

Article

Impact of Pressure and Temperature on Charge Accumulation Characteristics of Insulators in Direct-Current Gas-Insulated Switchgear

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Abstract: Direct-current gas-insulated switchgear (DC GIS) is an important device for promoting the lightweight and compact design of offshore wind power platforms. Gas pressure and temperature gradients are crucial factors that must be considered during the design process of the DC GIS. In this study, the multi-physics coupling model of basin insulators considering surface charge accumulation was established, and the corresponding real-sized insulator surface charge measurement platform was constructed. The effects of gas pressure and temperature gradient on the surface charge accumulation characteristics were investigated, respectively. The results show that the effect of gas pressure on the surface charge distribution characteristics depends on the dominant mode of surface charge. When volume conduction is dominant, the effect of gas pressure on the surface charge is negligible. However, when gas conduction is dominant, the accumulation of a uniform charge pattern on the insulator surface increases with the rise in gas pressure. Furthermore, due to gas convection, the temperature of the upper part of the DC GIS is significantly higher than that of the lower part, which leads to a temperature difference between the upper and lower surfaces of the insulator. The charge density on the insulator upper surface near the central conductor rises with the increase in load current.

Keywords: DC GIS; gas pressure; temperature gradient; surface charge accumulation



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1. Introduction

According to the European Wind Energy Association, offshore wind capacity could reach 150 GW by 2030, meeting 14% of the EU's total energy demand [1]. The development of flexible DC transmission technology has made it feasible to connect deep and distant offshore wind power to the grid. DC GIS has the advantages of a large transmission capacity, high reliability, low impact from external environments, etc. In particular, its volume can be reduced by 70–95% compared with air-insulated DC equipment, and the volume of the corresponding offshore converter platform can be reduced by up to 10%. Therefore, ensuring the reliability of DC GIS is significant for the advancement of clean energy from offshore wind power.

Under DC voltage, due to the long-term application of the unipolar electric field, the charged particles in the SF₆ and the carriers in the insulating material are gradually transferred to the gas–solid interface along the field lines, leading to a significant interfacial charge accumulation phenomenon occurring on the surface of the insulator in the GIS, triggering the electric field distortion of the gas–solid interface, which is prone to inducing the flashover of the insulators along the surface [2,3]. Nowadays, it is widely accepted that the charge distribution at the gas–solid interface is decided by volume conductivity, gas

conductivity, and surface conductivity [4–6]. The ion mobility that varies with gas pressure will significantly affect the dark current of the gas side [7–9], thereby the investigation of the effect of gas pressure on charge distribution on the gas–solid interface is important for the design of DC GIS. Zavattoni et al. [10,11] measured the dark current with a parallel electrode system and found that the dark current increased with gas pressure. However, the effect of gas pressure on the insulator’s surface charge distribution is seldom reported.

Moreover, for the operation process of DC GIS, a temperature gradient inevitably occurs due to the Joule heating from the central conductor [12]. By affecting the gas conductivity and volume conductivity of insulators [13], the charge distribution under the temperature gradient is distorted, which has been the vital factor that threatens the reliability of insulation performance. Zhou et al. [14] found that the average surface potential increased by 277% and its variation increased by 309% when the temperature of the conductor increased from 303.2 K to 343.0 K. Zhang et al. [13] compared the simulation and experimental results of charge distribution under a temperature gradient, and they proposed that the measured charge density near the high voltage electrode increases due to the increases in volume conductivity of the insulator. Luo et al. [15] and Du et al. [16] investigated the effect of temperature on the surface charge of conical and tri-post insulators, considering gas convection, respectively. Thus, the temperature gradient must be considered during the design of the DC insulator.

In this paper, firstly, a multi-physics simulation model of ± 550 kV GIS insulator was established, and a real-sized charge measurement platform of ± 550 kV insulator was built. Then, the effect of the gas pressure on charge distribution was simulated, and the obtained rules were verified by experiments. Additionally, the temperature gradient and charge distribution under various load currents were calculated. The findings in this paper can provide a reference for the DC GIS design.

2. Simulation Model and Experimental Design

2.1. Geometry Models

Figure 1 shows the geometry of the insulator adopted. It is from a ± 550 kV SF₆-filled DC-GIS. It consists of a central HV conductor, a basin-type insulator, and a ground enclosure. The finite element simulation model was implemented in COMSOL Multiphysics.

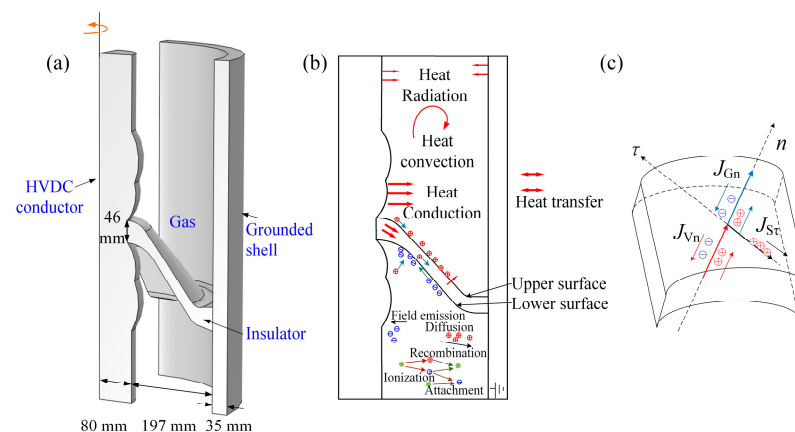


Figure 1. Simulation model. (a) The geometry of the DC insulator. (b) Schematic plot of electric field and thermal field. (c) Mechanism of surface charge accumulation.

2.2. Simulation Model of Charge Distribution

It is clearly shown in Figure 1 that the charge accumulation characteristics at gas–solid interfaces are attributed to the normal component of volume current density J_{Vn} , the normal

component of gas current density J_{Gn} , and the tangential component of surface current density J_S . Thus, the surface charge density σ_s was defined in (1) [4,5].

$$\frac{\partial \sigma_s}{\partial t} = J_{Vn} - J_{Gn} - \nabla \cdot (\gamma_s \cdot E_\tau) \quad (1)$$

where γ_s is surface conductivity and E_τ is the tangential component of electric field strength.

Volume current density J_V obeys Ohm's law and is composed of two parts, i.e., displacement current and conduction current. It could be calculated in (3) [4,5].

$$\gamma_V = A \cdot \exp(-B/T) \quad (2)$$

$$J_v = \frac{\partial D}{\partial t} + \gamma_V \cdot E \quad (3)$$

where D is electric flux; γ_V is volume conductivity; A and B are the coefficients that relate to the material's properties; and T is temperature.

To calculate gas current density J_G , we considered the drift, diffusion, generation, and recombination of charge carriers in SF_6 , which can be described by Equations (4)–(9).

The temporal change of the density of positive and negative ions n^+ and n^- can be described by the following equations [4,5]:

$$\frac{\partial n^+}{\partial t} = \frac{\partial n_{IP}}{\partial t} - k_r \cdot n^+ \cdot n^- - \nabla \cdot (n^+ b^+ E) + D^+ \cdot \nabla^2 n^+ \quad (4)$$

$$\frac{\partial n^-}{\partial t} = \frac{\partial n_{IP}}{\partial t} - k_r \cdot n^+ \cdot n^- + \nabla \cdot (n^- b^- E) + D^- \cdot \nabla^2 n^- \quad (5)$$

where $\frac{\partial n_{IP}}{\partial t}$ is the ion pair generation rate; k_r is the recombination coefficient; b^+ and b^- are the positive and negative ions' mobility; and D^+ and D^- are their diffusion coefficients. $\frac{\partial n_{IP}}{\partial t}$, k_r , and $b^\pm$ are related to the gas pressure, which can be obtained from [7–9].

$D^{+/-}$ is related to temperature, and it is obtained by Einstein's equation [4,5].

$$D^{+/-} = b^{+/-} \cdot \frac{k_B \cdot T}{e} \quad (6)$$

where k_B is Boltzmann constant; T is temperature; and e is elementary charge.

The electric field E can be computed from the negative gradient of the electric potential φ . Moreover, φ can be determined from the space charge density ρ according to Poisson's equation [4,5].

$$E = -\nabla \varphi \quad (7)$$

$$\nabla^2 \varphi = -\frac{\rho}{\epsilon} = -\frac{e \cdot (n^+ - n^-)}{\epsilon} \quad (8)$$

Thus, J_G could be calculated as follows [4,5]:

$$J_G = \frac{\partial D}{\partial t} + e \cdot E \cdot (n^+ \cdot b^+ + n^- \cdot b^-) - e \cdot \nabla \cdot (D^+ \cdot n^+ - D^- \cdot n^-) \quad (9)$$

The boundary conditions of charge densities are defined as follows [4,5]:

- (1) There is no positive charge on the boundary of the current outflows, and the negative charge gradient is 0.
- (2) There is no negative charge on the boundary where current occurs, and the positive charge gradient is 0.

2.3. Heat Transfer

During the operation process of the DC GIS, the ohmic heating of the central conductor inevitably leads to a temperature gradient. In Figure 1, three thermal transfer mechanisms need to be taken into consideration, i.e., heat conduction, convection, and radiation. The

heat conduction of the central HV conductor, the basin insulator, and the metal enclosure are the main approaches to heat transfer through solids. The flow of SF₆ in GIS, under the effect of buoyancy, exchanges heat within solids in the flow process. Heat convection also occurs between the grounded enclosure and the atmosphere. Moreover, the heat radiation from the central conductor and the insulator surface to SF₆ and the heat radiation from the metal enclosure to the atmosphere must be taken into account.

Heat conduction can be described according to Fourier's law as follows:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} + \rho \cdot C_p \cdot \mathbf{u} \cdot \nabla T + \nabla \cdot (-k \cdot \nabla T) = Q \quad (10)$$

where ρ is material density, C_p is the heat capacity, T is temperature, $\mathbf{u}$ is flow rate of insulating gas, k is heat transfer coefficient, and Q is the heat source.

Convection is a heat transfer method driven by the flow of a fluid. The gas flow behavior is expressed by Navier–Stokes and mass conservation equations as follows:

$$\rho \cdot \frac{\partial \mathbf{u}}{\partial t} + \rho \cdot \mathbf{u} \cdot \nabla \mathbf{u} = \nabla \cdot [-p \cdot \mathbf{I} + \mu \cdot (\nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} \mu \cdot (\nabla \cdot \mathbf{u}) \cdot \mathbf{I})] + \rho \cdot \mathbf{g} \quad (11)$$

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \cdot \mathbf{u}) = 0 \quad (12)$$

$$\rho = \frac{p \cdot M}{R \cdot T} \quad (13)$$

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \cdot \mathbf{u}) = 0$$

where p is gas pressure, M is the gas' mean molar mass, and R is the gas constant.

The radiation heat flux can be described by the Stefan–Boltzmann law as follows:

$$-n \cdot (-k \cdot \nabla T) = \varepsilon \cdot \sigma \cdot (T_{amb}^4 - T^4) \quad (14)$$

where T_{amb} is ambient temperature and σ is the Avogadro Boltzmann constant.

2.4. Experimental Platform for Surface Charge Measurement

As shown in Figure 2, a platform with a DC voltage generator, a real-sized GIS prototype with the tested insulator, and the movement mechanism controlling the electrostatic probe are established. The chamber containing this measurement system can withstand up to 0.6 MPa. The measurement resolution can be as accurate as 0.1 mm, and the range is ± 20 kV. The tested insulator is made of epoxy resin filled with Al₂O₃ micro-particles ($\varepsilon_r = 4.3$, $\gamma = 3 \times 10^{-14}$ S/m at 20 °C).

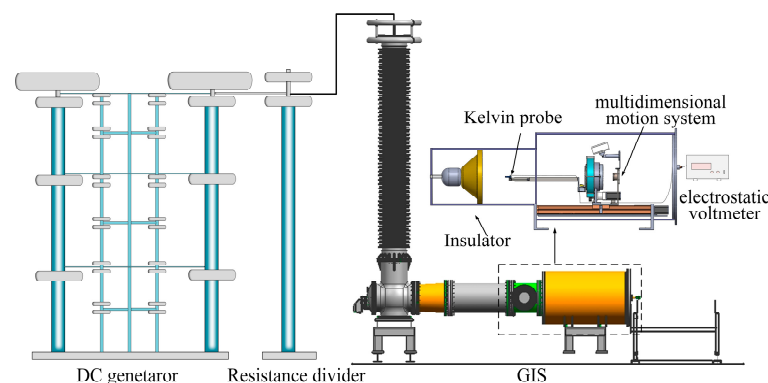


Figure 2. Schematic diagram of surface charge measurement.

Before each test, the chamber is vacuumed and then filled with various gases according to the requirements. After the completion of the measurement process, the contained gas is subsequently discharged, the motion mechanism is reset, and the insulator is thoroughly cleansed utilizing alcohol. Following this cleansing procedure, the surface charge

measurement of the basin insulator is conducted again, with the surface charge deemed eliminated when the maximum surface potential registers below 50 V [17]. During the measurement, an applied voltage of ± 100 kV was maintained for a duration of 4 h. Then, the movement mechanism is activated to run a preset program by which the probe is controlled to move and scan the entire surface at a distance of 2 mm. The voltage signal of the probe is synchronized to a voltmeter (Trek 341B) and evenly sampled $N = 64 \times 180$ times (180 times per circle and a total of 64 circles) to obtain the potential distribution of the surface. Through zonal scanning, the surface is meshed into N small regions, the potentials of which correspond to the N recorded outputs.

3. Influence of Gas Pressure

3.1. Simulation Results

Gas pressure plays a crucial role in determining the conduction current on the gas side. With the increase in gas pressure, the ion pair generation rate increases, the recombination coefficient increases, and the mobility of ions decreases [7–9]. The impact of gas pressure on surface charge density is depicted in Figure 3.

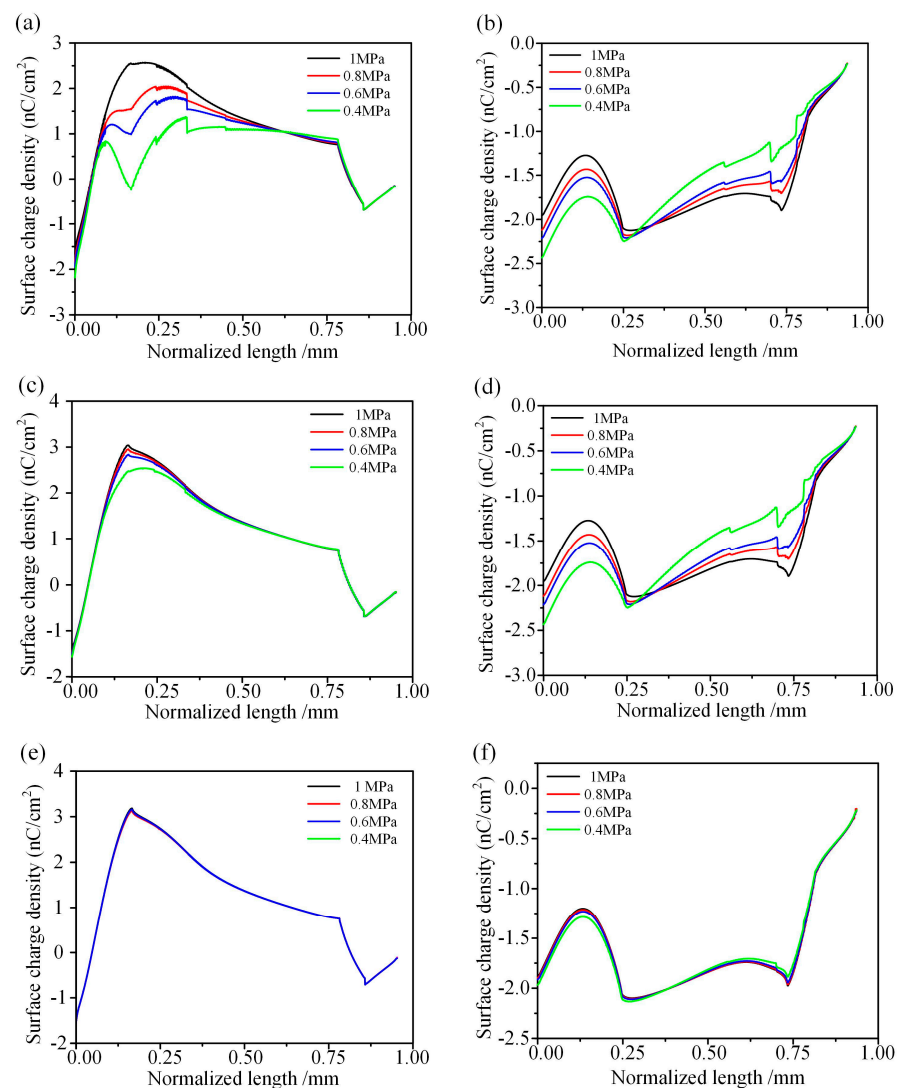


Figure 3. Surface charge distribution along the upper and lower surfaces of the insulator with different pressures and volume conductivity. (a) Upper, $\gamma_V = 10^{-16}$ S/m. (b) Lower, $\gamma_V = 10^{-16}$ S/m. (c) Upper, $\gamma_V = 10^{-15}$ S/m. (d) Lower, $\gamma_V = 10^{-15}$ S/m. (e) Upper, $\gamma_V = 10^{-14}$ S/m. (f) Lower, $\gamma_V = 10^{-14}$ S/m.

In Figure 3, the charge density on the upper surface exhibits an increasing trend with the rise in gas pressure. Conversely, on the lower surface, the charge density rises near the central conductor, then decreases near the grounded end. Moreover, as the volume resistivity increases, the influence of pressure on the surface charge density intensifies, albeit leading to a decrease in charge density. This phenomenon can be attributed to the predominant mode of surface charge. When the volume conductivity is $\gamma_V = 10^{-14}$ S/m, it becomes evident that the volume-conducted current predominantly influences the system, rendering the impact of pressure on the surface charge density almost negligible. However, when the volume conductivity is $\gamma_V = 10^{-16}$ S/m, the conduction in gas dominates the surface charge accumulation process, thereby leading to a significant influence of gas pressure variation on the charge density. Nevertheless, the surface charge density remains lower than the surface charge density when the volume conductivity is $\gamma_V = 10^{-14}$ S/m due to the decrease in bulk conduction current.

3.2. Experimental Results

To further explore the impact of gas pressure on the characteristics of surface charge distribution, measurements were conducted on the concave surface (lower surface) of the insulator at pressures of 0.2 MPa, 0.4 MPa, and 0.6 MPa, as shown in Figure 4.

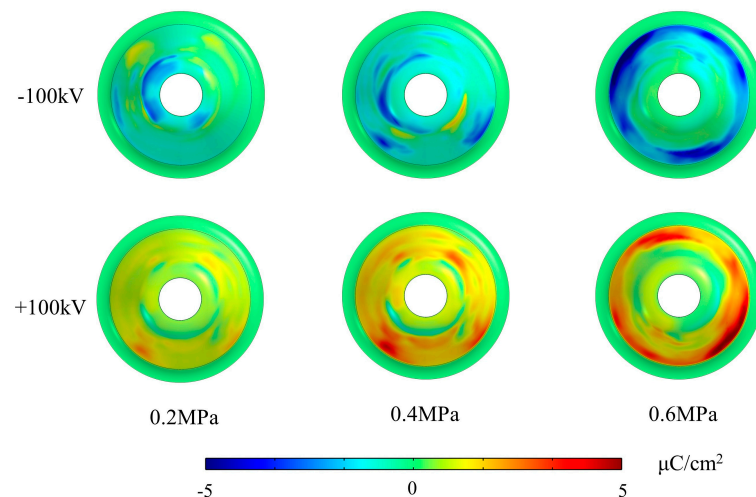


Figure 4. Surface charge distribution of a real-sized insulator under different pressures.

As illustrated, an increase in gas pressure leads to a significant augmentation in surface charge accumulation on the insulator. Concurrently, the scattered charge speckles on the insulator surface gradually disappear, giving way to the formation of a stable charge ring band. The distribution of charge can be primarily categorized into two patterns, i.e., uniform charging and random charge speckles [17]. The uniform charging is influenced by the electrode structure and applied voltage, while the charge speckles are primarily attributed to defects in the central conductor and insulator. As gas pressure increases, the corona inception voltage due to the defects decreases, subsequently resulting in a reduction in the number and charge density of charge speckles. Simultaneously, uniform charging progressively occupies the dominant charge distribution, accompanied by an increase in charge density. These findings align with the outcomes of the simulation analysis.

The charge distribution observed in Figure 4 can be categorized into two patterns, i.e., the charge speckle pattern and the uniform charging pattern, which were determined using the quadrature method [18]. Figure 5 displays the distribution of uniform charge patterns at different voltages, revealing a noticeable increase in the density of uniform charge as gas pressure rises. Additionally, the charge accumulated on the insulator's concave surface aligns with the polarity of the applied voltage.

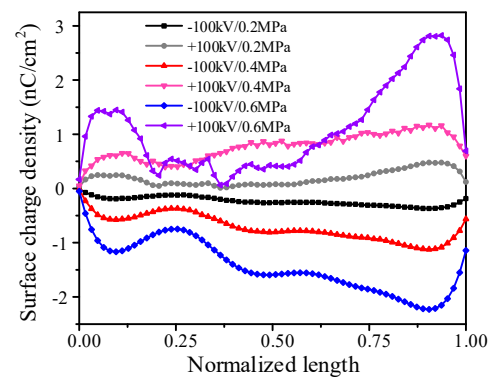


Figure 5. Charge distribution in the uniform charging mode at different pressures.

Gas dark current also plays a crucial role in determining the density of surface charge. With a higher applied electric field, the density of gas dark current experiences a significant increase as gas pressure rises [19,20]. Thus, as the gas conduction domain undergoes the surface charge accumulation process, the charge density of uniformly distributed charge gradually rises with the gas pressure, which agrees with the simulation results in Figure 3a,b.

The polarity of accumulated surface charge is influenced by the ion pair generation rate in the gas. Luo Yi et al. [21] discovered that as the ion pair generation rate increases, the polarity of the charge accumulated on the insulator surface gradually reverses. Three primary sources of gas-side charging must be taken into account, i.e., natural ionization due to background radiation, defect-induced micro-discharges, and field-induced emission from the conductor surface under high electric fields. During actual operation, despite the small average roughness of the central conductor, numerous small protrusions exist on its surface, with the size of these protrusions being dependent on their location and the machining method used [22]. The uneven distribution of these protrusions on the central conductor's surface leads to the generation of micro-discharges, resulting in a higher ion generation rate and dark current density on the gas side. As the rate of ion pair generation on the gas side continues to increase, the polarity of the charge accumulated on the insulator surface reverses. Therefore, it is evident that the measured surface charge is predominantly influenced by gas conduction with a high ion generation rate. This provides evidence that the polarity of the uniformly distributed charge aligns with the applied voltage, and the charge density undergoes significant changes with varying gas pressure.

4. Influence of Temperature Gradient

4.1. Temperature Distribution under Different Load Currents

In actual operation, the current in the inner conductor undergoes changes due to varying terminal loads, resulting in temperature distribution variations. The temperature gradient under different current levels of 3000 A, 5000 A, and 7000 A is drawn in Figure 6.

It is evident that as the current increases, the temperature gradient within the DC GIS experiences a significant and proportional increase, while its distribution characteristics remain consistent. Specifically, at load currents of 3000 A, 5000 A, and 7000 A, the temperature gradient from the high voltage conductor to the enclosure of the DC GIS measures 10.06 °C, 24.86 °C, and 44.54 °C, respectively. Furthermore, the presence of convection heat transfer contributes to the variation in temperature distribution between the two sides of the DC GIS, as depicted in Figure 7, which displays the gas flow rate distribution within the DC GIS. Heat convection facilitates the upward transfer of heat from the conductor, resulting in a temperature concentration primarily at the connection between the lower surface and the high-voltage conductor. Thus, the temperature gradient in the upper part of the DC GIS is significantly higher than that in the lower part. The existence of a temperature gradient further leads to temperature variations on both sides of the insulator. At load currents of 3000 A, 5000 A, and 7000 A, the temperature gradients on the upper and lower

surfaces are 1.8 °C, 4.4 °C, and 7.6 °C, respectively. With an increase in load current and temperature gradient, the flow rate of convection heat transfer within the DC GIS also increases, resulting in further amplification of the temperature gradient on the upper and lower surfaces.

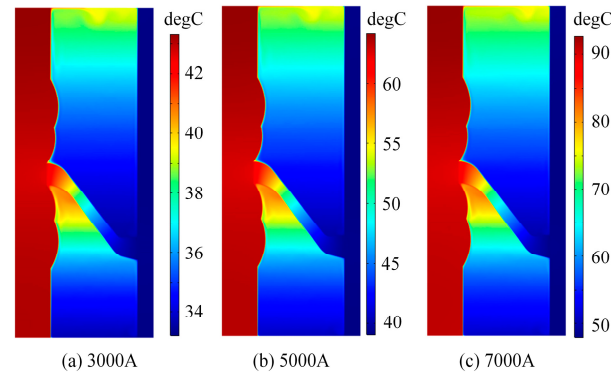


Figure 6. Temperature distribution under different load currents.

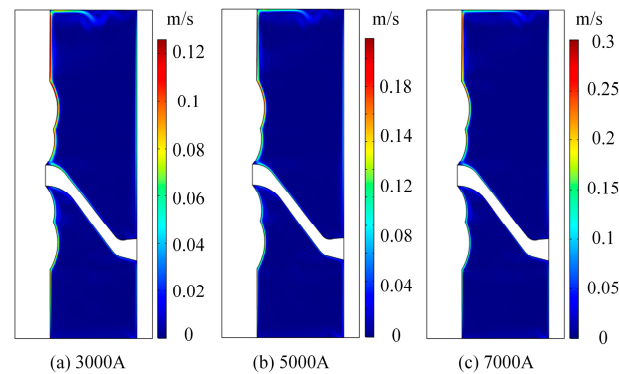


Figure 7. Gas velocity distribution under different load currents.

Meanwhile, a temperature rise test was conducted on the ± 500 kV GIS with a load current of 5000 A. When the temperature distribution reached a steady state, the temperature of the central conductor, the gas, and the grounding shell were measured before and after the application of the load current. The obtained results are presented in Table 1. The difference in temperature before and after the current at different locations was measured, and it can be clearly seen that the results of the simulation show good correspondence with the actual measurement results.

Table 1. Difference in temperature before and after the current is switched on.

Location	Differences in Temperature (°C)	
	Measured	Simulated
Central Conductor	29.7	32.606
	28	
	29.2	
Gas	12.4	30–10
	16.1	
	20.1	
Shell	14.1	10.3
	10.1	
	12.3	

4.2. Surface Charge Density under Different Thermal Gradients

Figure 8 illustrates the charge distribution on the two sides of the insulator at load currents of 3000 A, 5000 A, and 7000 A. As the thermal gradient intensifies, the charge density on both surfaces experiences a significant increase. Specifically, on the upper surface of the insulator, the rise in charge density is primarily concentrated at the junction between the insulator and the high-voltage conductor. Both the volume and surface conductivity of the insulator demonstrate a nonlinear increase with the thermal gradient [13], with the highest temperature occurring near the conductor. Consequently, the volume conduction current escalates, resulting in an elevation of the surface charge density in the vicinity of the high-voltage conductor on the upper surface of the insulator. The overall augmentation in charge density on the insulator's lower surface can be attributed to the temperature gradient, although the impact of different load currents on charge density is minimal.

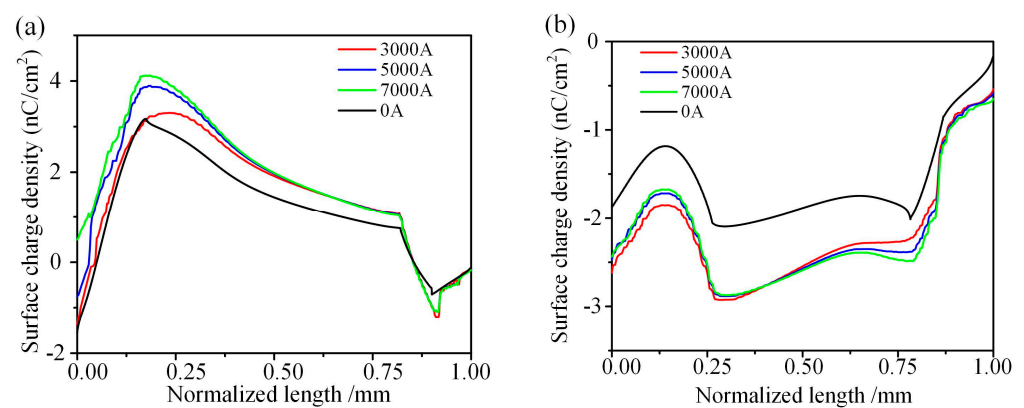


Figure 8. (a) Upper and (b) lower surface charge distributions with different load currents.

5. Conclusions and Perspectives

In this study, the effects of gas pressure and temperature gradient on the surface charge characteristics of insulators are investigated, employing a combination of simulation and experimentation. The conclusions obtained are drawn as follows:

(1) The influence of gas pressure on surface charge depends on the volume resistivity of the insulator. When the volume resistivity is low and the gas side dominates the surface charge accumulation, increasing gas pressure leads to a significant rise in surface charge density. Conversely, when the volume resistivity is high and the solid side dominates the surface charge accumulation, gas pressure has a minimal effect on surface charging.

(2) During the actual operational process, the presence of charge speckles on the insulator surface gradually diminishes with increasing gas pressure, while the density of uniformly distributed charge gradually increases. Furthermore, the mechanical processing of the central conductor results in the inevitable presence of small protrusions. Simultaneously, natural ionization and micro-discharges on the gas side contribute to the dominance of gas-side accumulated surface charge, which aligns with the applied voltage's polarity.

(3) The temperature gradient of the insulator amplifies as the load current on the central guide escalates. This gradient leads to a temperature discrepancy between the upper and lower surfaces. As the temperature gradient intensifies, there is a substantial increase in charge density on the upper surface of the insulator near the central conductor, while the change in charge density on the lower surface is comparatively smaller.

Finally, some outlooks for future work are presented. Although SF₆ is widely used in GIS/GIL, it has been significantly restricted due to its serious global warming effect. Promising eco-friendly alternatives such as C₄F₇N mixtures and clean air (or technical air or dry air) have been proposed for application. However, there has been limited attention paid to a comprehensive investigation of the surface charge characteristics exhibited by SF₆-alternative gases in DC GIS [23–25]. In particular, their pressure-dependent surface charging phenomena are expected to differ considerably from what has been observed

in SF₆. Recently, with an increasing amount of fundamental physicochemical properties being acquired for these gases [26], including swarm parameters [27,28] and collision cross sections [29], it is now feasible to model the transport of charge carriers under a DC field and compare it with that of SF₆. In view of the urgent need for SF₆-alternatives, making a breakthrough in the key insulation technologies of eco-friendly DC GIS will undoubtedly be one of the most important research avenues in the future.

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