. Besides, the influence of DC polarity to PD amplitude in the function of gas composition is evidenced. Higher PD amplitude is always observed under negative polarity for SF6 while it is observed under positive polarity for SF6 alternative gases.

Moreover, a steady-state is observed under positive polarity for all investigated gases, where the PD amplitude remains constant regardless of the increase of applied voltage. This observation is completely different compared to PD behaviour under AC, where the PD amplitude usually increases with the increase of applied voltage. Concerning the PD repetition frequency, the investigated alternative gases show higher PD repetition frequency compared to SF6. For example, at the voltage of 100 kV, PD repetition frequency is 3520, 10200, 16600 and 35900 1/s for SF6 at 5 bar abs, 10% FN-CO2, 4% FN-CO2 and 6.6% FK-Air, respectively.

3.4.3 PD EVOLUTION IN FUNCTION OF TIME

Figure 15 reports the evolution of PD amplitude and the PD repetition frequency in function of voltage application time. One underlines that PD amplitude increases with time before reaching a steady-state and the PD repetition frequency for alternative gases is higher compared to SF6. For more information about PD behaviour in function of time, please refer to [8].

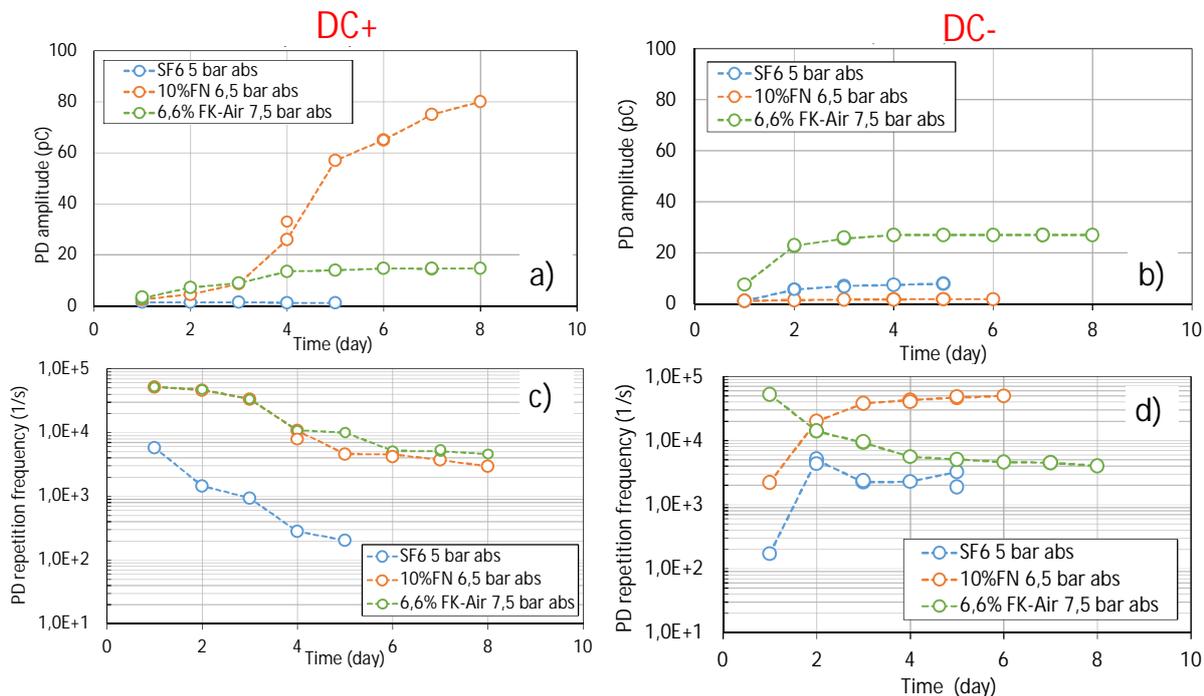


Figure 15: Evolution of PD behaviour in function of time for a 10 mm protrusion defect. (a), (c) Positive polarity, (b), (d) Negative polarity

3.4.4 DIELECTRIC BEHAVIOUR: INSULATION SYSTEM TEST WITH FK-MIXTURE

Placeholder, PMG extension? Annexe? New revision?==>underconsideration

3.4.5 SUMMARY & REMARK

In the perspective of future HVDC meshed network, DC GIS/GIL should acquire the same reliability levels of AC GIS. In particular, the capability of detection of partial discharge under DC voltage must be effective. As the partial discharge experience feedback is still missing for HVDC and even more for SF₆ alternative gases, partial discharge measurements with defects are performed in SF₆ and SF₆ alternative gases with same theoretical SF₆ dielectric strength under both polarities of DC Voltage with different measuring systems. In case of a protrusion, some differences in terms of partial discharge inception voltage are observed although the gases have the same theoretical dielectric strength.

Moreover, the studied alternative gases show higher PD amplitude under positive polarity while the PD have higher amplitude under negative polarity for SF₆. The PD repetition frequency is always higher for the SF₆ alternative gases than SF₆ under both polarities. These results highlight the influence of the field inhomogeneity and gas composition on the partial discharge characteristics. Even though there are some differences between gases, PD behaviour of alternative gases is comparable to SF₆. Effective PD monitoring systems can thus be developed for HVDC GIS with alternative gas

3.5 SPECIAL CONSIDERATIONS FOR PRE-STANDARDIZATION OF DC GIS

3.5.1 HARMONISATION OF DEFINITIONS

PROMOTiON deliverable D 15.2 gives all DC GIS-related definitions and their symbols. The standardization should pay attention to harmonise all definitions with other DC components which avoid confusion.

3.5.2 PRE-TESTS AND SUBSEQUENT TESTS

Based on DC insulation breakdown characteristics and the conditioning effect of rough-finish electrodes, the DC GIS test object is allowed to have a pre-conditioning test before being subjected to any dielectric tests on behalf of the manufacturer. Therefore, there are pre-tests arranged to calibrate relevant values and check the test set-up before the prototype installation test. After completing the long-term voltage test, the subsequent tests are recommended after the prototype installation test before disassembling the test objects for inspection. For instance, there are AC PD measurement, DC PD measurement and lightning impulse test and switching impulse test listed.

- The AC PD measurement is to check if there is no any installation failure before the prototype installation test.
- The DC PD measurement is to check the condition of the test object before and after the prototype installation test. The results of the PD measurement can be compared.
- The test object has low capacitance of 3 nF. Therefore, a proper test setup is needed to make a standard lightning impulse wave (1.2/50 μ s) and switching impulse wave (250/2500 μ s).
- The proper set-up is to limit the overshoot of lightning impulse within 10% (Figure 16).
- The external capacitor (5 nF) parallels to the test object to have a 250 μ s front time (Figure 17).

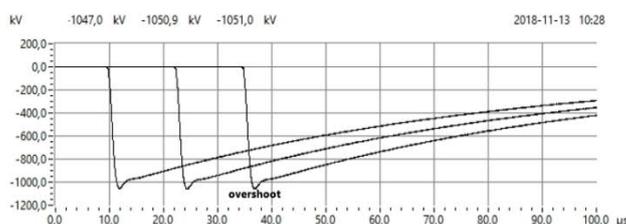


Figure 16: the lightning impulse graphs at 1050 kV

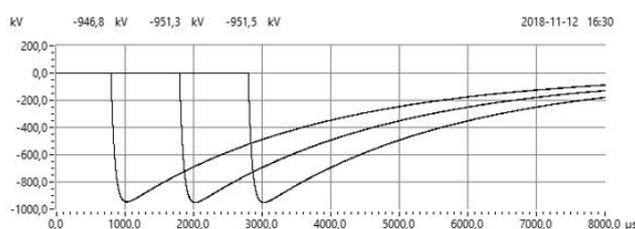


Figure 17: the switching impulse graphs at 950 kV

4 CONCLUSION

The objective of PROMOTioN WP 15 is to develop a thorough understanding of technical and operational requirements of DC GIS systems in meshed offshore HVDC grids, develop and demonstrate monitoring and diagnostic methods, develop meaningful standardized test programs based on existing standardization work and increase technology readiness level (TRL) of DC GIS technology from 6 to 8 by demonstrating a full-scale prototype in an independent test lab.

This project has also combined the specification from TSO's perspective. Therefore, the specification focuses on the main differences to the specification of AC GIS, in which TSO builds knowledge and experience. The detailed specific testing guideline and requirement of a test object are described.

Prototype installation test is a special and optional test which is not in the category of a type test program. However, it is a proposed test to be performed after the type tests, to indicate the long-term (more than one year) performance of a complete HVDC gas-insulated system. Within PROMOTioN project, the prototype installation test consists of six 60-day blocks plus two 15-day blocks of DC stress, terminated by superimposed switching and lightning impulse withstand voltage tests, respectively. In order to represent the typical GIS lifetime of 40 years, the DC voltage level (± 420) is increased to 20% above the rated value (± 350) in the long-term phase.

Partial discharge measurements can be carried out in HVDC GIS following the traditional UHF method. However, the UHF method is not able to properly estimate the apparent charge due to the frequency bandwidth of the sensors and the propagation modes in the UHF range in the GIS. A new method based on magnetic antennas has been developed at the Delft University of Technology. Due to their constructive aspects, the magnetic loop antennas work in the HF and low VHF range. The detail descriptions can be found in [6].

Due to lack of the partial discharge experience feedback is still missing for HVDC and even more, for SF6 alternative gases, partial discharge measurements with defects are performed in SF6 and SF6 alternative gases with same theoretical SF6 dielectric strength under both polarity of DC Voltage with different measuring systems. In case of a protrusion, some differences in terms of partial discharge inception voltage are observed although the gases have the same theoretical dielectric strength. The detailed descriptions and results refer to D 15.8. Although there are some differences between gases, PD behaviour of alternative gases is comparable to SF6. Effective PD monitoring systems can thus be developed for HVDC GIS with alternative gas.

All PROMOTioN WP 15 achievements will be contributed to the standardization of HVDC GIS.



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