Transient Surface Charge Characteristics of DC-GIL Insulator Under Thermal-Electric Coupled Fields

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ABSTRACT The insulator in direct current gas-insulated transmission lines (DC-GIL) would suffer discharge risk due to surface charge accumulation under thermal-electric coupled fields. In this paper, the transient surface charge accumulation characteristics of a basin-type DC-GIL insulator is investigated via finite element method based on a three-dimension horizontally installed GIL model. The stationary temperature distribution of the model is obtained and then applied to the transient simulation of charge. Weak form partial differential equation is employed to deal with the ion transportation equation. Equations and parameters in the simulation are optimized to reduce the computing memory and time. Results indicate that the charge accumulation is accelerated due to the promotion of conduction through the insulator under thermal gradient. Higher charge density is obtained under thermal gradient. And the surface charge density of the convex surface is higher due to the promoted conduction. The highest field strength increases and the corresponding location moves along the convex surface during the transient process. This could attribute to the influence of transient charge behavior under thermal gradient on the electric field distribution. This study indicates that the thermal gradient and transient charge accumulation should be considered when dealing with the insulation characteristics of DC-GIL with insulators.

INDEX TERMS Gas insulated transmission lines, insulator, surface charge, thermal-electric coupled fields.

I. INTRODUCTION Gas-insulated transmission lines (GIL) and gas-insulated switchgear (GIS) are widely applied in power systems due to the advantages of space-saving, easy maintenance, large capacity, and high reliability [1]. Inside GIL enclosure pipe or GIS bus subsection, gas with excellent insulating property functions as the insulating medium, and the current flows through the central conductor. Besides, insulators consisting of epoxy resin composites supply necessary supporting and insulating functions. Although both the gas and the insulator show considerable insulation properties, surface discharge would occur at the gas/insulator interface [2]. This may be attributed to the partial electric field distortion as the consequence of surface contamination or surface charge accumulation [3]. With the development of high voltage direct current (HVDC) transmission system, the safe operation of GIL and GIS under DC voltage should be concerned especially for the gas/insulator interface insulation characteristics.

Surface charge accumulation is considered a key factor that affects the field distribution of HVDC insulators and further increases the risk of insulating failure [4]. In the decades, much attention has been paid to the surface charge characteristics of GIS/GIL insulators via measurement and simulation. Kumada and Okabe [5], Zhang et al. [6], Pan et al. [7] applied downsized models to study the surface charge distribution of DC insulators. Du et al. [8] conducted measurements on a real-type insulator and investigated the influence of applied voltage amplitude, polarity, and duration time on the surface charge characteristics. According to the simulation result [9], [10], this surface charge accumulation process would last thousands of hours. While in most measurements, the DC high voltage was only applied to the insulator for tens to hundreds of hours. Thus, simulation shows an
obvious advantage over measurement in dealing with the surface charge characteristics of the insulator during long-term operation in real GIS/GILs.

On the other hand, large current flows through the central conductor, and the thermal gradient would be established inside the pipe due to Joule heat [11]. Meanwhile, it was found that the electric conductivity of the insulator would affect the surface charge distribution characteristics [12], [13]. Thus, this thermal gradient should be involved when dealing with the electric field property of the insulator under DC stress considering the temperature-dependent electric conductivity of the insulator [14]. Since ion mobility varies with temperature [15], the influence of thermal gradient on the ion transportation should be considered as well. Recently, efforts have been paid on the surface charge characteristics under the stress of electric-thermal coupled field and discussed the transient [16], [17], and stationary [18] charge characteristics. While most of the research was based on the rotational symmetric model, and two-dimension (2D) geometry model was employed in the simulation of thermal gradient and subsequent surface charge. Three-dimension (3D) model was seldom applied due to the high computational complexity. Thus, the surface charge distribution of the insulator in 3D mode can’t be obtained. This leads to the impossibility of the investigation in some conditions, for example, the horizontally installed GIS/GILs. Since spatial distributed thermal gradient is established in the pipe and the insulator, and 3D geometry model is needed in the simulation.

In this paper, a 3D simulation model based on a ±200 kV real-type insulator was employed. An improved method was introduced to deal with the simulation of transient surface charge under thermal-electric coupled fields. The transient surface charge accumulation process of the basin-type insulator was discussed. Then, the influence of surface charge on the transient electric field distribution characteristics was investigated. This work can be beneficial to evaluate the insulation property of DC-GIS/GILs during long-term operation.

II. SIMULATION MODEL

A. GEOMETRY MODEL

To investigate the surface charge distribution under thermal gradient, a 3D geometry model was applied. The simulation model is a ±200 kV GIL with a basin-type insulator inside as shown in Fig. 1. This model is horizontally installed. The central conductor is made of aluminum and the enclosure is made of aluminum alloy. The geometry parameters of this simulation model are illustrated in Fig. 2.

B. MECHANISM OF HEAT TRANSFER

When the large current flows through the central conductor, considerable Joule heat will be generated as defined in (1).

\[
P = I^2R = \frac{I^2L}{S_{\text{cond}}\sigma_{\text{Al}}} \tag{1}
\]

Here, \( P \) is the heating power of the conductor. \( I \) is the load current. \( R \) is the resistivity of the conductor. \( L \) is the length of the conductor. \( S_{\text{cond}} \) is the sectional area of the conductor. \( \sigma_{\text{Al}} \) is the temperature-dependent electric conductivity of the conductor as defined in (2).

\[
\sigma_{\text{Al}}(T) = \frac{\sigma_{20}}{1 + 0.004(T - 293)} \tag{2}
\]

Here, \( \sigma_{20} \) is the conductivity at 20 °C which is 3.02 \times 10^{-8} \text{ S/m} [19], \( T \) is the temperature of the conductor. Since this GIL model operates under the stress of DC voltage and current, eddy current is neglected in this study.

The heat generated from the conductor is transferred to the insulator, \( \text{SF}_6 \) gas and enclosure through conduction, radiation and convection. The heat conduction in this paper is defined as (3) and (4),

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (q + q_r) = Q \tag{3}
\]

\[
q = -\kappa \nabla T \tag{4}
\]

where \( \rho \) is the density, \( C_p \) is the specific heat capacity at constant stress, \( q \) is the heat flux by conduction, \( q_r \) is the heat flux by radiation, \( \kappa \) represents the thermal conductivity, \( T \) is the absolute temperature, and \( Q \) contains additional heat sources which are zero for insulator and gas. The temperature-dependent thermal conductivity and specific heat capacity of the insulator were measured by the Transient Hot-Wire (THW) method and Differential Scanning Calorimetry (DSC) method, respectively. The thermal conductivity is 0.946, 0.967, 0.934 and 0.917 \text{ W m}^{-1} \text{ K}^{-1} at the temperature of 25, 50, 75 and 100 °C, respectively. While the specific heat capacity is 880, 949, 1018 and 1075 \text{ J kg}^{-1} \text{ K}^{-1} at the corresponding temperature.

The radiation functions between the conductor and the enclosure, between the conductor and the insulator, between

![FIGURE 1. The ±200 kV DC-GIL model and the insulator in this study. The cross-section represents the symmetry plane in the simulation.](image1)

![FIGURE 2. The geometry of the model in this simulation.](image2)
Besides, SF\textsubscript{6}− form metastable association complex (SF\textsubscript{6}− attached to molecules by resonance capture (within 1 ps) and laminar flow model should be used \cite{22}. According to the dimensionless numbers of Rayleigh (Ra) and Grashof (Gr) numbers inside the pipe was regarded as natural convection, dimensional analysis was defined by Sutherland’s law \cite{21}. Since the convection and dynamic viscosity of SF\textsubscript{6} gas at different temperatures were defined by Sutherland’s law \cite{21}. Since the convection inside the pipe was regarded as natural convection, dimensionless numbers of Rayleigh (Ra) and Grashof (Gr) numbers were applied to evaluate whether turbulent flow model or laminar flow model should be used \cite{22}. According to the calculation, both Ra and Gr fell into the range between 10\textsuperscript{9} to 10\textsuperscript{10}, thus the turbulent flow model was employed \cite{23}. And Shear Stress Transport (SST) flow model was applied attributing to the advantage at near-wall region compared with k-ε model \cite{24}, \cite{25}. The more accurate surface temperature of the insulator and the conductor can be obtained based on the SST model. After a given duration time, the thermal gradient can be establish inside the enclosure pipe which would further affect the charge accumulation process inside the pipe.

The ionization inside the GIL is mainly caused by cosmic radiation. Electrons generated by ionization are slowed down to thermal energies within some tens of picoseconds. Because of the high electron affinity of SF\textsubscript{6}, low-energy electrons are attached to molecules by resonance capture (within 1 ps) and form metastable association complex (SF\textsubscript{6}− attached to molecules by resonance capture (within 1 ps). Thus, the dominant negative charge carries in this study are SF\textsubscript{6}− ions. Besides, SF\textsubscript{6}+ ions are regarded as the dominant positive ions.

The current density through SF\textsubscript{6} gas \(J_G\) can be defined as the sum of ion migration and ion diffusion shown in (7),

\[
\begin{align*}
J^+_G &= q \cdot E \cdot n^+ b^+ - q \cdot D^+ \nabla n^+ \\
J^-_G &= q \cdot E \cdot n^- b^- + q \cdot D^- \nabla n^- \\
J_G &= J^+_G + J^-_G
\end{align*}
\]

where \(J^+_G\) and \(J^-_G\) represent the current density attributing to the ion migration and negative ion migration, respectively. \(E\) is the electric field strength. \(n^+, b^+\) and \(D^+\) are the density, ion mobility, diffusion coefficient of the positive ion. \(n^−, b^−,\) and \(D^−\) represent the corresponding parameters of the negative ion. In this study, elementary charge \(q\) is given for both positive and negative ions.

According to the continuity equation of current, the divergence of the current density can be defined by (8) and (9), respectively.

\[
\begin{align*}
\nabla \cdot J^+_G &= -\frac{\partial n^+}{\partial t} - q \cdot n^+ \cdot k_n \cdot n^− + q \cdot \frac{\partial \rho_{IP}}{\partial t} \\
\nabla \cdot J^-_G &= -\frac{\partial n^-}{\partial t} - q \cdot n^- \cdot k_n \cdot n^+ + q \cdot \frac{\partial \rho_{IP}}{\partial t}
\end{align*}
\]

\(k_n\) represents the recombination rate which varies with the gas pressure. \(\frac{\partial \rho_{IP}}{\partial t}\) represents the ion pair generation rate in SF\textsubscript{6} at a given pressure.

Then, the governing (10) and (11) can be obtained for the positive and negative ion by substituting (7) into (8) and (9).

\[
\begin{align*}
\frac{\partial n^+}{\partial t} &= \frac{\partial \rho_{IP}}{\partial t} - n^+ k_n n^− - b^+ \nabla \cdot (n^+ E) + D^+ \nabla^2 n^+ \\
\frac{\partial n^-}{\partial t} &= \frac{\partial \rho_{IP}}{\partial t} - n^- k_n n^+ + b^- \nabla \cdot (n^- E) + D^- \nabla^2 n^−
\end{align*}
\]

On the other hand, the current density through the insulator \(J_I\) can be defined based on Ohm’s law,

\[
J_I = \sigma_I E
\]

where \(\sigma_I\) is the volume electric conductivity of the insulator.

The transient surface charge accumulation process can be defined by (13) considering the conduction through the gas phase, the conduction through the solid (insulator) phase, and the conduction along the gas/insulator interface.

\[
\frac{\partial \rho_s}{\partial t} = J_{In} - J_{Gn} - \nabla \cdot (\sigma_I E)
\]

Here, \(\rho_s\) is the surface charge density, \(J_{In}\) and \(J_{Gn}\) are the normal components of the current density through the insulator and gas phase, respectively. \(\sigma_I\) is the surface electric conductivity.

Considering the inhomogeneous temperature distribution inside the insulator and the temperature-dependent electric conductivity of the insulator, space charge accumulation inside the insulator can be expected under the thermal-electric coupled fields stress. Thus, the transient space charge accumulation process can be defined by (14),

\[
\frac{\partial \rho_I}{\partial t} = \nabla \sigma_I \cdot \nabla \phi - \frac{\sigma_I}{\varepsilon_I} \rho_I
\]

where \(\rho_I\) represents the space charge density. \(\varepsilon_I\) represents the permittivity of the insulator which varies slightly in the temperature range in this study.

The ion pair generation rate in SF\textsubscript{6} gas was obtained from measurement data which is 30 cm\textsuperscript{3}\textper秒 at 0.5 MPa \cite{27}. Both the positive ion mobility and the negative ion mobility were obtained from \cite{15}. And the ion mobility at different...
pressure and temperature \(b(p, T)\) can be obtained by (15) for both positive and negative ions.

\[
b(p, T) = \frac{b_0 p_0 T}{p T_0}
\]

(15)

Here, \(b_0\) represents the measured data at \(p_0\) (101 kPa) and \(T_0\) (273 K) [15].

The diffusion coefficient can be obtained based on the measured ion mobility and (16).

\[
D^\pm = \frac{k \cdot T \cdot b^\pm}{q}
\]

(16)

Here, \(k\) represents the Boltzmann constant.

The recombination rate was obtained from [15].

The temperature-dependent surface and volume electric conductivity of the insulator was obtained from Zavattoni’s measurement. The surface conductivity with varying electric field strength and temperature can be defined by (17).

\[
\rho_s(E, T) = 6.1 \times 10^{26} \times e^{-(0.06T + 1.03E)}
\]

(17)

Here, the unit of the temperature \(T\) is degree centigrade and the unit of the field strength is kV/mm.

In the simulation, positive 200 kV DC voltage was applied to the conductor, and the enclosure was grounded. Besides, on the boundary of current flowing out, the positive ion density is zero, and the gradient of negative ion density is zero as well. While on the boundary of current flowing in, the negative ion density is zero, and the gradient of positive ion density is zero as well.

III. OPTIMIZATION OF SIMULATION

In Section 2, the mechanism of heat generation, heat transfer, charge accumulation and the influence of thermal gradient on the charge accumulation has been discussed. However, it is difficult to conduct simulations directly based on these equations with a 3D geometry model due to the large computing time and memory cost. Thus, an improved method is needed focusing on the optimization of the multi-physics field simulation.

A. OPTIMIZATION OF GEOMETRY MODEL

The GIL model in this study is horizontally installed and rotational symmetry. Considering the symmetry of the geometry, symmetric thermal gradient distribution can be obtained with the vertical plane as the symmetric plane as shown in Fig. 1 [25]. Since the rotational symmetric distribution of electric field and charge accumulation can be obtained without thermal gradient [12], bilateral symmetric electric field and charge distribution corresponding to the thermal gradient can be expected considering the influence of thermal gradient on the electric conductivity and ion transportation. Thus, the temperature, electric field strength and charge density distribution was calculated with a half model. In the simulation of temperature field, the symmetry plane was set as a thermal insulating plane. In the simulation of electric field, the symmetry plane was set as an electric insulating plane. In the simulation of ion flow, the normal component of the flux at the symmetry plane was 0. According to the simulation result, there is no difference between the result with the half model and the result with the full model. Thus, half of the ±200 kV GIL model was applied in this study. In this way, nearly half of the mesh and computing memory can be reduced.

B. OPTIMIZATION OF SOLVING METHOD

Even half of the GIL model is applied, it costs much computing time and memory to conduct the simulation of transient charge accumulation under the coupled field. According to the investigation of transient temperature rise of the GIL, after about 7 hours the thermal gradient inside the pipe including the insulator reached the quasi-stationary state. On the other hand, the transient charge accumulation process would last for thousands of hours. In the first 10 hours, slight charge would accumulate on the insulator surface as indicated in Fig. 3. Thus, it can be regarded that the charge accumulation process occurs after the stationary thermal gradient field has been established. In this study, the thermal gradient was first obtained. And then, the simulation of transient charge accumulation was conducted considering the influence of stationary thermal gradient field on the electric conductivity and ion transportation.

![FIGURE 3. The comparison of transient process between the temperature rise and charge accumulation. The arrow indicates the position of given point for the temperature and surface charge.](image-url)
of accuracy. Moreover, even with the treatment of isotropic diffusion or streamline diffusion, it is still difficult to deal with a 3D model. Since too much memory is needed. In this investigation, the partial differential equation (PDE) in weak form was applied to deal with the convective domination ion transportation equation. Compared with the treatment of additional diffusion terms, nearly 90% of the degree of freedom and memory can be reduced while the solution shows better accuracy.

C. OPTIMIZATION OF EQUATIONS AND PARAMETERS
Moreover, optimization of the equations and parameters was conducted, and the efficiency of the simulation was promoted further. Since convection (migration) dominates over diffusion in ion transportation, the influence of diffusion term on the simulation result was evaluated. A simulation without the diffusion term in (10) and (11) was arranged. The simulation with original equations was arranged as the reference. The result indicated that there is no difference between the results with and without diffusion term. While nearly 70% of the computing time and more than 80% of the computing time can be reduced if diffusion terms are removed from (10) and (11). Besides, the influence of the diffusion term in the current density equation (7) was evaluated. Results showed that there is no difference can be found between the result with and without diffusion term. While a slight promotion of computing efficiency can be achieved if the diffusion terms are removed from (7). Thus, in this study, the diffusion terms in (10) and (11) were removed.

On the other hand, since the ion mobility varies slightly below 3 kV/mm and the field strength in the gas domain is lower than 3 kV/mm, the influence of the electric field strength was neglected.

IV. INFLUENCE OF THERMAL GRADIENT ON CHARGE AND FIELD CHARACTERISTICS
A. TEMPERATURE DISTRIBUTION OF THE INSULATOR AND THE GIL
Simulation of thermal gradient was conducted under the ambient temperature of 20 °C, SF$_6$ pressure of 0.5 MPa and load current of 3150 A. The stationary temperature distribution of the insulator surface and the GIL is shown in Fig. 4. It can be found that the temperature of the upper part is higher than that of the lower part. This could be attributed to the convection effect inside the pipe. The gas heated by the conductor is lifted up to the top of the enclosure. Then, the gas goes down along the inner surface of the enclosure to the bottom. During this process, the gas is cooled. Finally, the gas is lifted up to the conductor again to complete the circulation. In this way, the gas temperature of the upper part is higher than the lower part as shown in Fig. 4. The upper part of the insulator is heated by the hot gas, while the lower part of the insulator is cooled by the cool gas. Thus, the temperature of the upper position is higher than the corresponding lower position of the insulator. Besides, it can be found that the temperature of the convex surface is higher than that of the concave surface, especially in the region near the conductor.

The spatial distribution of the thermal gradient indicates the necessity of the application of the 3D geometry model in dealing with the temperature distribution in this case. Moreover, a temperature difference of about 30 °C is obtained under this operating condition as shown in this figure. This will lead to an increase of 6.4 times in volume electric conductivity of the insulator due to the increase in temperature. This finally would affect the surface charge distribution characteristics in the stationary state and the accumulation process.

B. INFLUENCE OF THERMAL GRADIENT ON THE TRANSIENT SURFACE CHARGE ACCUMULATION
The influence of thermal gradient on the surface charge distribution was studied. The gas pressure in the simulation of charge accumulation was 0.5 MPa. The transient charge accumulation process was obtained, and the case without the influence of thermal gradient was conducted as the reference. Taking convex surface as a typical example, the transient surface charge accumulation process is shown in Fig. 5 for both the cases with and without thermal gradient. The results after the coupled fields have been stressed for 10, 50, 100, 200, 300, 1000, and 10000 hours were selected. For each subfigure, the left half represents the result with the influence of thermal gradient, while the right half represents the result without the influence of thermal gradient.

As shown in this figure, positive charge accumulates on the surface for both cases during the stress process. The electric field lines distribution of the two cases is shown in Fig. 6. It is obvious that the field lines flow out of the insulator at the convex surface. Thus, the positive charge accumulation indicates the dominative factor of bulk conduction over the surface conduction and gas conduction in the charge accumulation process for both cases.

Besides, due to the asymmetric distribution of the temperature referring to the radial direction, the surface charge
FIGURE 5. The transient surface charge accumulation process of the convex surface. In each subfigure, the left half represents the result with thermal gradient, and the right half represents the result without thermal gradient.

FIGURE 6. The electric field lines distribution of the insulator for the cases (a) with thermal gradient and (b) without thermal gradient.

shows asymmetric distribution in the radial direction. It is obvious that at 100 hours, the upper part shows higher charge density compared with the lower part. The corresponding charge density along the surface in different radial directions was obtained and is shown in Fig. 7. Here, the distance is defined as the distance along the surface from the high voltage conductor. The distance 0 represents the joint point at the conductor and the insulator. It can be seen that a difference of 4 \( \mu \text{C} \cdot \text{m}^{-2} \) is achieved. This is due to the promotion of bulk conduction of the upper part as the consequence of high temperature. This would further affect the electric field distribution in different radial directions. This phenomenon indicates the necessity of employing the 3D model in the investigation of surface charge characteristics under thermal-electric coupled fields stress.

Moreover, compared the results with and without thermal gradient, obvious acceleration of charge accumulation can be achieved with the help of thermal gradient. After about 300 h, the charge distribution nearly reaches the stationary state under the stress of coupled fields. While this time is increased to 1000 hours for the charge to reach the stationary state without the influence of thermal gradient. Taking the charge density at the given point, the transient surface charge density during the stress process was obtained for both cases. The result is illustrated in Fig. 8. It is obvious that under the influence of thermal gradient, the charge accumulation is accelerated. The time for the charge density to achieve the stationary state is reduced by about 80% at this point.

According to (13), charge accumulation is defined by the bulk conduction, the gas conduction and the surface conduction. Thus, any disturbance to the three terms would affect the charge accumulation characteristics. As indicated in (12), the charge accumulation is affected by the volume electric conductivity of the insulator and the electric field strength. According to (7), the charge accumulation process is affected by the electric field strength and the ion transportation characteristics under electric field. Thus, any factor that could show influence on the ion transportation would affect the charge accumulation from the view of gas conduction, for example the ion mobility.

The thermal gradient would affect the bulk conduction via the temperature-dependent electric conductivity of the insulator. Consequently, the charge accumulation would be affected by the bulk conduction. This acts as the direct effect
of thermal gradient on the charge accumulation. As discussed above, the bulk conduction dominates the charge accumulation in this study. Thus, the influence of thermal gradient on the bulk conduction was first evaluated. In the case without thermal gradient, the temperature was set at 20 °C for the gas and the insulator. In the case with thermal gradient, the stationary temperature distribution along the convex surface in radial direction is shown in Fig. 9. Corresponding volume conductivity along the surface is shown in this figure as well. As shown in this figure, the temperature varies from 33 to 63 °C, and the volume conductivity varies from 4.51 × 10^{-16} to 0.65 × 10^{-16} S·m⁻¹. While the volume electric conductivity at 20 °C is 0.11 × 10^{-16} S·m⁻¹ for the case without thermal gradient. Thus, the bulk conduction is promoted under the thermal gradient. This would contribute to the acceleration of charge accumulation under the thermal gradient.

Meanwhile, the DC electric field distribution would be affected by the thermal gradient, since the volume electric conductivity is affected by the thermal gradient. Then, the affected electric field distribution would show influence on the charge accumulation process. This acts as the indirect effect of thermal gradient on the charge accumulation. Thus, the influence of thermal gradient on the electric field distribution was investigated in this study. The electric field distribution without the influence of charge accumulation was calculated for the case under uniform temperature distribution of 20 °C and the case under the influence of thermal gradient, respectively. And the results are illustrated in Fig. 10 for both cases. It can be seen that the electric field strength under thermal gradient is slightly higher compared to the result with uniform temperature. But they nearly follow the similar tendency. The electric field distribution under thermal gradient would show no obvious influence on the charge accumulation process. Thus, by comparing the increase of electric field strength and the increase of volume electric conductivity under thermal gradient, it can be concluded that the promotion of bulk conduction due to the increase of volume electric conductivity dominates the acceleration of transient surface charge.

Moreover, the charge density is higher in the case with thermal gradient at each corresponding time including the stationary result compared to the case without thermal gradient. The difference can be 50% during the transient process as indicated in Fig. 8. This could attribute to the promotion of bulk conduction with high electric conductivity under the influence of thermal gradient during the whole stressing process. As illustrated in Fig. 5, an obvious difference can be found in the results at several hundreds of hours. This is because that the charge accumulation is accelerated under thermal gradient. Thus, the time to the stationary state is reduced. After several hundreds of hours, the charge density nearly approaches the stationary state. While the charge accumulation without thermal gradient is still in the stage of slow increase during this time interval. Thus, an obvious difference can be found.

Besides, the ion mobility would be affected by the thermal gradient as defined in (15). The ion mobility would affect the current density as indicated in (7). Also, it would affect the ion transportation process according to the governing equations (10) and (11). Consequently, the ion density would be affected. Finally, this disturbance due to ion mobility would show influence on the charge accumulation. In this way, the thermal gradient would affect the charge accumulation via the ion transportation. While according to our previous simulation result, there is no obvious difference can be observed between the result with and without the influence of thermal gradient on the ion mobility.

In summary, the thermal gradient would show influence on the charge accumulation through three approaches:

1. The direct effect of thermal gradient on the bulk conduction due to the temperature-dependent electric conductivity of the insulator. This dominates in the acceleration of charge accumulation under thermal gradient.

2. The indirect effect of thermal gradient on the electric field distribution due to the temperature-dependent electric conductivity of the insulator. While it is not the dominative effect with respect to the variation of charge accumulation under thermal gradient in this investigation.

3. The effect of thermal gradient on the ion transportation due to the temperature-dependent ion mobility. Since the bulk conduction dominates over the gas conduction, this effect is not the dominative mechanism in the charge accumulation under thermal gradient.
C. TRANSIENT VARIATION OF CHARGE DENSITY AT DIFFERENT LOCATIONS

To investigate the transient surface charge accumulation process more quantitatively, the charge density along the insulator surface in radial direction is illustrated in Fig. 11 for both the convex and concave surfaces. It can be seen that the charge density of the convex surface is higher than that of the concave surface. The charge density along the whole convex surface increases with time. It costs less than 1000 hours for the convex surface to reach the quasi-stationary state.

While for the concave surface, the charge density in some region doesn’t show a monotonically increasing tendency, for example, the region between 70 to 120 mm. Similar non-monotonic tendency can be observed in the case without thermal gradient, which is not illustrated in this study.

To investigate the different transient behavior in different region, the charge density at different locations was obtained with varying the time. The locations of 26 mm (Point A) and 80 mm (Point B) on the convex surface, and the locations of 102 mm (Point C) and 145 mm (Point D) on the concave surface were selected. The result is shown in Fig. 12. It can be seen that different points show different increasing tendencies. For point A, it costs about 300 hours to reach the stationary level. For points B and D, the time is about 700 and 1000 hours, respectively. While for point C, the negative charge density first increases with the time, and then the charge density decreases. The charge density reaches the maximum at about 200 hours. It doesn’t reach the stationary level even after 10000 hours. This could attribute to the transient variation of field distribution. The domination among the conduction through the gas, the conduction through the insulator and the conduction along the insulator surface is affected by this transient field distribution. The charge density variation at each point is affected by the entire field distribution. This charge density variation at different points can’t be analyzed independently.

D. TRANSIENT ELECTRIC FIELD DISTRIBUTION UNDER THERMAL GRADIENT

To investigate the influence of thermal gradient on the transient field distribution, a comparison between the results with and without thermal gradient was conducted. The influence of surface charge on the field distribution was considered for the conditions with and without thermal gradient. Thus, the electric field distribution corresponding to Fig. 5 was obtained.

In Fig. 13, the transient electric field distribution of convex surface at 10, 50, 100, 200, 300, 1000 and 10000 hours is illustrated. As shown in this figure, the field strength with thermal gradient is higher at each time point compared with the result without thermal gradient. The field strength in the case with thermal gradient increases with increasing the time. While the field strength in the case without thermal gradient varies slightly during the stress.

The transient electric field distribution under thermal gradient was abstracted along the insulator surface in radial direction. The result of convex and concave surface is shown in Fig. 14 which is corresponding to the result in Fig. 11. It can be seen that the electric field strength at 0 mm is very low. This could be attributed to the high voltage insert and high temperature near the conductor. The temperature rise near
the conductor will lead to the sharp increase in the volume conductivity. As a result, the grown volume conductivity greatly weakens the electric field strength near the conductor [14], [18]. Moreover, the high voltage insert can lead to a relatively low electric field strength near the high voltage conductor [29]. Both of the two factors result in the relatively low field strength near the conductor in this simulation.

For the convex surface, the field strength increases with increasing time, and reaches the stationary level after several hundreds of hours which is in accordance with the variation of surface charge accumulation process. During this variation, the point corresponding to the highest field strength moves towards the enclosure. For the concave surface, the variation of field strength with increasing time shows non-monotonically increasing tendency. This in turn can explain the non-monotonically increasing tendency of the charge with increasing time as shown in Fig. 11(b). The point corresponding to the highest field strength shows no obvious variation along concave surface. Besides, the field strength of the convex surface is higher than the concave surface.

The transient electric field distribution without the influence of thermal gradient was abstracted along the insulator surface in radial direction as a control. Since the convex surface displays higher field strength, only the result of convex surface is shown in Fig. 15. With increasing the time, the field strength increases slightly compared with Fig. 14(a). Besides, the point corresponding to the highest field strength doesn’t move in this time variation.

The different tendencies with increasing time in Fig. 14(a) and Fig. 15 could attribute to the charge accumulation under the influence of thermal gradient. In the beginning, for example at the stress time of 10 hours, a slight difference of distribution pattern can be found between the two cases. In this stage, the charge density is very low for both cases as indicated in Fig. 5. Thus, the influence of charge accumulation on field distribution can be ignored. Since there are only two factors that can affect the field distribution, i.e. the influence of temperature-dependent electric conductivity and the influence of surface charge accumulation in the two cases. This phenomenon indicates that the direct influence of temperature-dependent conductivity on the field distribution can be ignored, which confirms the result in Fig. 10. Thus, the different field distribution during the subsequent process in the two cases should be attributed to the different behavior of charge accumulation during the transient process.

To investigate the increasing tendency of field strength more quantitatively, the field strength at a typical point on the convex surface was abstracted with increasing time. Since the highest field strength appears at about 100 mm as shown in Fig. 14(a), the typical point was selected at this position. The result is illustrated in Fig. 16 for the cases with and without thermal gradient. It can be seen that the thermal gradient leads to acceleration to the field strength increase. This should attribute to the accelerated transient charge accumulation under thermal gradient. Besides, a difference of about 25% is achieved at the stationary state between the two cases. According to the comparison of field strength, it can be concluded that the thermal gradient should be considered when evaluating the field distribution and further insulation characteristics of the DC-GIL insulator.
It is noted that only the simulation result is provided in this study. If measurement is selected to deal with this issue, the experimental system should involve both high voltage and high current which are connected to the conductor to provide the thermal-electric coupled field during long-term operation. While it is difficult to achieve in the laboratory. In the future, effort will be made to design the experimental system which can provide both high voltage and high current to the real-type insulator for the long-term experiment.

V. CONCLUSION
The transient surface charge accumulation process of a basin-type insulator was investigated under the thermal-electric coupled fields. The conclusion can be summarized as follows:
1. The stationary thermal gradient was first calculated and then applied to the calculation of transient surface charge. Weak form PDE was applied to deal with the ion transport equation in the simulation of charge. Besides, the diffusion term was removed from this equation. The improved method was proved to show considerable accuracy and efficiency in dealing with the transient surface charge under electric-thermal coupled field with a 3D geometry model.
2. The surface charge accumulation is accelerated and the charge density is higher under the stress of thermal gradient compared to the result without thermal gradient. This could attribute to the promotion of the conduction through the insulator under the thermal gradient. The surface charge on the upper part with high temperature is higher than that of the lower part with low temperature due to the promotion of bulk conduction. Besides, the surface charge density at each point doesn’t increase synchronously. In some region on the concave surface, the charge density even shows non-monotonically increasing tendency.
3. The point corresponding to the highest field strength moves towards the enclosure along the convex surface during the transient process under thermal gradient. And this highest strength increases synchronously. While both the highest strength and the point vary slightly for the case without thermal gradient.
4. The result of transient field distribution indicates that the influence of thermal gradient and transient charge accumulation should be considered when dealing with the insulation characteristics of DC-GIL and the insulator. The suggested method in this paper can be applied to evaluate the transient charge and electric field characteristics of DC-GIL during various operating conditions.

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