Surface Charge Accumulation on HVDC-GIS-Spacer

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Abstract

The paper deals with the surface charge accumulation on spacers of Gas-Insulated Substations (GIS) applied to HVDC. The surface charge accumulation on solid insulators is a major problem of HVDC systems because it will distort the field distribution and reduce the breakdown voltage. The paper presents the mechanism and effects of surface charge accumulation on standard spacers used in GIS. A tool based on numerical field calculation has been developed to simulate and analyse the transient surface charging process and to gain the final steady state of a fully charged spacer. The numerical results are confirmed by measurements in a real GIS setup. Possible solutions to prevent surface charging are presented and discussed.

Introduction

For the development of a Gas-Insulated Substation (GIS) for HVDC different aspects have to be considered. The electric field distribution under DC stress is controlled by the conductivity κ of the insulation material. Since the field distribution for DC is different from that for AC, some components designed for AC GIS cannot be used for a DC GIS. But the main problem of HVDC GIS is the phenomena of surface charge accumulation on solid spacers in the system. This charge accumulation leads to field distortion and may reduce the breakdown voltage of the system.

Theory

Charges, released by different sources [3], are led to electrode or spacer surfaces by the electric force of the field. The initial field plays an important role in this charge accumulation process.
Investigations have shown that gas conduction by ions seems to be the dominant mechanism [1]-[4] for surface charge accumulation.

Ions move in the gas along the electric flux lines onto the surfaces. Figure 1 shows as an example a field line in a GIS which leads to the spacer of the system. The trapped charges move only along the spacer surface

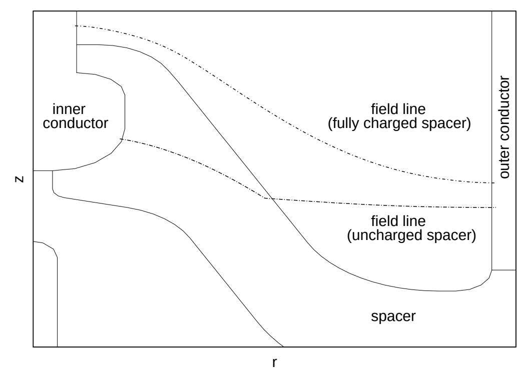

Figure 1: Field lines for an uncharged and fully charged spacer

if the surface conductivity provides adequate mobility. Hence a charge accumulation on spacer surface takes place, if the surface resistivity is too high. The accumulated charges will counteract the initial field at the spacer surface. The normal component E_{1n} of the electric field on the gas side is reduced, while the field E_{2n} on the spacer side is enhanced gradually until the steady state condition is reached [3]:

$$E_{1n}(i) = 0 \qquad (1)$$

The saturated charge density σ_{sat} can be calculated by the following boundary condition:

$$\varepsilon_1 E_{1n} - \varepsilon_2 E_{2n} = \sigma_{sat} \qquad (2)$$

where ε_1 is the permittivity of the SF_6 and ε_2 the permittivity of the spacer material. If the normal component of the electric field is zero, the spacer is fully charged and no field line will touch the spacer surface but sweep over it (Figure 1).

The charge distribution of a fully charged spacer is correlated to the profile of the initial normal field E_{1n}. The polarity of the accumulated charge is opposite to the polarity of E_{1n}. The resulting normal field in the gas caused by the accumulated charges equals E_{1n} in magnitude, but is opposite to E_{1n} in direction [3].

Investigations

To investigate the charging process a real GIS setup has been realized [3]. Figure 2 shows the setup with inner conductor, spacer and outer conductor. Centered between two edges a field sensor has been installed to measure the electric field strength at the outer conductor.
A long term test has shown that the charging process of standard spacers has not been finished after several hours [3]. Time periods of weeks are needed to get the final steady state condition of the surface charge accumulation. In order to reduce the necessary test period for the investigations and to take into account the effect of defects, the charging process has been accelerated by artificial edges at the external electrode which intensify the ion generation (Figure 2).

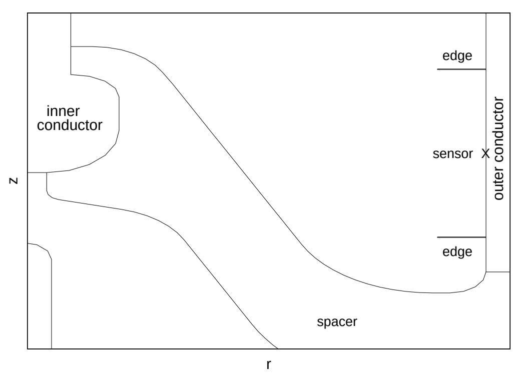

Figure 2: Simulation model of the test setup with installed edges

In addition to the experimental investigations numerical field calculations based on the Boundary-Element-Method (BEM) including surface resistivity, accumulated charges on dielectric boundaries and fully charged dielectric boundaries have been made [3].

Simulation tool

The final steady state field distribution of a fully charged spacer can be calculated with the additional boundary condition $E_{1n} = 0$ [3]. However, the situation during the charging process is different and may be even worse. Therefore a numerical tool has been developed, that can simulate the transient charging mechanism in order to investigate the field distribution on the spacer during this process.
The following calculation scheme explains the principal procedure of the simulation tool:

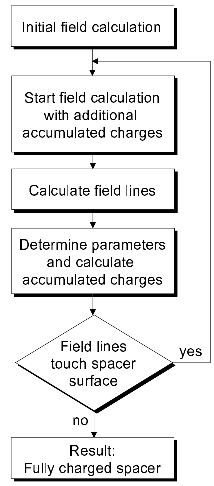

Figure 3: Principal scheme to simulate the transient charging process

The negative SF_6-ions move along the field lines to the spacer surface. All the field lines, which are starting from both edges, are conduction paths in the gas. To calculate the value of the accumulated charge at each contour point, the following parameters have to be determined:

- The number of the contour point where the field line touches the spacer.
- The length l of the fieldline from the edge to the spacer surface.
- The mean field strength E_{mean} of the field line between the edge and the spacer surface.

The single steps of the calculation have been carried out for a defined time interval Δt. The time t_{ion}, which a negative SF_6-ion needs to move from the edge to the spacer surface is defined as

$$t_{ion} = \frac{l}{v_e} = \frac{l}{b \cdot E_{mean}} \quad (3)$$

where v_e is the mean directed drift velocity, b is the mobility of the SF_6-ion and E_{mean} the mean field strength on the field line.

Therefore the accumulated charge q_{acc}, in the time interval Δt, can be calculated for every field line:

$$q_{acc} = \frac{\Delta t}{t_{ion}} \cdot q_{const} \quad (4)$$

q_{const} is a constant, that defines a charge value, which depends on the discharge current of the used defects. This constant has been determined by a parameter study. Combining (3) and (4), the accumulated charge q_{acc} for every field line can be written as:

$$q_{acc} = \frac{\Delta t \cdot b \cdot E_{mean}}{l} \cdot q_{const} \quad (5)$$

Finally, the results of all field lines have to be summed up and the accumulated charge of every contour point on the spacer is defined for the next calculation step. The value of the accumulated charge is added to the value of the last calculation step. Then the next field calculation will be carried out. The simulation stops, when no field line is touching the spacer any more.

Charging process

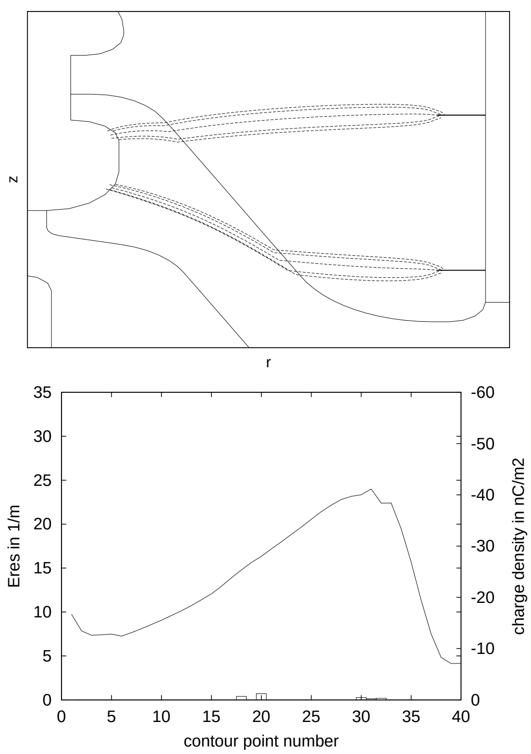

Figure 4: Initial field lines, field and charge distribution for the spacer

At the beginning of the charging process, the field distribution for a standard spacer is gained (Figure 4, starting with contour point 0 at the outer conductor and contour point 40 ending at the high voltage electrode). The field lines of each edge are leading close together to the spacer surface. Only two very narrow areas of the spacer surface will be charged initially. The charges for the next step will be put on the contour points 18, 20 and 30 - 32.
The next presented step of the simulation is the field distribution after 53 hours. This is the end of the experimental test (Figure 8). The field distribution has

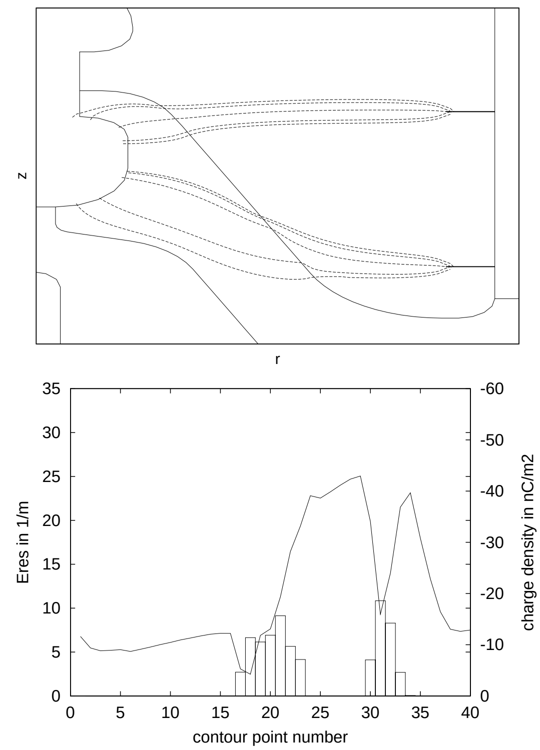

Figure 5: Results of the charging process after 53 hours

changed (Figure 5). The maximum value is already increased and the areas where the charges are accumulated have considerably reduced field strengths. The field lines are more widely spread over the spacer surface. This indicates that the charging area on the spacer is extended as proven by the charge density distribution. After 53 hours, the areas of contour points 17 - 23 and 30 - 34 have been charged.

An intermediate stage with the highest field strength occurs after 315 hours (Figure 6). A maximum resultant field of nearly 35 1/m will be reached at contour point 29. Furthermore, the part of the spacer adjacent to the high voltage electrode is already fully charged and no field lines are touching the spacer in this area any more.

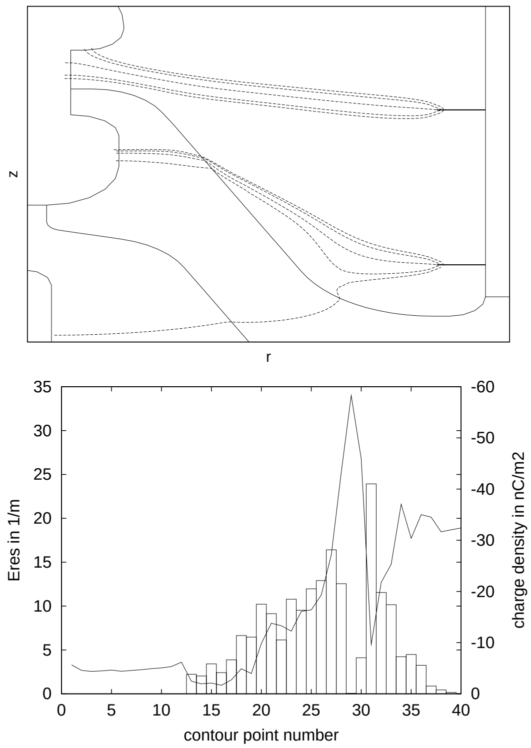

Figure 6: Results of the charging process after 315 hours, when the highest field strength on the spacer is reached

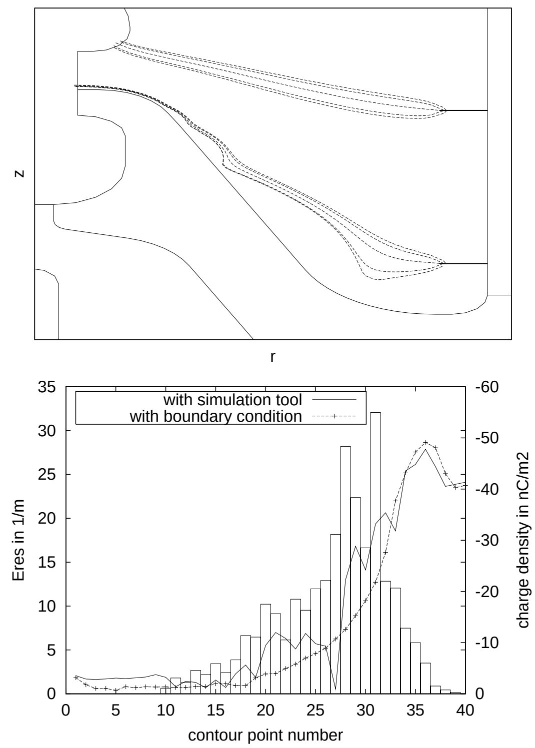

Figure 7: Results for the fully charged spacer, which is reached after 838 hours

Finally, the results for the fully charged spacer are presented. The charging process is finished in the simulation after 838 hours. No field line touches the spacer surface any more. All charges from the edges move to the high voltage electrode. Figure 7 shows the resultant field distribution on the spacer, calculated with the simulation tool and the boundary condition $E_{1n} = 0$. Both curves are in good agreement. The field distribution has completely changed. The maximum value of the field strength is considerably increased. But the decisive fact is that the region of the spacer adjacent to the high voltage electrode, will be extremely stressed. Such a field distribution permits only a poor utilization or leads to surface flashover in the GIS.

The distribution of accumulated charges on the spacer shows that some parts of the spacer have not been charged at all: the area adjacent to the grounded side of the spacer and a minor part adjacent to the high voltage electrode. The initial normal field at these regions of the spacer is very low and prevents from the beginning a charging.

Figure 8 shows the simulated transient development

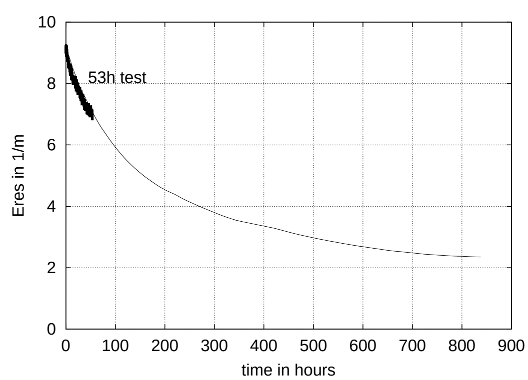

Figure 8: Comparison between measured and simulated field strength at the outer conductor

of the field strength at the position of the sensor at the outer conductor. The figure includes the results of the 53 hours test. The curve proves that a final steady state for the sensor field is reached at a value of about 2.3 1/m which is exactly the same value that can be calculated with the boundary condition $E_{1n} = 0$ for a fully charged spacer [3]. This indicates that the simulation results correspond with the theory of the charging process and the measuring results.

Methods to prevent surface charge accumulation

As mentioned before, the charges move in the gas onto the surface of the spacer. If there is an adequate surface conductivity, the surface charge will be restricted by the discharge towards the electrodes.

By using a spacer with a conductive surface coating with a surface resistivity in the range of $\rho_{sur} = 10^{11} - 10^{12}\,\Omega$ the current density on the spacer surface $j_{sur} = \kappa E_{tan}$ is very high in comparison to the discharge current of possible defects in the system. With such a high surface current density due to surface coating the current at the edges in the range of some nA can be neglected.

$$j_{sur} \gg j_{edges}$$

Therefore at any point of the spacer the surface current density will not be influenced by the current of the edges and the performance in service of the system will not be influenced by the edges. A high resistance surface coating has been found, investigated and applied in a DC GIS test system [3]. The results have shown that this is a promising method to realize a compact insulation system for DC GIS.

Conclusions

The mechanism and effects of surface charge accumulation on HVDC-GIS-Spacer have been presented. A software tool has been developed to simulate the charging process of a standard, uncoated spacer. The field distribution on the spacer during the charging process can be investigated with this tool.

- The real transient charging process can be simulated appropriately.
- The field distribution of a fully charged spacer can also be calculated with the boundary condition $E_{1n} = 0$. The results of the simulation tool correspond with this calculation.
- The simulation tool enables to investigate the behavior of the spacer during the charging process. The highly stressed parts of the spacer can be identified with this tool.
- The highest field strength on the spacer will occur in an intermediate stage during the charging process.
- A sufficiently conductive surface coating prevents a surface charge accumulation. This is a promising measure to realize a DC GIS.

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