HVDC GIS cable connection assembly fully qualified for ±525 kV following dimensions of the HVAC standard interface

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ABSTRACT

Within a joint collaboration, a ±525 kV HVDC GIS cable connection assembly has now been fully qualified for the first time with a type test and a pre-qualification test according to CIGRE TB 852. The interface design of this gas-insulated cable connection assembly is based upon the dimensions used in the HVAC GIS standard IEC 62271-209. Using this standard will reduce risk during implementation due to the well-known scope split. The paper describes the cable connection assembly interface, the testing philosophies and the performed tests. All tests were performed successfully.

KEYWORDS

525 kV; Cable connection assembly; HVDC; HVDC cable; HVDC GIS; HVDC termination; qualification; XLPE

INTRODUCTION

With the increasing demand for higher transmission capacity and the integration of renewable energy, high-voltage direct current (HVDC) system voltage levels of up to U_0 = ±525 kV will be realized. HVDC gas-insulated switchgear (GIS) and HVDC cables for ±525 kV voltage level have been introduced to the market several years ago. Development and qualification of the required HVDC technology solutions need also to cover their combination and interfaces, e.g. the combination of cable systems and gas-insulated systems for the most space-saving HVDC installations.

"Compact gas-insulated metal-enclosed systems for high-voltage direct current applications (HVDC GIS) have been developed for HVDC projects in need of space-saving installations, such as offshore platforms, cable transition stations or multi-terminal switching stations." [1] In 2018 the type tests of HVDC GIS up to rated DC voltages of ±550 kV according CIGRE TB 842 [2] and relevant parts of IEC 62271 series have been successfully passed [3].

With using HVDC GIS, the required space for HVDC switchyards can be reduced to a minimum compared to same-functional air-insulated switchgear (AIS). When using an HVDC GIS, the HVDC cable can be connected directly to the HVDC GIS using a gas-insulated HVDC cable termination. This solution required less allocated space in comparison to the alternative of an air-insulated outdoor cable termination and additional gas/air-bushing. Furthermore, the gas-insulated HVDC cable connection assembly, consisting of the HVDC GIS and the HVDC cable termination, also completely omits flammable insulating materials, resulting in a zero fire load. This allows the saving of a dedicated room for the DC switchyard and allows the integration of the DC switchyard into another technological room compared to the usage of possible oil-filled AIS outdoor cable-terminations.

Application examples of cable connection assemblies

The direct connection of an HVDC GIS with an HVDC cable is part of several HVDC solutions: converter stations, transition stations and switching stations.

The development of HVDC GIS in the past decade was mainly driven by the offshore grid connection systems. Gas-insulated switchgear design can reduce the volume of the HVDC switchyard to a twentieth resulting in a smaller offshore converter station decreased weight of the platform, lower resource consumption and lower CO_2 footprint. "Although, space constraints are less important for onshore than for offshore converter stations, DC GIS remain an attractive option for specific cases with strict space constraints, high risk of lightning strikes, or installations at high altitude." [1]

Especially as a solution for long HVDC transmission lines, transition stations enable separation and safe earthing of each line section and can also include necessary measurement and analysis systems. Space-saving aspects usually correspond with the station's visual amenity. The actual achievable reduction may vary from station to station, depending on each particular project's boundary conditions and the whole station layout. Nevertheless, some examples, reported in [1], give an impression of the substantial space-saving possibilities of HVDC GIS applications: Only considering the primary equipment, footprint may be reduced by 90% for cable-cable transition stations.

Currently, many initiatives are developing concepts for multi-terminal offshore grids [4], [5]. These concepts include cable connected offshore HVDC switching stations and as such benefit from HVDC GIS implementation by reducing the required footprint.

CABLE CONNECTION ASSEMBLY AND ITS INTERFACES

The combination of cable systems and gas-insulated systems for HVAC application is standard in testing and operation since decades. The interface is described in IEC 62271-209 [6]. However, experience in development, testing and operation of such systems for HVDC application is limited. As reported in CIGRE TB 842 [2], there is a mismatch between the recommended test approaches for type testing and long-term testing of cable systems according to CIGRE TB 852 [7] and gas-insulated system according to CIGRE TB 842. The related technical challenges are currently assessed and evaluated in the ongoing CIGRE joint working group B1/B3/D1.79 "Recommendations for dielectric testing of HVDC gas insulated system cable sealing ends". Appropriate testing is the key to ensure reliability, not only for the single components but also for their combination operating in the overall system.

Since one of the main challenges in HVDC insulation systems is the understanding and control of the electric field especially at the interfaces, detailed evaluation and testing is required for the combination of cable and GIS systems. According to IEC 62271-209 [6], this combination is called 'cable connection assembly'. It consists of the 'cable connection enclosure' (clause 3.3 of [6], scope of GIS manufacturer), the 'main circuit end terminal' (clause 3.2 of [6], scope of GIS manufacturer) and the 'cable termination' (clause 3.1 of [6], scope of cable manufacturer).

The most obvious approach is to follow the well-known HVAC GIS standard IEC 62271-209 also for the HVDC cable connection assembly. IEC 62271-209 defines with the scope split between GIS and cable manufacturers also the two relevant interfaces: the interface at the main circuit end terminal and the interface at the flange of the enclosure (see Figure 1). Within the GIS scope, there are only metallic components (conductor with main circuit end terminal; cable connection enclosure). The connection to the cable manufacturerer's scope consists of standardized interfaces with, e.g. t_1 defining the center diameter for the four holes used for the connection from main circuit end terminal to cable termination.

The cable connection assembly presented within this paper is following the geometrical dimensions of a fluid-filled cable connection per IEC 62271-209 with rated voltage of 362 to 550 kV [6]. The components inside the most outer dashed line of Figure 1 is what has been considered in defining the test scope of the cable connection assembly presented in this paper.

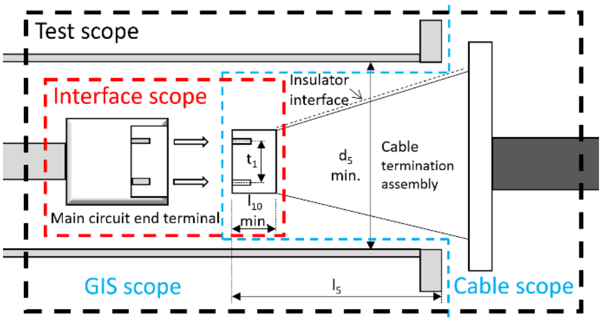

Figure 1: Components of a cable connection assembly and the scope of work separated with dashed lines

The conductor and connection parts on the GIS side, i.e. the main cirucit end terminal including a suitable conductor connection, are typically tested within the type test of the HVDC GIS. Similary, the cable top connection will most likely have been proven previously. Therefore, it is not necessary to consider an additional scope of testing for the connection points itself. However, for the main circuit end terminal and its shielding electrode, modifications may be required to control the electric field in the vicinity of the cable termination. This is since IEC 62271-209 only defines the distance from the top of the termination to the sealing surface of the enclosure, l_5, but not the main circuit end terminal dimensions nor the shape of its shielding electrode, neither does it consider the shape of the cable termination epoxy insulator. This is what has been defined as the interface scope and what would be required to be tested.

TESTING PHILOSOPHIES

Typically, all high-voltage components are qualified separately. The differences between the test philosophies are due to the differences in the core components, their insulating technology and the respective insulation materials.

Currently, there is no standard that addresses HVDC GIS cable connection assembly testing. Although, CIGRE JWG B1/B3/D1.79 is currently working on recommendations for dielectric testing of HVDC gas insulated system cable sealing ends. However, CIGRE TB 842 discusses an approach, where HVDC GIS testing might be covered by HVDC cable system testing. Hence, testing the cable connection assembly according to CIGRE TB 852 is followed within this joint collaboration. (NOTE: CIGRE TB 852 replaced its predecessor, CIGRE TB 496 [8], during the period of testing. The update did not affect the tests planned, the reference is therefore made to the latest recommendation in this paper.)

Testing of HVDC GIS

The type tests for HVDC GIS shall prove the dielectric performance of the equipment under both DC and AC electric field conditions. As the insulating system of GIS, consisting of cast-resin epoxy insulator and an insulating gas does not show any relevant ageing [8], it is not required to force ageing mechanisms during qualification of the equipment with increased voltage stresses. The focus for HVDC GIS testing is at the performance under transient voltage stresses superimposed to steady state under DC voltage conditions.

A selection of performed relevant dielectric and thermoelectric type tests for a ±550 kV HVDC GIS [3] is given in Table 1. The dielectric tests at zero load are testing the dielectric performance of the equipment at electrostatic field conditions. HVDC GIS are affected from a field transition process from initial electrostatic field distribution to electric flow field distribution under continuous DC voltage stress. The highest field strength in the gas-insulated system is different between AC and DC conditions. Therefore, it is necessary to test also the integrity of the insulation system under steady-state resistive conditions. For this reason, the so-called 'DC insulation system test' was introduced in CIGRE TB 842. The DC insulation system test is a thermoelectric test that proves the dielectric performance of the "loaded" DC field conditions under high load and superimposed transient voltage stress. After reaching a steady-state temperature gradient between conductor and enclosure corresponding to the rated current, the HVDC GIS shall be stressed with rated DC voltage followed by superimposed impulse voltage stress. The duration of DC pre-charging prior to superimposed impulse stress needs to be at least t_{90}. The duration t_{90} defines the time from initial electrostatic field distribution to at least 90% of steady-state resistive field distribution. It is dependent on the material parameters of the insulating materials as well as on the temperature distribution in the system and can last from hours to months.

Table 1: Selection of relevant dielectric and thermoelectric type tests for ±550 kV DC GIS

Dielectric tests acc. CIGRE TB 842 (*zero load* – without temperature gradient)	**Level**
DC withstand voltage test (1 min)	±825 kV DC
Composite voltage test DC and LI voltage with 2 h of DC pre-stress ±550 kV (15 impulses)	±550 kV DC & ±1550 kV LI (all 4 quadrants)
Composite voltage test DC and SI voltage with 2 h of DC pre-stress ±550 kV (15 impulses)	±550 kV DC & ±1175 kV SI (all 4 quadrants)
Insulation system test acc. CIGRE TB 842 (*high load* – with temperature gradient)	**Level**
Composite voltage test DC and LI voltage with >120 h [3] of DC pre-stress ±550 kV (3 impulses)	±550 kV DC & ±1550 kV LI (all 4 quadrants)
Composite voltage test DC and SI voltage with >120 h [3] of DC pre-stress ±550 kV (3 impulses)	±550 kV DC & ±1175 kV SI (all 4 quadrants)

Testing of HVDC cable system

Testing the HVDC cable connection assembly with geometrical dimensions according to IEC 62271-209 with elevated DC voltage followed by lightning and switching impulse tests was considered to be most effective for approving the interface scope. Hence, cable system type test was seen as the most appropriate approach.

However, to further confirm the HVDC GIS cable connection assembly could withstand also long-term electrically accelerated ageing, especially for the cable termination material combination, a cable system pre-qualification test was also included to be performed. This also guarantees reaching steady state during a test, for both warm and cold conditions.

The test regime for approval of cable system components is based on electricallly accelerated ageing tests in combination with thermo-mechanical stresses which shall represent 40 years life-time. There were mainly two tests of different duration which have been considered and are summarized in Table 2 with typical test voltage levels for a ±525 kV cable system stated for direct comparison. The pre-qualifcation test is focused on the general long-term performance on the materials of the cable system and will achieve steady state for the various load conditions. On the other hand, the type test is more focused on the specific configuration of a component to be installed and is additionally testing margins of accessory designs with the elevated voltage.

A notable difference to HVDC GIS test regime is that rest periods is allowed in-between load cycle blocks with different polarities, consisting of 24 hours of heating without voltage and grounding. Superimposed impulses are only applied at the end of the load cycle tests and the levels are selected from what the system could be subjected to in operation. However, before the impulse application, the test object shall be pre-stressed with rated DC voltage at the rated cable conductor maximum temperature for at least 10 hours.

Table 2: Selection of relevant cable system tests for ±525 kV DC (VSC)

Pre-qualification test acc. CIGRE TB 852	**Level**
160x24 h load cycles (4x40 blocks)	±762 kV
80x24 h high load (2x40 blocks)	±762 kV
120x24 h zero load	-762 kV
Superimposed Switching Impulse (SI),10 + 10, opposite polarity	±525 kV DC & ±630 kV SI
Superimposed Lightning Impulse (LI),10 + 10, opposite polarity. (if installed system exposed to lightning)	±525 kV DC & ±1102 kV LI
Type test acc. CIGRE TB 852	**Level**
12x24 h load cycles, negative polarity	-971 kV
12x24 h load cycles, positive polarity	+971 kV
3x48 h load cycles, positive polarity	+971 kV
DC voltage pre-stress before impulses are applied >10 h, warm conditions	±525 kV DC
Superimposed SI, 10 + 10, opposite polarity	±525 kV DC & ±630 kV SI
Superimposed SI, 10 + 10, same polarity	±525 kV DC & ±1102 kV SI
Superimposed LI 10 + 10, opposite polarity.	±525 kV DC & ±1102 kV LI

SUMMARY OF THE TEST RESULTS

Within the joint collaboration, a combined test setup consisting of a cable system and components of a gas-insulated system to form a cable connection assembly was used. The tests have been performed according to CIGRE TB 852 for VSC systems with a nominal voltage level of U_0 = ±525 kV.

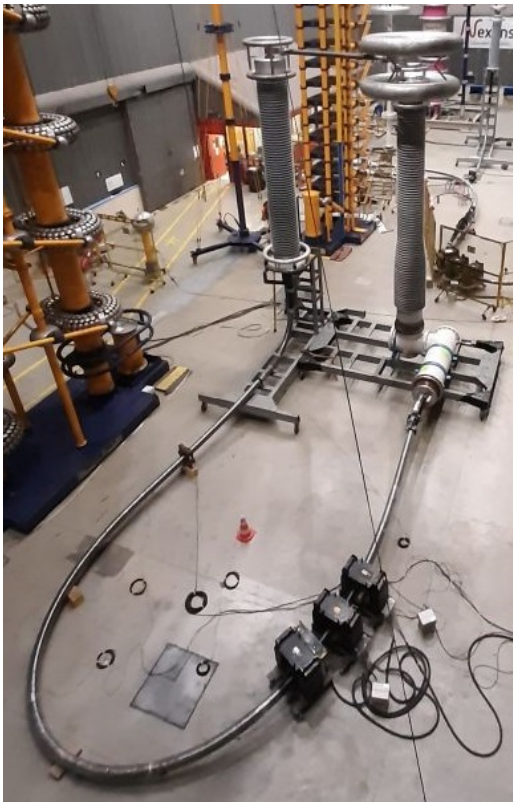

Figure 2: Cable connection assembly test setup for ±525 kV Type Test

Type test ±525 kV

The test loop for the type test with the HVDC cable connection assembly (Figure 2) installed on one end of 30 m ±525 kV cross-linked polyethylene (XLPE) cable with a 2500 mm^2 aluminum conductor. The gas-insulated HVDC cable termination was connected to the HVDC GIS with the cable connection enclosure and the main circuit end terminal. The HVDC GIS configuration was further utilizing a T-module and a gas/air-bushing without any DC GIS partition insulators. The gas pressure during the common type test procedure was equalling the minimal functional pressure of DC GIS components. On the other cable end, a ±525 kV AIS cable termination was used to close the loop. The conductor heating was realized with reverse-operated AC current transformers up to a level of 70 ºC. The test program according to CIGRE TB 852 is summarized in Table 3 and included rest periods between polarities as well as 10 hour DC voltage pre-stress with heating applied before impulse sequences. All tests were successfully passed [10].

Table 3: Type test program

	LC	LC	LC (48 h)	S/IMP	DC
Number of cycles or duration	12	12	3	n.a.	2 h
Test voltage	- U_T	+ U_T	+ U_T	$U_{P2,S}$, $U_{P2,O}$, U_{P1}	- U_T

U_T = 971 kV
$U_{P2,S}$ = 1102 kV
$U_{P2,O}$ = 630 kV
U_{P1} = 1102 kV

Pre-qualification test ±525 kV

The test loop for the pre-qualification test of the HVDC cable connection assembly (Figure 3) had a total length of 127 m with a ±525 kV XLPE cable with a 2500 mm^2 copper conductor. Two gas-insulated HVDC cable terminations were connected to the HVDC GIS with the cable connection enclosure and the main circuit end terminal. The HVDC GIS was presented in a back-to-back configuration without any DC GIS partition insulators. The gas pressure during the pre-qualification test procedure was equalling the minimal functional pressure of DC GIS components. A DC current generator was used for cable conductor heating up to a level of 80 ºC. After the long duration voltage test, the type test sqeuence for superimposed impulses was used. The full test sequence is summarized in Table 4. All tests were successfully passed [11].

Table 4: Pre-qualification test program

	LC	LC	HL	HL	ZL	LC	LC	S/IMP
Number of cycles	40	40	40	40	120	40	40	n.a.
Test voltage	+ U_{TP1}	- U_{TP1}	+ U_{TP1}	- U_{TP1}	- U_{TP1}	+ U_{TP1}	- U_{TP1}	$U_{P2,S}$, $U_{P2,O}$, U_{P1}

U_{TP1} = 762 kV
$U_{P2,S}$ = 1102 kV
$U_{P2,O}$ = 630 kV
U_{P1} = 1102 kV

Figure 3: Cable connection assembly test setup for ±525 kV PQ test

CONCLUSION

This publication presents the experiences of qualifying an ±525 kV HVDC cable connection assembly. The different test philosophies of HVDC GIS and HVDC cables are revealed and the performed tests described.

The HVDC cable connection assembly presented in this paper is based on the dimensions described in the HVAC standard for cable connection assemblies IEC 62271-209 for 362 to 550 kV fluid-filled cable terminations. To follow this well-known HVAC standard in terms of dimensions of the cable termination and scope-split was the most obvious approach for HVDC applications.

First investigations and recommendations on testing the interface between HVDC GIS and HVDC cables including the different test philosophies of the two assets were presented in CIGRE TB 842. It was concluded that testing as recommended in CIGRE TB 852 might also cover the recommendations given in CIGRE TB 842 for the example presented. Hence, testing the cable connection assembly according to CIGRE TB 852 was followed within this joint collaboration. However, CIGRE JWG B1/B3/D1.79 is currently working on recommendations for the dielectric testing of HVDC cable connection assemblies.

The HVDC GIS cable connection assembly presented in this publication has been successfully qualified with a type test and a pre-qualification test in accordance with the recommendations of CIGRE TB 852. All cycles, superimposed voltages and final tests/ checks were successfully passed. Hence, this publication presents the world's first full qualification of an ±525 kV HVDC cable connection assembly.

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GLOSSARY

AIS: Air-insulated switchgear
GIS: Gas-insulated switchgear
HVDC: High voltage direct current
TB: Technical brochure
VSC: Voltage source converter
XLPE: Cross-linked polyethylene