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Compact Gas-insulated Systems for High Voltage Direct Current Transmission: Design and Testing

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***Abstract*—New DC insulators for HVDC GIS were designed by geometrical optimization and insertion of a current collector. With additional marginal changes at interface components, and with the development of special current- and voltage transformers, it is possible to provide gas-insulated systems for HVDC. Type tests standards for gas-insulated systems specific for HVDC are not yet available today. Based on insulation co-ordination studies, test values were defined, which take all technical aspects into account. Based on the development and research results combined with the service experience new type test philosophy was developed. The manufacturer of HVDC GIS systems has already successfully concluded the component tests and the technology is now ready for its first pilot installations.**

***Index Terms*-- HVDC GIS, Gas-insulated Switchgear, Gas-insulated System, Dielectric Test, Insulation System Test**

I. Introduction

For the worldwide plans of vast integration of new renewables in the electrical energy supply, large expansion of electric power transmission is needed. Especially in the case of offshore wind farms, which are planned on a large scale, the connection to shore will be made by means of HVDC Light® (VSC – a HVDC system using voltage source converters) technology, with the offshore converter station mounted on platforms.

The increasing demand for HVDC technology requires the adaptation of gas insulated switchgear (GIS) or lines (GIL), which were originally developed for the AC grid. GIS are particularly relevant for applications where building volume or right-of-way are critical issues, e.g. for mega-city in-feed or densely populated areas in general.

II. Design

A. Insulator Base Design

Based on the research for material characterisation and the usage of multi-physics simulation tools the analysis of electrical field distribution is now possible with high precision, taking the following parameters into consideration: temperature and electrical field depended characteristics of the used insulating materials, accumulation of space- and surface charges and the superposition of DC and impulse voltages. For the new DC design, the improvement shown with a significant reduction of the dielectric stress was obtained by geometrical optimization and insertion of a current collector, compared to the AC design. The temperature gradient across the insulation considered for the simulation is equal to the worst case under service conditions and maximum continuous current.

B. Gas-insulated Sytem

With additional marginal changes at interface components, like cable termination, and with the development of special current- and voltage transformers, it is possible to use gas-insulated HVDC systems for both onshore and offshore applications in the near future [4]. Just as in AC power systems, the DC-GIS technology spans a number of switchgear components as shown in Figure 1, for example:

- Bus-ducts and high voltage DC conductors (A)
- Disconnect- and earthing switches (B)
- Bushings (C) and cable terminations (D)
- Current (E) - and voltage (F) transformer
- Surge arresters (G)

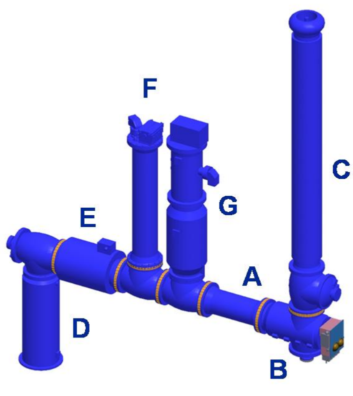

Figure 1 HVDC GIS components

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These components can be applied in various HVDC applications such as:

- DC pole equipment in HVDC converter stations including the DC switchyard.
- Gas-insulated transmission lines
- Cable to overhead line transition stations

Based on insulation co-ordination studies, test values were defined, which take all technical aspects into account. Tests of DC-GIS components have now confirmed the required performance for the ratings as shown in TABLE I. The DC gas-insulated system was presented for the first time in 2013 [3].

TABLE I. RATED VALUES FOR 320 KV / 350 KV HVDC GIS

Nominal DC voltage	± 320	kV_{dc}
Rated (maximum continuous operating) DC voltage	± 350	kV_{dc}
Rated lightning impulse withstand voltage	± 1050	kV
Rated superimposed lightning impulse withstand voltage Lightning impulse voltage DC voltage	 ± 1050 ± 350	 kV kV_{dc}
Rated switching impulse withstand voltage	± 950	kV
Rated superimposed switching impulse withstand voltage Switching impulse voltage DC voltage	 ± 950 ± 350	 kV kV_{dc}
Rated DC withstand voltage phase-to-earth	± 610	kV_{dc}

C. *Voltage Transformer*

For new gas-insulated HVDC systems, the primary DC voltage can be measured with RC-divider technology as in outdoor substations. For this reason, a new HVDC RC-divider, type *RGK320DC*, was developed and type tested [6]. The RC-divider was tested in combination with a complete sample HVDC GIS field. These tests should cover more realistic operating conditions to qualify all components used within a HVDC GIS field (Figure 2).

Figure 2 type test of the RC-divider

The RC-divider active part is placed within the GIS housing. The high-voltage connection to the GIS system is realized using a partition, which guaranties gas separation to the GIS system. The low-voltage side is hermetically sealed off with an end-plate on which the secondary terminal box, the gas valves and the gas-overpressure system are mounted (Figure 3).

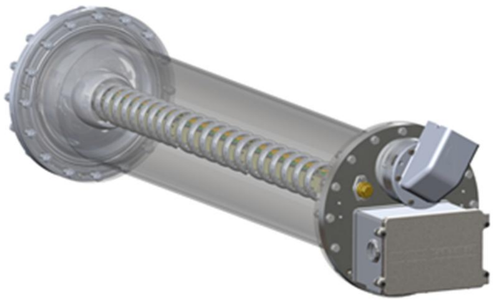

Figure 3 3D-design RC divider

The active part of the RC-divider consists of 4 single RC-units connected in series. Each unit is a combination of several single RC-elements, capacitance and resistance components connected in parallel, connected in series. The resistor part consists of several single resistors connected in series arranged in a meandering configuration. Because of the experience gained from outdoor HVDC applications as well as from the HVDC GIS system in Japan, appropriate tests were specified. The type tests performed on the test object, an *RGK320DC* HVDC divider, cover the service conditions expected. The manufacturer of the HVDC GIS RC-dividers has already successfully concluded all tests [7].

III. DIELECTRIC TESTING

Special type tests standards for gas-insulated HVDC systems are not yet available today. CIGRE SC D1 installed a new working group for a short time, which should give recommendations for testing of gas-insulated HVDC systems: *JWG D1/B3.57 Dielectric Testing of gas-insulated HVDC Systems*. In particular, standards for dielectric development tests and possible prequalification tests have to be developed, which take into account the special characteristics of DC applications.

All analyses and development testing prior to commencing the type tests were completed. The development work and analyses included the following:

Figure 4 Test arrangement for superimposed voltage tests

- An evaluation of the materials and processes employed (electrical resistivity assessments, breakdown tests and space / surface charge measurements).

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- An analysis of the electric stress distribution within the gas-insulated system for a range of typical installation and loading conditions.
- An assessment of the long-term stability (possibly involving factory experiments to assess the ageing effects of various parameters, e.g., electrical stress, temperature, environmental conditions etc.).
- An assessment of the sensitivity of the electric stress distribution to the expected variations in dimensions, material composition and process conditions.

Based on development and research results as well as on the service experience described above, the following dielectric type tests were performed:

- DC withstand voltage test (duration 2 hours)
- Lightning and switching impulse voltage test
- Superimposed lightning impulse voltage tests (bipolar and unipolar superposition) – see Figure 4
- Superimposed switching impulse voltage tests (bipolar and unipolar superposition) – see Figure 4
- Polarity reversal tests (required only for LCC[1] applications)

All dielectric tests were performed under High Load (HL) conditions. After a heating-up period, the maximum conductor temperature and maximum temperature drop across the insulation was reached and maintained for the rest of the dielectric HL test (see Figure 5). The duration of the heating-up period was determined during continuous current tests and is normally shorter than 8 hours. For heating-up, a DC current or an induced AC current could be used. The effect was already verified in previous continuous current tests and was considered during dielectric testing [5].

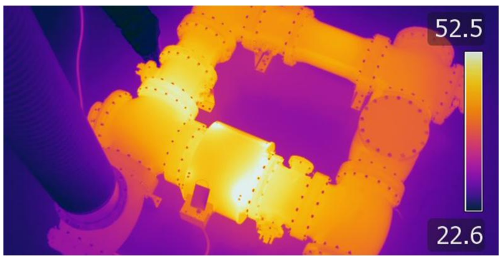

Figure 5 Thermal image of the test pole during HL test

Partial Discharge (PD) measurements were performed at maximum continuous operating DC voltage. Some typical defects like hopping particles can be more easily detected by using AC voltages. Therefore, an additional PD measurement with AC voltages was performed at Zero Load (ZL[2]).

When a DC voltage is applied, the low effective DC conductivity of the alumina-filled epoxy composite solid insulation determines the rate of transition from a capacitive to a resistive field distribution in the system. A resistive field distribution forms, while the capacitive field distribution relaxes on the time scale $\tau_m = \varepsilon_0 \varepsilon_r / \sigma$. For a DC conductivity σ = 10^{-14} to 10^{-17} S/m, the transition to a DC field distribution takes hours to months in the solid. Temperature gradients define primarily, via the temperature dependence of the DC conductivity, where field enhancement and space charge accumulation occurs in the solid, but also shapes the capture volume for ions in the vicinity of the solid-gas interface. Moreover, the surface field can reach its minimum or maximum value during the transition between voltage switch-on and DC steady state. This, associated to the variety of possible operation conditions requires long-term DC insulation system tests [2].

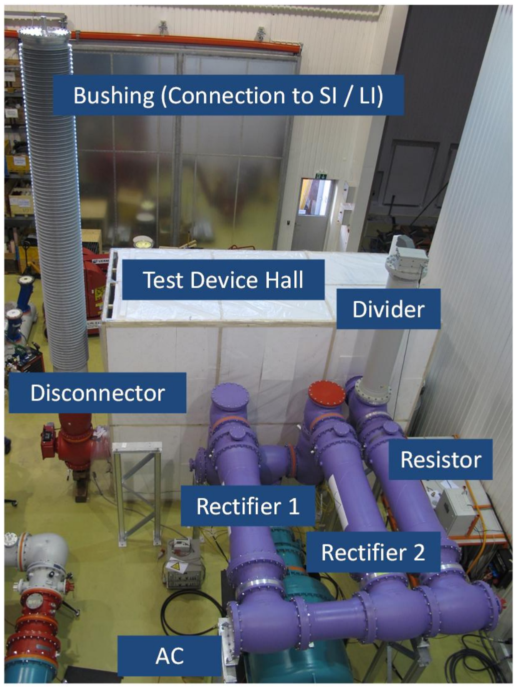

Figure 6 DC insulation system: test set-up

For the DC insulation system test, a new gas-insulated DC test generator was developed suitable for continuous DC voltage tests up to 500 kV (see Figure 6). Using an overhead connection to an impulse voltage generator, also superimposed voltage tests are possible.

The DC insulation system test was completed after the development tests had been carried out. The insulation system test needs only to be carried out once, unless there is a substantial change in the solid insulating system with respect to materials, manufacturing processes, construction, design parameters or requirements. The insulation system test is not intended to indicate the long-term performance of the complete gas-insulated system, because:

- The electrical lifetime at DC voltage stress of solid insulating material used for GIS/GIL is equal or even better compared to AC voltage stress [1].

[1] A HVDC system using Line Commutated Converters. LCC is a converter that has the feature of changing voltage polarity on the cable system when the direction of power flow is reversed IEC 60633.
[2] No heating is applied.

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- Experiences with AC GIS show that various parts of the insulation system that have been considered which are manufactured in sound condition according to the quality requirements do not reveal any ageing mechanisms which cause critical ageing.
- Additional mechanical stresses caused by load cycles similar to cables are of minor interest for GIS applications and are covered by thermal cycles performance tests of each insulator design according to IEC 62271-203 (6.106).

Figure 7 DC insulation system test: test device (partitions)

As DC insulation system test, more than 10 insulators assembled in realistic arrangements were tested (Figure 7). A dielectric routine test or preconditioning was considered before starting the insulation system test. The normal sequence of tests was as described in TABLE II.

TABLE II. SEQUENCE OF DC INSULATION SYSTEM TEST

Test	Conditions		
	Test Values	***Load***	***Remarks***
Pre-tests	Heating Dielectric Pretests		
Long duration continuous DC voltage test	Maximum continuous operating DC voltage (-)	HL	duration d_{DC}
Superimposed lightning impulse voltage tests (bipolar and unipolar superposition) Superimposed switching impulse voltage tests (bipolar and unipolar superposition)	Rated values	HL	
Polarity reversal		HL	
Long duration continuous DC voltage test	Maximum continuous operating DC voltage (+)	HL	duration d_{DC}
Superimposed lightning impulse voltage tests (bipolar and unipolar superposition) Superimposed switching impulse voltage tests (bipolar and unipolar superposition)	Rated values	HL	

The time duration d_{DC} of the long duration continuous DC voltage test depends on the transition time from capacitive to resistive field conditions and was calculated before starting the tests. The transition itself depends on the local temperature distribution and on the lowest temperature. Based on a full simulation of the dielectric strength on the insulator surface and the influence of the ambient temperature the test time duration d_{DC} was determined (see Figure 8). The time duration d_{DC} of 30 days was chosen to reach at least 90 % of the DC steady field at each location of the insulator surface. The time duration was reduced by increasing the ambient temperature to 40°C, realized by an additional housing around the test device and ventilation for homogeneous temperature distribution inside the housing.

The insulation system test was performed under high load conditions. After a heating period the maximum conductor temperature and maximum temperature drop across the insulation was achieved and maintained for the complete test duration. The induced AC current during the test was a little higher compared to the rated current of 4000 A and was adjusted during the test due to changing ambient temperature conditions to limit the conductor and enclosure temperature to the rated temperature limits. During the entire test partial discharges (UHF PD monitoring), temperature (ambient and test device), test current and test voltage were monitored and the measured data were recorded. The measured temperatures were compared to data obtained from calibration measurements from previous continuous current tests.

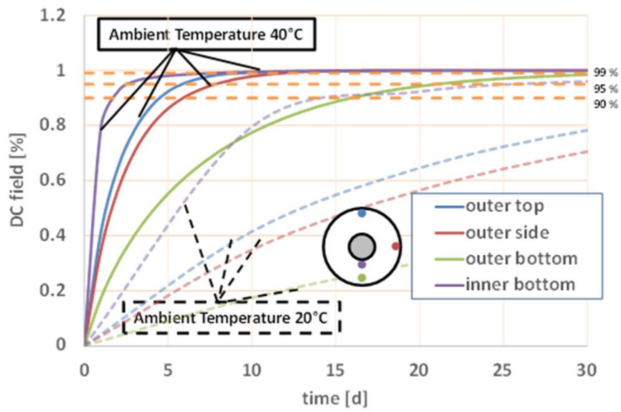

Figure 8 Transition time for the insulator, depending on the location and ambient temperature
Time duration d_{DC} defines the time to reach at least 90 % of the DC steady field

For gas-insulated systems the DC insulation system test is applicable for LCC and VSC systems. The manufacturer has already successfully finished the DC insulation system test for 320 kV/350 kV gas-insulated systems and the technology is ready for pilot installations.

IV. APPLICATION POSSIBILITIES

A HVDC GIS installation can be built with a much higher degree of compactness and significantly lower sensitivity to ambient factors than with air-insulated switchgear (AIS). The most obvious cost-saving potential can be found on offshore converter platforms. At present nine offshore HVDC links have been delivered or are under construction ranging from 400 MW to 900 MW, all in the German Bight. A converter station rated at 800-900 MW will connect three wind farms, which appears a reasonable size for operational and investment reasons. Such converter stations are at present challenging to handle during construction and installations phases. High dependence on weather conditions and supporting structures could be mitigated if the platforms size could be reduced. Such compactness would not only bring down the cost of the platform but also render additional cost savings due to flexibility during construction and installation.

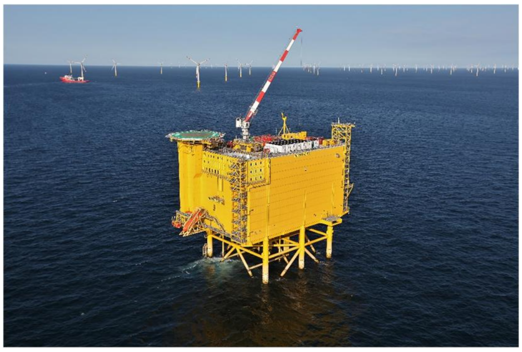

Figure 9 The DolWin1 grid connection can integrate 800 MW of offshore wind power around 75 kilometers off the German coast, enough to supply around one million households with clean energy

All AC connections to the platforms are already GIS, so the opportunity to use compact HVDC-GIS would be an immediate advantage in design of the platforms. Hence, long air-clearances at a DC voltage of ±320 kV for the AIS switchgear leads not only to much larger and heavier offshore structures, but also limits the design options. By using HVDC-GIS, the volumetric space of the switchgear installation itself can be drastically reduced e.g. by 70%- 90%, which may results in a size reduction of circa 10% of the total platform and a compact building block for planning of the offshore station layout. If future offshore grids would be considered with multiterminal or switching stations off-shore, the gain would be considerably larger.

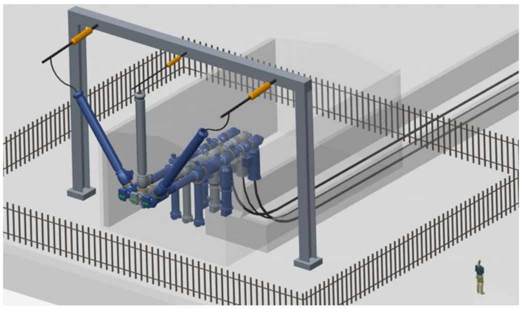

Figure 10 Gas-insulated cable to overhead line transition station

Following the successful installed offshore converter stations of today, exemplified by the Dolwin alfa offshore station in Figure 9, future designs are foreseen to achieve a size / weight reduction of at least 60% to make remote offshore wind more attractive. HVDC-GIS is one of the solutions to be implemented in future designs to achieve this target. In Germany alone, the ambitious energy transition roadmap, called “Energiewende”, foresees the generation of more than 6.5 gigawatts (GW) from offshore wind by 2020 and 15 GW by 2030. Onshore HVDC installations may also be reduced in land-size and building height by applying DC-GIS although these savings must be considered in the light of more costly switchgear components. On example for a cable to overhead line transition station is shown in Figure 10. Just as in AC-systems, the technology decision has to be done by case-by-case analysis considering the total life-cycle costs.

V. Conclusions

Specific type tests standards for gas-insulated systems specific for HVDC are not yet available today. Based on insulation co-ordination studies, test values were defined, which take all technical aspects into account. Based on the development and research results combined with the service experience new type test philosophy including insulation system tests were developed. ABB has already successfully finished the verification tests 320 kV/ 330 kV gas-insulated insulators and the technology is ready for its pilot installation. Once dimensioning guidelines have been established, development of higher voltage ratings will follow.

From the successful tests performed so far by ABB and reference installations, it can be expected that DC-GIS components will have equally long lifetime and minimal maintenance requirements as in AC-GIS. The sealed and compact HVDC-GIS installation would give gains both in required land area in switching stations between overhead lines and cables, and in onshore converter stations switchyards.

Acknowledgment

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