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

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***Abstract*—The design of insulating elements for HVAC GIS is optimized for a capacitive field distribution. An intrinsic difference between AC and DC is however that the DC conductivity of insulation materials is strongly temperature dependent, while their permittivity varies only weakly with temperature. As a consequence, the resistive field is enhanced where the DC conductivity is at its minimum, i.e. in cold regions of the insulation. Besides, the accumulation of space and surface charges have to be observed as well as the specific load at superposition of impulse voltages. Using of multi-physics simulation tools the analysis of temperature and electrical field distribution is now possible with high accuracy, taking the following parameters into consideration: temperature and electrical field dependent characteristics of the insulating materials, accumulation of space and surface charges and the superposition of DC and impulse voltages.**

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

I. INTRODUCTION

The dimensioning of a HVDC GIS requires the knowledge of electric field distributions, which depend on the conductivity of the gas and the solid, on the interface charging, and on the injection behavior of the contacts. First, DC conduction mechanisms are strongly sensitive to many parameters like temperature, field and processing conditions. Secondly, the solid-gas interface, i.e. the surface of the insulator, can be charged up. This is again a process with large variability due to effects like surface conductivity, trapping in surface states or presence of particles and surface roughness. Thirdly, the electrode contacts may play a crucial role in providing the charge carriers which govern the electric conduction.

Not only DC, but also transient fields must be predicted: i.e. during the transition between an initial capacitive distribution and the final resistive distribution, or after polarity reversal or impulses superimposed on DC fields. In these cases, additional contributions, e.g. polarization currents in the solid insulation, or surface charge accumulation from gas ions might play a significant role.

II. HISTORICAL REVIEW

GIS technology was introduced to the market in 1966 with the first 170 kV GIS underground substation delivered to the Zürich city center (see Figure 1). In 1976, ABB delivered the first 500 kV GIS to Claireville, Canada. With the installation of the first 800 kV GIS in South Africa in 1986, ABB has proven its technology leadership also at the ultra-high voltage (UHV) level. This so-called alpha substation has been in operation for more than 20 years without any failures or unplanned interruptions. The 500 kV GIS in Itaipu, Brazil was long time the world’s largest installation but is now overtaken by the ABB GIS inside the Three Gorges Dam in China.

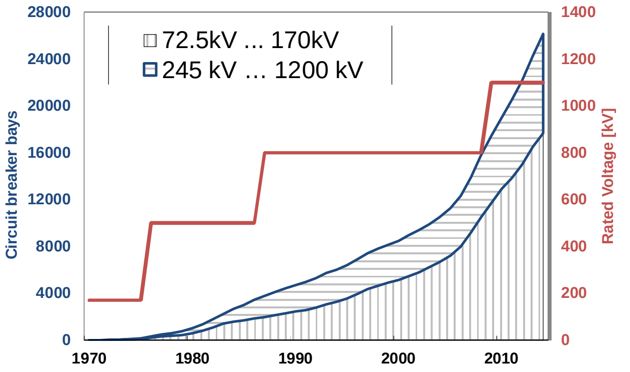

Figure 1 50 years ABB GIS milestones

The potential of gas-insulated systems for High Power DC (HiPoD) applications was recognized and studied in the 1960s following the first installation in 1983. But the commercial application of HVDC GIS was limited to only few applications (see Figure 2). The further use of gas-insulated systems was hampered by a tendency for the insulating materials to fail during polarity reversal tests. This was generally attributed to the presence of space charges trapped within the insulation. Today, the increasing demand for HVDC connections for both submarine and land applications was the reason to develop new HVDC gas-insulated systems.

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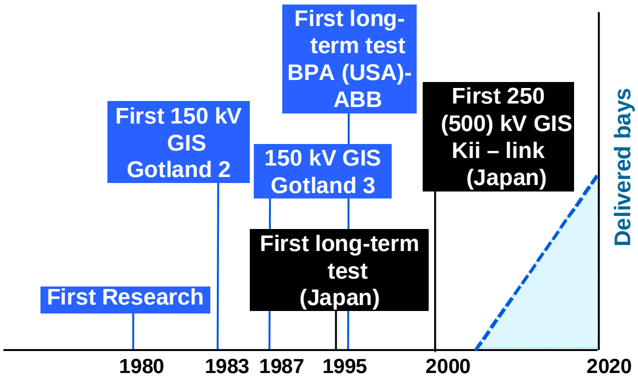

Figure 2 DC GIS milestones

The first commercial HVDC-GIS was installed in the year 2000 in Japan [1]. The ± 500 kV HVDC-GIS Anan Converter station of Shikoku Electric Power consists of disconnectors and one bus bar. Since commissioning the operating voltage is only ± 250 kV [2]. A DC busbar with superimposed DC voltage of ± 150 kV is in operation since 1983/1987 in Gotland (Sweden), gas insulated connections between the converter transformer and the valve hall as shown in Figure 3 [3]. In 1986 ABB and BPA have performed together a development of ± 500 kV HVDC-GIS. From 1990 until 1995, long-term tests at BPA's test centre were carried out [4]. The project involved energizing a test pole containing the elements of an SF_6 insulated station for duration of approximately 2 years. The elements of the test pole consisted of GIS spacers, SF_6 air bushings, air insulated arrester, SF_6 insulated arrester, and SF_6 oil bushing. The long term tests were successfully completed in 1996.

Figure 3 Gotland 2, Svenska Kraftnät, transformer to valve connection

Today, the increasing demand for HVDC connections for both offshore and onshore applications connected with cost reduction efforts, the goal to be more environmentally friendly is the reason to develop new HVDC gas-insulated systems. The high level of quality of the GIS technology provides security of supply and high availability of electricity.

III. ELECTRIC FIELD AT DC VOLTAGE STRESS

A. *Basic Considarations*

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. As long as the resistivity and permittivity are constant over the domain of interest, the electric fields in the transient (capacitive) and DC (resistive) limit are equal. However this situation is hypothetical. Already potential gradients in the direction of discontinuities of conductivities such as the interface between SF_6 and insulators result in surface charging of the insulator [5].

As GIS are currently optimized for AC application, it is useful to recall what governs field distribution in that case. At frequencies of 50 Hz or 60 Hz, polymer insulation materials behave as linear dielectrics, $\boldsymbol{D} = \varepsilon_0 \varepsilon_r \boldsymbol{E}$, and the Laplace equation $\boldsymbol{\nabla} \cdot (\varepsilon_0 \varepsilon_r \boldsymbol{\nabla} \phi) = 0$ governs the electric potential ϕ. Space charges are in most cases irrelevant, and charges are only present on metallic parts like the conductor or the enclosure: a capacitive field distribution is built in the system [6].

In DC applications however, current conservation implies that $\boldsymbol{\nabla} \cdot \boldsymbol{j} = \boldsymbol{\nabla} \cdot (\sigma \boldsymbol{E}) = 0$ for long times (steady state). After switching-on a DC voltage, an initially capacitive field distribution evolves into a resistive field distribution with a characteristic relaxation time $\tau_m = \varepsilon_0 \varepsilon_r / \sigma$ [7]. In the solid, for a DC conductivity $\sigma = 10^{-18}$ to 10^{-14} S/m, the transition to a DC field distribution takes hours to months. After that time, a space charge density $\rho = \varepsilon_0 \varepsilon_r \boldsymbol{E} \cdot \boldsymbol{\nabla} \ln \tau_m$ is present in the system [8]. A robust DC GIS design should therefore limit local fields during DC operating and test conditions, with their combinations of superimposed capacitive stress (switching and lightning impulses, both polarities), and this at all times during the transient [1].

B. *Physical Effects*

Interfaces are critical locations in the system: failure occurs in the gas, but is often mediated by charges accumulated on insulators: surface flashovers generally follow a short path of high electric field. In practice, this often means that the field component tangential to the insulating surface is critical.

The magnitude and sign of charge accumulation on the insulator depends on the difference between the normal components of electrical current from the gas and from the solid. In contrast to conduction in the solid, conduction in the gas is inherently non-linear. Already at low voltage levels, gas ions generated in the gas are rapidly removed from the gas volume, and, following field lines, contribute to charging of the gas-solid interfaces [5]. Therefore, the relative influence of gaseous insulation on the electrical field at the solid-gas interface depends on the voltage level, the system geometry, and the nature and magnitude of gas ion sources. While voltage-independent ion sources like natural ionization have a limited effect on DC GIS systems under HVDC operation conditions, additional local, voltage-dependent ion sources (e.g. by field electronic emission and following gas ionization from particles, electrode roughness or protrusions) may already lead to large currents if the inception field is locally exceeded.

Furthermore, many modifications might affect locally the properties of the epoxy composite gas/solid interface. Some of them are: chemical filler/epoxy segregation, corrosion by gaseous by-products, and change in humidity content. Interfaces are also sensitive to variations in production quality, such as differences in roughness, presence of surface defects, or unevenness (e.g. “scars” due to the casting process) of the epoxy insulator’s surface. All these parameters have a large influence on the robustness of the insulation, as seen by the large variability in measured surface charge patterns on insulators exposed to the same conditions. Further information are given in [9]-[12]. Figure 4 shows the relevant electrical effects in solid and gas insulation, and at their interfaces for the insulation design of a DC GIS, at first presented in [9] and later reproduced in [13].

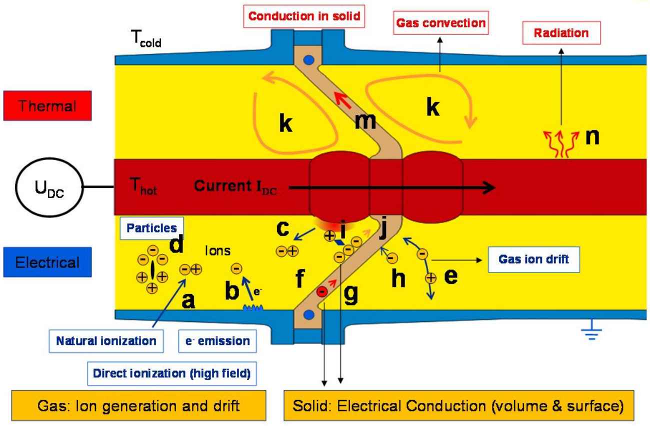

Figure 4 Physical effects in HVDC gas-solid insulation - important effects (and quantities) for the insulation design of a DC GIS

Electrical effects: **Solid insulation**: electronic and/or ionic conduction (*effective conductivity* σ), polarization (*permittivity* ε’), and space charge accumulation (*space charge density* ρ)

In gas insulation: Ions generation by (a) natural radiation, (b) field electron emission from electrodes, (c) direct ionization by high local field; (d) charged metallic particles, (e) ion drift

On interfaces/surfaces: (f) surface charge accumulation (*surface charge density* ρ_s), (g) surface conduction (*surface conductivity* σ_s), (h) charge transfer into solid, (i) charge recombination with gas ions, (j) injection/emission at electrode/solid insulation interface.

Thermal effects: heat generated by ohmic losses of the nominal current I_{DC} in the conductor is transferred to the ambient by (k) **gas** convection, (m) conduction through the **solid insulation** and (n) radiation, leading to a thermal gradient (T_{hot}-T_{cold}) across solid insulation.

C. Simulation

The simulation model takes into account all relevant charge transport processes in the gas as well as in the solid insulation. Because temperature gradients in the insulation have typically a large influence on the DC field distribution, heat fluxes from the hot conductor to the outer colder enclosure are taken into account. For both AC and DC cases, heat generation is dominated by ohmic losses of the current flowing in the conductor and contacts, and the knowledge of heat fluxes from the conductor to the metallic enclosure is essential to ensure that the temperature of the device remains within preset boundaries. An intrinsic difference between AC and DC is however that the DC conductivity of insulation materials is strongly temperature dependent, while their permittivity varies only weakly with temperature. As a consequence, the resistive field is enhanced where the DC conductivity is at its minimum, i.e. in cold regions of the insulation. For a concentric geometry with temperature gradient across the insulation like the GIS, this means the radial field distribution is changed during the capacitive-resistive transition [14]. A more detailed knowledge of the temperature gradient across the insulation is therefore needed for DC than for AC application, especially near interfaces and triple points. The temperature distributions could be determined by means of measurement, thermal networks and CFD. Figure 5 shows the simulation result of temperature distribution inside the gas-insulated busbar at a current of 4000 A. The results were verified by comparison with measurements and used as input for the dielectric simulation.

The required material parameters were obtained by separate material characterization measurements, as shown in [9]. The resulting fields and surface charges are validated with the help of dedicated experiments such as surface potential measurements [15]. The physical processes taken into account in the model include [9]:

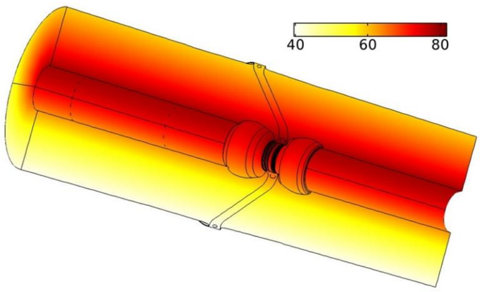

Figure 5 Temperature distribution [°C] inside the busbar at a current of 4000 A

- Solid insulation: polarization, temperature-dependent DC conduction, charge injection from metallic contacts, heat conduction, influence of charged particles and aging.
- Gaseous insulation: gas convection, ion pair generation and recombination, and ion drift along field lines toward insulation surfaces.
- Interface gas-solid: surface charge accumulation and transfer to solid.

D. *Results*

This field simulation helps to improve the design of solid insulation in DC gas-insulated components by reducing electric field in critical regions and minimizing local surface charging. The tool is used for the optimization of the GIS geometry and material properties of the insulators, and for the verification of design changes.

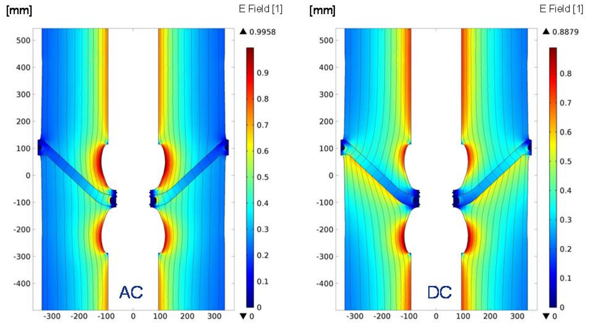

Figure 6 AC and DC field distribution at 330 kV: AC (left) and DC without ion drift (right)

The results from for a conical partition in a GIS arrangement is shown in Figure 6. Elliptical metallic electrodes are placed in the gas and into the insulator to shield the triple points and act as current collectors. Background gas conduction is 10^{-21} S/m, and the ion pair production rate from natural ionization $R_n = 29$ IP/(cm^{3}s), from [5]. To study the potential influence of additional ion sources, an IP production rate of 10 R_n is also considered. The nominal current in the conductor results in a 20 K temperature gradient across the insulator.

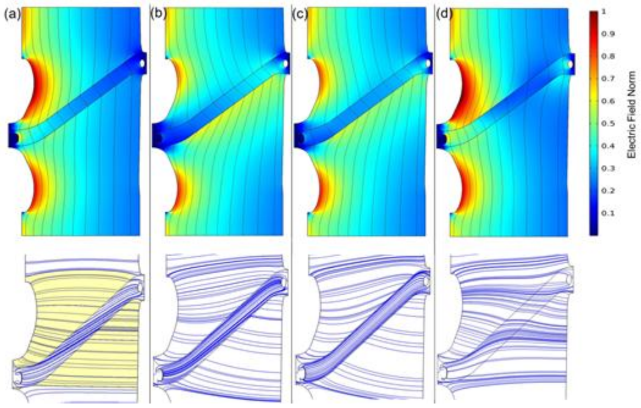

Figure 7 Field distribution and equipotential lines for a conical insulator; Bottom: Field lines (yellow filled area: ion capture volume) at 330 kV for (a) capacitive, (b) DC, 10^{-21} S/m residual gas conductivity, 0 IP/cm^3/s, (c) DC, 29 IP/cm^3/s (ions from natural ionization), (d) DC, 290 IP/cm^3/s (10x natural ionization). 20 K temperature gradient on insulator surface

The simulation is solved time-dependent with a voltage ramping phase ($t < 60$ s), followed by constant voltage until steady state (DC: $t = 10^8$ s). As an example, $U = 330$ kV was used. Distributions of the field amplitude and direction for various cases (capacitive and DC with increasing gas ion generation rates) are shown in Figure 7.

The capacitive field distribution (a) is governed by the permittivity, which is assumed to be temperature-independent. Shown in this figure is also the initial capture volume (in yellow) for the insulator surface. The DC field distribution in the absence of ion pair generation (b) is determined in the solid insulation -and on its surface- by the temperature-dependent DC conductivity. This moves equipotential lines towards the colder region of the insulator near the enclosure. The resistive field in (b) is also decreased on one side of the insulator (upper surface in Figure 7, gas side) and increased on the other side with respect to the capacitive field in (a). Additional gas conduction and surface charging due to gas ions from natural ionization (c) is slightly screening the field at surfaces, but does not change the DC field markedly at this voltage level. However, already an increase by a factor 10 of the IP generation rate (d) has a large effect on the field distribution.

E. *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 dependent characteristics of the used insulating materials, accumulation of space- and surface charges and the superposition of DC and impulse voltages. Hence, the comparison between capacitive and steady-state resistive electric field strength distribution (gas side) for the HVAC partition insulator (Figure 8) and the new developed HVDC partition insulator (Figure 9), shows lower dielectric stress on the DC-design and under DC with some minor drawback in the case of AC.

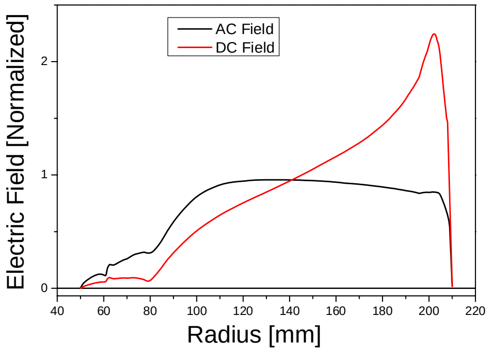

Figure 8 Comparison between capacitive and steady-state resistive electric field strength distribution (gas side) for the HVAC partition

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.

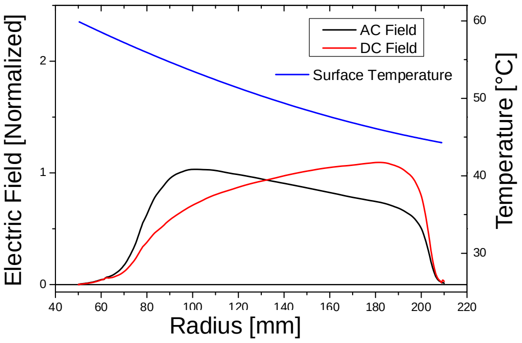

Figure 9 Comparison between capacitive and steady-state resistive electric field strength distribution (gas side) for the new HVDC partition

Other DC specific phenomena like the influence of particles on the dielectric behaviour or switching of bus-transfer currents are investigated more in detail by co-operation research partners [16]-[18].

IV. CONCLUSIONS

Using of multi-physics simulation tools the analysis of temperature and electrical field distribution is now possible with high accuracy, taking the following parameters into consideration: temperature and electrical field dependent characteristics of the used insulating materials, accumulation of space- and surface charges and the superposition of DC and impulse voltages. New DC insulators were designed by geometrical optimization and insertion of a current collector. With additional marginal changes at interface components, like cable termination, and with the development of special current- and voltage transformers, it is possible to provide gas-insulated HVDC systems for onshore and offshore applications.

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