Effect of Insulator Bulk Conductivity Non-uniformity on Surface Charge Accumulation

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Abstract. In order to clarify the effect of insulator bulk conductivity non-uniformity, controlled by electric field, on surface charge accumulation under dc high voltage, a simulation model involving multi-physics, which includes transition from initial capacitive to stationary resistive field, is established. In terms of this, the characters of surface charge accumulation are obtained. It is found that non-uniformity of electric conductivity contributes to the change of surface charge distribution profile, but not to the increase of the maximum surface charge density when the applied voltage is less than 1000 kV. After voltage exceeds 1000 kV, the maximum charge density becomes smaller compared to the case with uniform conductivity. The results indicate that electric conductivity non-uniformity relating to electric field is a source contributing to surface charge accumulation through insulator bulk, and should not be neglected.

1. Introduction
Due to the advantages of compact size, high reliability and little maintenance, gas insulated switchgear (GIS) has been widely used in ac transmission system, and is attracting more and more attention from dc one. For the latter case, surface charge accumulation at the interface between cone-type insulator and SF6 is more serious, which is attributed to the following reasons: on one hand, because voltage polarity keeps unchanged, surface charges generated by partial discharges need a long time to dissipate [1]; on the other hand, electric field under dc voltage is determined by electric conductivity, but at the instant of voltage application, it depends on dielectric permittivity, and surface charge accumulation inevitably takes place during the transition from initial capacitive to stationary resistive field distribution [2]. Because surface charge accumulation leads to the decrease of insulator surface flashover performance [3], the application of dc GIS is restricted. Therefore, it is necessary to clarify the accumulation mechanism.

At present, three mechanisms about surface charge accumulation have been proposed, i.e. electric conduction along insulator surface, electric conduction within gas volume and electric conduction through insulator bulk. The first one depends on the environment humidity, and it can be neglected in the dry gas [4]. Focusing on the second one, ionic flow model, instead of constant conductivity, is used to describe gas conduction recently. Based on it, surface charge accumulation owing to electric conduction within gas volume could be precisely calculated. As for the third one, charges result from dielectric non-uniformity and then drift to insulator surface. Microscopically, the accumulation processes are closely related to charge transportation, which is described by a macroscopic parameter, electric conductivity.

As we all know, electronic conduction dominates the electric conduction of the insulator which is
made of epoxy resin in the operation of GIS. And several theories have been established to clarify it, such as hopping theory, space charge limited current (SCLC) and Poole-Frenkel effect. Correspondingly, different expressions about electric conductivity can be obtained, in which the dependence of electric conductivity on temperature and electric field is nonlinear [5-6]. However, when the effect of electric conductivity on surface charge accumulation was studied, electric conductivity of epoxy resin was usually assumed to be a constant [7]. In fact, this is satisfied when electric filed is about at 0~7 MV/m, but an exponential relationship between field and conductivity appears when the field is beyond this range [7], which is common in an ultra HVDC circumstance. In this case, the character of surface charge accumulation would change.

In this paper, a simulation model involving multi-physics, which includes heat conduction in solid and transition from initial capacitive to stationary resistive field, is established. In terms of this, the effect of conductivity non-uniformity controlled by electric field on surface charge accumulation is studied.

2. Simulation Model

2.1. Physical model

A geometric model with coaxial electrode arrangement, including simplified insulator made of epoxy resin and SF$_6$, is employed, as Figure 1. The inner and outer radius of axisymmetric model is 90 mm and 200 mm, respectively. The width of the insulator is 20 mm, and its height is 100 mm.

![Figure 1. Electrode configuration for simulation model](image)

In order to study the effect of conductivity non-uniformity, controlled by electric filed, on surface charge accumulation, a simulation model involving multi-physics, which includes transient electric field in solid, is established. On the one hand, when dc voltage is applied, surface charge accumulation depends on the transition from the initial capacitive to the stationary resistive field distribution, which can be described by the following equations:

$$
-\nabla (\sigma \nabla \phi) = \frac{\partial (\nabla \cdot \epsilon \nabla \phi)}{\partial t}
$$

(1)
\[
\frac{\partial \sigma}{\partial t} = \gamma_i E_{in} - \gamma_g E_{gn}
\]

where \(\gamma\) indicates bulk conductivity, \(\phi\) is electric potential, \(\varepsilon_0\), \(\varepsilon_r\) represent vacuum permittivity and relative permittivity, respectively, \(t\) is time, \(\sigma\) indicates surface charge density, \(E_n\) is normal component of electric field at the interface, \(i\) and \(g\) represent insulator and gas, respectively. High voltage is applied to the inner conductor, and the outer conductor is grounded.

The above parameters of SF6 and epoxy resin are listed in Table 1. Except for solid electric conductivity, the other parameters are assumed to be constant. It should be noted that the relative humidity of SF6 in our model is assumed to be zero, so electric conduction along insulator surface can be neglected. Besides, gas constant conductivity, instead of complex ionic flow model, is employed so that the simulation model could be simplified. And this simplification has no effect on electric conduction through insulator bulk.

| Parameter | SF6 | Epoxy resin | unit |
|-----------|-----|-------------|------|
| \(\varepsilon_r\) | 1  | 5           | -    |
| \(\gamma\) | \(1 \times 10^{-16}\) | see section 2.2 | S/m |

**2.2. Electric conductivity of epoxy resin**

Lots of researchers have measured electric conductivity of epoxy resin [5-6], yet the results vary a lot due to the differences of test condition and sample. The results from Evgeni Volpov are widely accepted (as Figure 2), but nonlinear dependence of electric conductivity on electric field is usually neglected [7, 8]. In this section, a group of piecewise functions are employed to fit Evgeni Volpov’s results [7]. When electric filed is below 5.76 kV/mm and higher than 10.25 kV/mm, electric conductivity is \(1.34 \times 10^{-14}\) S/m and \(7.72 \times 10^{-13}\) S/m, respectively. Apart from this, it satisfies the following formula:

\[
\gamma_E = 7.454 \times 10^{-17} e^{0.9019E}
\]

where \(E\) is in kV/mm. As for the effect of temperature on electric conductivity, an exponential relationship between them has been widely used [5], as follows:

\[
\gamma_T = A e^{B(T-273.15)} \gamma_E
\]

where \(B\) is set to be 0.1 K\(^{-1}\), \(T\) is in K. From the results in Figure 2, \(A\) can be calculated and equals to 0.0907. Because of nonlinear dependence of conductivity on electric field, equation (1) is actually a nonlinear one. We use PDE module of COMSOL to solve it.

Figure 2. Electric conductivity of epoxy resin at 24 °C
2.3. Confirmation of simulation model validity

In order to confirm the validity of simulation model, a popular type of electrode configuration is tested (as Figure 3a). Compared with curve 4 in Fig. 1 from paper [9], identical distribution of surface charges are obtained when $\gamma_i$ and $\gamma_g$ are set to be $10^{-14}$ S/m and $10^{-16}$ S/m (as Figure 3b).

3. Results

Different levels of voltage, e.g. 300 kV, 500 kV, 800 kV, 1000 kV, are applied to the inner conductor so that the effect of insulator bulk conductivity non-uniformity controlled by electric field on surface charge accumulation can be studied. Figure 4 shows electric conductivity of insulator at the instant of voltage application when temperature is 24 °C. When the potential of inner conductor is 300 kV, the electric field within the insulator bulk is below 5.76 kV/mm, and hence electric conductivity is uniform and equals to $1.34 \times 10^{-14}$ S/m. After voltage increases to 500 kV, electric field at the area near the inner conductor is between 5.76 kV/mm and 10.25 kV/mm, and electric conductivity exceeds $1.34 \times 10^{-14}$ S/m. As voltage becomes higher, electric field at the area can exceed 10.25 kV/mm, and electric conductivity reaches the saturation value with $7.72 \times 10^{-13}$ S/m. Because of the variation of electric field during the transient process, the conductivity correspondingly changes.

Figure 5 shows surface charge distribution at stationary state under different levels of voltage when temperature is 24 °C. When the potential of inner conductor is 300 kV, the profile of charge distribution on the upper surface is plateau-like, while two peak points of charge density appear on the lower surface of the insulator. The distinct profiles are attributed to the difference of electric field distribution between two surfaces [8]. After voltage increases to 500 kV, charge distribution profile on both surfaces keeps unchanged except for the area near the inner conductor. As voltage further increases, surface charge distribution profile changes significantly. When applied voltage is 300 kV, 500 kV, 800 kV and 1000 kV, the maximum charge density is 37.0 μC/m², 61.6 μC/m², 98.9 μC/m².
and 116.9 μC/m² on the lower surface, and -21.4 μC/m², -35.8 μC/m², -57.7 μC/m² and -64.7 μC/m² on the upper surface, respectively.

In order to clarify the effect of conductivity non-uniformity on surface charge accumulation, surface charge distribution under different levels of voltage is calculated when electric conductivity is set to be 1.34×10⁻¹⁴ S/m (corresponding to the case in Figure 4a) and keeps unchanged with electric field, as Figure 6. It is found that the maximum charge density is 37.0 μC/m², 61.6 μC/m², 98.5 μC/m² and 123.2 μC/m² on the lower surface at different levels of voltage, and the maximum value on the upper surface is -21.4 μC/m², -35.8 μC/m², -57.3 μC/m² and -71.2 μC/m², respectively. Compared with the results in Figure 5, the maximum surface charge density is almost identical except for the case with the voltage application of 1000 kV.

Figure 5. Surface charge distribution under different levels of voltage at 24 °C

Figure 6. Surface charge distribution with electric conductivity as 1.34×10⁻¹⁴ S/m
4. Discussion

Non-uniformity of electric conductivity is considered as a source contributing to the generation of space charges, which can be expressed as

\[ \rho = -\varepsilon_0 \varepsilon_r \nabla \gamma_i \]  

(5)

where \( \rho \) is space charge density, \( \varepsilon_0 \) indicates relative permittivity of insulator, \( E_i \) represents electric field within the insulator. The space charges within insulator bulk drift with the help of electric field, and accumulate at the interface between solid and gas. In detail, electric conductivity non-uniformity results from its nonlinear dependence on electric field, which can contribute to surface charge accumulation.

On the other hand, when applied voltage is below 1000 kV, conductivity non-uniformity caused by electric field only contribute to the change of surface charge distribution profile, but not to increase of the maximum surface charge density which results from the increase of voltage amplitude. After voltage exceeds 1000 kV, the maximum charge density becomes smaller compared to the case of uniform conductivity. It means that neglect of conductivity non-uniformity controlled by electric field may lead to overestimation of surface charge density.

5. Conclusion

In this paper, the effect of electric conductivity non-uniformity controlled by electric field on surface charge accumulation is studied by simulation. It is found that non-uniformity of electric conductivity contributes to the change of surface charge distribution profile, but not to increase of the maximum surface charge density when applied voltage is less than 1000 kV. After voltage exceeds 1000 kV, the maximum charge density becomes smaller compared to the case with uniform conductivity.

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