



Review Review of Surface Charge Accumulation on Insulators in DC Gas-Insulated Power Transmission Lines: Measurement and Suppression Measures

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Abstract: Gas-insulated power transmission lines (GILs) can replace cables and overhead transmission lines, playing an important role in DC transmission systems. However, the influence of surface charge accumulation on insulation reliability cannot be ignored as the operational voltage of the DC GIL increases. In this paper, the measurement methods for the insulator surface potential are summarized, including, dust maps, the Pockels effect method, and the electrostatic probe method. Then, a typical surface charge inversion algorithm is introduced. The main influencing factors of surface charge accumulation are analyzed, such as the applied voltage, insulation gas, insulator shape, and temperature. The charge accumulation pathway is revealed. Furthermore, methods for inhibiting the accumulation of surface charges on insulators. Finally, the development direction of DC GIL insulators is predicted. We anticipate that the online monitoring of surface charge distribution, clarifying the percentage of charge accumulation pathways, and optimizing the insulator casting process will be the research directions for the insulator surface charge topic in the future. This article provides a comprehensive understanding of the surface charges of GIL insulators and a reference for the insulation design of DC GILs.

Keywords: gas-insulated power transmission line (GIL); surface potential measurement; surface charge inversion algorithm; surface charge accumulation mechanism; surface charge suppression measure

1. Introduction

Primary energy is mainly distributed in the northwest of China, while most electric energy is consumed in the central and eastern regions. Therefore, it is necessary to implement high-capacity and long-distance power transmission to meet the increasing demand for electricity [1–3]. Compared with AC, high-voltage DC transmission has advantages such as low losses, a large transmission capacity, and convenience for grid interconnection. DC transmission has been widely used in the long-distance transmission of electric energy [4–6]. Ultra-high voltage (UHV) and high-voltage direct current (HVDC) power transmission systems have rapidly developed since the 1950s [7,8]. The DC system is of great significance for China to optimize its energy allocation [9,10]. However, the HVDC transmission lines are facing new challenges, such as high altitudes, large drops, harsh meteorological conditions, low electromagnetic radiation, and strict environmental protection rules [11,12], and the overhead transmission lines and power cables cannot meet these requirements. Under such power supply requirements, gas-insulated transmission lines (GILs) with a SF₆ or SF₆/N₂ gas mixture as the insulation medium have many advantages, such as a large transmission capacity, small footprint, high operational stability, and environmental friendliness [13–15].



Citation: Liang, F.; Luo, H.; Fan, X.; Li, X.; Wang, X. Review of Surface Charge Accumulation on Insulators in DC Gas-Insulated Power Transmission Lines: Measurement and Suppression Measures. *Energies* **2023**, *16*, 6027. https://doi.org/ 10.3390/en16166027

Academic Editor: Abu-Siada Ahmed

Received: 8 June 2023 Revised: 7 August 2023 Accepted: 12 August 2023 Published: 17 August 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). GILs can be directly buried underground or installed in tunnels. Therefore, GILs are an excellent choice for large-scale power transmission in addition to overhead transmission lines and power cables [16].

DC GILs will play an important role with the development of DC transmission [17–19]. However, the GILs in operation are basically a AC systems. There are only a few DC GILs due to the difference between AC and DC insulation systems [20,21]. This is because of the different electric field distributions caused by the surface charge accumulation on the insulator [22]. For AC systems, the distribution of the electric field depends on the permittivity. However, the DC system is mainly determined by the resistivity of the material [23,24]. The electric field distribution gradually transitions from the initial capacitive electric field to a steady resistive electric field due to surface charge accumulation [25,26]. Furthermore, the internal insulation system of a DC GIL consists of insulators and compressed gas (e.g., SF_6 or a SF_6/N_2 gas mixture) [16,27]. However, the SF_6 in GILs is one of the greenhouse gases limited by the Kyoto Protocol. Its greenhouse effect is 23,500 times greater than that of CO₂ [28]. The arc extinguishing capability of insulation gas is not required. This is because there are no switchgears in GILs [16]. Furthermore, the SF_6/N_2 gas mixture has the advantages of good insulation strength, stable chemical properties, and lasting mixing characteristics. The SF_6/N_2 gas mixture has been widely used in second-generation GILs to reduce the use of SF_6 [29]. Moreover, the cost can be further reduced due to the low price of N_2 . For example, a 20% SF₆/80% N_2 gas mixture has 69% of the insulation strength of pure SF_6 under the same gas pressure. The pressure of the gas mixture needs to be increased by 45% in order to achieve the same insulation strength. However, the use of SF₆ is reduced by 71% [16]. Therefore, the impact of greenhouse gases has been reduced. As a result, the insulator has become the weakest component in DC GILs [30,31].

The insulator is the core component of a GIL [32]. GIL insulators are mainly divided into basin insulators and tri-post insulators. High-voltage conductors are supported by insulators. The conductor is mounted on the axis of the GIL. Additionally, high-voltage conductors are kept insulated from the ground by the insulator [33–36]. The gas seal of the pipeline is achieved by a basin insulator with a sealing ring. The installation position of the tri-post insulator can be easily adjusted. This is because the grounded electrode of the tri-post insulator has a wheel. GIL insulators are mainly composed of epoxy resins with high resistivity [37–39]. As a result, the accumulated surface charge cannot dissipate for a long time. Therefore, the operation of the GIL is threatened due to the flashover triggered by the accumulated surface charges [40–43].

The critical boundary parallel to the insulator surface was selected as the flashover pathway by Kumara et al. The line originated from the maximum electric field on the cathode. A flashover voltage model considering the influence of surface charges was established by determining the initiation, development, and maintenance of the streamer. Under Gaussian distribution, the pulse flashover voltage was decreased by nearly 11% when the maximum positive charge density was 125 μ C/m² [44]. Furthermore, the DC ±500 kV gas-insulated switchgear (GIS) developed by the Kansai Electric Power Company, Shikoku Electric Power Company, and Power Development Company of Japan has been successfully applied in the Anan converter station. However, the actual operation voltage is only half of the rated voltage due to the influence of the insulator surface charges [45–47]. This means that the surface charge accumulation of insulators leading to a decrease in the flashover voltage is the issue restricting the development of DC GILs [48–51].

In this paper, the surface charge measurement technology, inversion algorithm, accumulation mechanism, and inhibitory strategies for GIL insulators are summarized. Additionally, the research trends in insulator surface charges are identified. This article provides a reference for the surface charge accumulation of DC GIL insulators.

2. Surface Potential Measurement

The study of surface charges should be based on the accurate measurement of the surface potential distribution on the GIL insulator [52]. The measurement of surface potential

is different from that of the voltage for a high-voltage conductor. This is because a certain insulation gap must be maintained between the probe and the measured surface to prevent the leakage of the induced charge onto the probe. At present, the main measurement methods for insulator surface potential include dust maps, the Pockels effect, and electrostatic probes. [53,54].

2.1. Dust Map

Dust maps, also known as Lichtenberg figures, were proposed by Lichtenberg in 1777 [52]. Firstly, the red lead oxide and yellow sulfur are selected. The powder is uniformly suspended in gas. The charged powder with different polarities is absorbed on the insulator surface due to the electrostatic attraction of the surface charges. As a result, the visual analysis of the charge distribution is realized. However, the surface charge distribution cannot be quantitatively measured by a dust map [55]. Since the dust particles are adsorbed on the measured surface, it is not possible to achieve repeated measurements through a dust map [56]. The movement of charged dust particles is also affected by gravity and buoyancy [57]. Furthermore, the original surface charge distribution may be changed. This means that the accuracy of dust maps needs to be further improved. Based on a dust map established by quartz and feldspar powder, the surface charge distribution characteristics with a hollow ring structure are shown in Figure 1 [58].



Figure 1. Dust map of surface charge distribution with a hollow ring [58].

2.2. Pockels Effect

The Pockels effect method was proposed by Takada in 1991. The principle was based on the electro-optical effect of Pockels crystals, such as $Bi_{12}SiO_{20}$ and Bi_4GeO_{12} [12,59]. The refractivity of Pockels crystals varies linearly with the electric field [60]. Once the electric field inside the crystals is changed due to the accumulated surface charge, the phase of the incident laser is delayed. The phase delay of light is transformed into a difference in light intensity. Then, the electric field distribution inside the crystal is obtained. As a result, the surface charge density is calculated, as shown in Figure 2 [61]. The real-time and quantitative measurement of surface charges on certain thin and transparent materials can be realized by the Pockels effect [18]. Furthermore, the method is only applicable to the measurement of insulator surface charges under an AC voltage or impulse voltage due to the electrostatic relaxation of Pockels crystals [12].



Figure 2. Schematic of the Pockels effect [61].

2.3. Electrostatic Probe

The electrostatic probe method is a non-contact measurement technique [62,63]. There are two commonly used electrostatic probes: capacitive electrostatic probes based on electrostatic induction and Kelvin electrostatic probes designed according to the principle of electric field compensation [64,65]. The capacitive electrostatic probe was proposed by Davies in 1967 [66]. The quantitative measurement of surface charges can be realized by a voltage-following circuit. The data acquisition unit of the probe is composed of a high-input-impedance operational amplifier [67]. In contrast to capacitive probes, Kelvin probes are active probes. Furthermore, Kelvin probes are not affected by the surrounding gas. Kelvin probes are widely used due to their higher accuracy. Their measurement principle is shown in Figure 3 [64].



Figure 3. Measurement principle of a Kelvin electrostatic probe [64].

The inductive electrode in the probe is kept vibrating by an oscillator. As a result, the capacitance between the electrostatic probe and the measured surface is changed. If the voltage on the probe is not equal to the measured surface potential, a displacement current is generated on the induction electrode. The voltage on the probe is adjusted until the induced current becomes zero. At this moment, the voltage on the probe is equal to the measured surface potential [68]. Since there is no potential difference between the probe and the measured surface, the partial discharge triggered by the electrostatic probe during the measurement is avoided [57]. This method is an ideal measurement method for surface charges. Typical products include the Trek-341B [69], Trek-347 [70,71], and Monroe 244A electrostatic voltmeter [72,73].

3. Surface Charge Inverse Algorithm

For an electrostatic probe, only the surface potential can be directly measured. Therefore, it is essential to calculate the surface charge density by the inversion algorithm [52]. There have been a number of inversion algorithms proposed in the past, such as the linear algorithm, λ function method, improved λ function method, analytical method, and φ function method [1].

3.1. Linear Algorithm

The linear algorithm was proposed by Davies in 1967. The linear relationship between the surface charge and the induced voltage on the probe is established based on the equivalent measurement circuit, as shown in Figure 4 [1]. The measurement circuit of a capacitance probe consists of two parallel branches, where C_d is the capacitance of the dielectric, C_g is the capacitance formed by the gap between the grounded electrode and the dielectric, C_p is the capacitance between the probe and the measured surface, C_m is the capacitance of the electrostatic probe to the ground, and A is the effective area measured by the probe.



Figure 4. Measurement through capacitive electrostatic probes: (**a**) measurement diagram, (**b**) equivalent circuit [1].

When the gap between the electrostatic probe and the measured surface is small enough, the electric field between them is approximately uniform. Based on the principle of capacitor voltage division, the linear relationship between the surface charge density σ and induced voltage on the probe U_g can be obtained [74].

 σ

$$= M \cdot U_{\rm g}$$
 (1)

where *M* is the scaling coefficient.

The calculation of the linear algorithm is very simple. However, the method is only suitable for thin films smaller than 5 mm. This is mainly because the equivalent circuit is not always consistent during the measurement. Furthermore, the influence of the surface charge outside the measurement area on the results cannot be ignored [67].

3.2. λ Function Method

The relationship between the induced charge on the probe and the surface charges was established by Perdersen et al. based on the λ function [75].

$$q = \iint_{A_0} \lambda \sigma \mathrm{dA} \tag{2}$$

where *q* is the induced charge on the electrostatic probe, A_0 is the measured area, and λ is the solution of the Laplace equation for the insulation system.

Compared with the linear algorithm, the λ function method has a higher accuracy. However, the method is only suitable for geometrically symmetric insulation systems. Furthermore, the influence of the measurement position of the electrostatic probe is ignored [1].

3.3. Improved λ Function Method

The improved λ function method was proposed by Kumada et al. in 2004 with reference to digital image processing technology [76]. The convolution operation in the spatial domain is transformed by two-dimensional Fourier transform into the product calculation in the frequency domain.

$$\boldsymbol{\Phi}(\boldsymbol{\mu},\boldsymbol{\nu}) = \boldsymbol{H}(\boldsymbol{\mu},\boldsymbol{\nu}) \cdot \boldsymbol{\sigma}(\boldsymbol{\mu},\boldsymbol{\nu}) \tag{3}$$

The calculation of the inversion matrix is avoided. The surface charge density in the frequency domain is solved by division. Finally, the surface charge density $\sigma(x, y)$ in the space domain is obtained by inverse Fourier transform. Thus, the calculation of the surface charge is greatly simplified. Furthermore, the Wiener filter is used in the frequency domain for noise reduction to further improve the accuracy. However, this method is only applicable to shift-invariant systems, such as large-area flat plates and long cylindrical tubes [77].

3.4. Analytical Method

The analytical method was proposed by Ootera et al. [78]. The method considering all surface charges was based on the theory of electrostatic fields. When the high-voltage electrode is grounded, the insulator surface is divided into n grid units based on the finite element method. Once the mesh is fine enough, the surface charge can be considered uniformly distributed in any cell. According to the superposition theorem of potential, the potential V_i of any element i satisfies the following formula:

$$\begin{bmatrix} P_{11} & P_{12} & \cdots & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & \cdots & P_{2n} \\ \vdots & \vdots & & & \vdots \\ P_{n1} & P_{n2} & \cdots & \cdots & P_{nn} \end{bmatrix} \begin{bmatrix} \sigma_1' \\ \sigma_2' \\ \vdots \\ \vdots \\ \sigma_n' \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ \vdots \\ V_n \end{bmatrix}$$
(4)
$$P_{ij} = \frac{1}{4\pi\varepsilon_0} \int_{S_i} \frac{1}{r_{ij}} dS$$
(5)

where ε_0 is the vacuum permittivity; σ_i and S_i are the apparent surface charge density and area, respectively; and r_{ij} is the distance between elements *i* and *j*.

Based on the dielectric interface conditions, the relationship between the apparent surface charge density and free surface charge density σ can be written as follows:

$$\begin{bmatrix} F_{11} & F_{12} & \cdots & \cdots & F_{1n} \\ F_{21} & F_{22} & \cdots & \cdots & F_{2n} \\ \vdots & \vdots & & & \vdots \\ F_{n1} & F_{n2} & \cdots & \cdots & F_{nn} \end{bmatrix} \begin{bmatrix} \sigma'_1 \\ \sigma'_2 \\ \vdots \\ \vdots \\ \sigma'_n \end{bmatrix} = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \vdots \\ \sigma_n \end{bmatrix}$$
(6)

$$F_{ij} = \begin{cases} \frac{\varepsilon_2 + \varepsilon_1}{2\varepsilon_0} & i = j\\ (\varepsilon_2 - \varepsilon_1) \frac{1}{4\pi\varepsilon_0} \int\limits_{S_i} \frac{r_{ij} \cdot n_j}{r_{ij}^3} dS & i \neq j \end{cases}$$
(7)

where subscripts 1 and 2 represent the insulator side and the gas side, respectively; ε is the permittivity of the material; and *n* is the unit normal vector in the positive direction pointing from the insulator to the gas.

 σ

Therefore, the surface charge density is:

$$=TV$$
 (8)

The inversion matrix *T* is only determined by the material and geometry of the model. Therefore, a surface charge density of $1 \,\mu\text{C/m}^2$ is defined for the element to solve the surface potential distribution on the insulator. As a result, the inversion matrix *T* is obtained by moving the unit charge [79].

3.5. φ Function Method

Based on the λ function method, the relationship between the induced voltage on the probe and the surface charge was constructed by Faircloth et al. [80]. The insulator surface is divided into many small regions based on the finite element method. The surface charge of all regions contributes to the surface potential.

V

$$=\sigma\Phi$$
 (9)

For a particular insulation system, the inversion matrix $\boldsymbol{\Phi}$ only depends on the geometric size and material. The $\boldsymbol{\Phi}$ matrix is solved by finite element software, such as ANSYS and COMSOL Multiphysics. Firstly, an inversion calculation model is built. The unit charge is defined on the surface of the measured insulator to calculate the surface potential distribution. As a result, the complete $\boldsymbol{\Phi}$ matrix is solved. The $\boldsymbol{\varphi}$ function method takes the motion of the electrostatic probe into account, thus improving the accuracy. However, the amount of calculation increases with the dimensions of the inversion matrix.

4. Surface Charge Accumulation Mechanism

The surface charge accumulation of a DC GIL insulator is affected by the applied voltage, insulation gas, insulator shape, temperature, etc.

4.1. Applied Voltage

Under a DC voltage, the surface charge density increases with the applied time. The surface charge distribution is similar under different voltage levels [39]. Furthermore, the polarity of surface charges is reversed due to the increase in the DC voltage when only natural radiation is considered for the generation of charged particles in gas [25]. Since the conductivity of the insulation gas and insulator is a function of the electric field [81], the surface charge accumulation is also affected by the electric field.

4.2. Insulation Gas

In order to reduce the use of SF₆, the insulation gas of second-generation GILs is a SF₆/N₂ gas mixture [16]. Therefore, the surface charge distribution of insulators in 0.5 MPa pure SF₆ and a 20% SF₆/80% N₂ gas mixture were compared by Wang et al. [82]. The results showed that the amount of surface charge was larger in the 20% SF₆/80% N₂ gas mixture under -30 kV. This was mainly because the partial discharge in the gas increased with the decrease in the SF₆ content. Furthermore, the accumulation of surface charges on insulators in the pure SF₆ had a significant polarity effect. That is to say, the surface charges under a negative voltage were obviously larger than those under a positive voltage. However, no significant polarity effect was observed in the 20% SF₆/80% N₂ gas mixture. This was because the pure SF₆ was more sensitive to metal particles. The ionization coefficient of the gas sharply increased due to the enhancement in the local electric fields. As a result, the sources of the surface charges increased [83,84]. For the 20% SF₆/80% N₂ gas mixture, a polarity effect was not observed. This was mainly because the sensitivity of the partial discharge to the electric field distortion was reduced by the N₂.

4.3. Insulator Shape

The accumulation of surface charges is inevitably affected by the geometry of the insulator. Early on, cylindrical insulators were used as simplified models for GIL insulators. Then, cylindrical insulators with shielded electrodes were adopted by Wang et al. [62]. In order to truly reflect the operational conditions of GIL insulators, the circular insulator was proposed by Li et al. [70]. Furthermore, proportionally reduced conical insulators were adopted by Deng et al. [29]. Bowl-shaped insulators were designed to achieve the self-adaptation of surface charges based on nonlinear materials [85]. In addition, an actual GIL basin-type insulator was researched by Qi et al., as shown in Figure 5 [86].



Figure 5. Different insulator shapes: (a) cone-like frustum, (b) cone, (c) bowl type, (d) basin-type [29,70,85,86].

Based on a surface charge transport model considering the microscopic parameters of the gas, the influence of the insulator shape was analyzed by Ma et al. The initial capacitive electric field distribution was compared with the steady-state resistive electric field distribution [87]. The results showed that the surface charge distribution was similar to the normal component of the initial capacitive electric field. The amount of surface charge accumulated on the conical insulator was the largest.

4.4. Temperature

Due to the Joule heating of the operational current, the temperature of the internal conductor in a GIL may rise to 90 °C [88]. Furthermore, the volume conductivity of epoxy insulators is a function of the temperature. The partial discharge in a gas is also affected by the temperature [89]. Therefore, the influence of the temperature on the surface charge accumulation cannot be ignored. The temperature distribution inside a GIL was calculated by Zhou et al. based on thermal convection, radiation, and conduction [90]. The results showed that the temperature distribution inside the GIL gradually decreased from the center conductor to the grounded shell. The temperature gradient was 30 K under a current of 3450 A. The peak of surface charge density was 7.68 nC/cm², which increased by 60%. Additionally, high-temperature oil circulation was used to heat the internal conductor of the GIL. As a result, a surface potential measurement platform for DC GIL insulators under a temperature gradient was established, as shown in Figure 6 [91].

Once the temperature gradient was 70 $^{\circ}$ C, the average value of the surface potential increased from 278 V to 1670 V under a positive voltage. Under a negative voltage, the average surface potential increased nearly twofold. Tang et al. pointed out that the mean free path of electrons increased with the temperature. Therefore, the initial voltage of the corona decreased. As a result, the positive charge density increased under the temperature gradient [41].

The above factors affecting insulator surface charges are mainly due to the differences in the charge accumulation pathway. There are three pathways to accumulating charge on an insulator surface: through the insulator volume, insulation gas, and along the insulator surface [92]. For the ideal case of ignoring the insulation defects inside the GIL, the surface resistivity of the insulator is large enough. The current along the insulator surface is small enough to be ignored. Therefore, the charge accumulated through the insulator volume is uniformly distributed [18]. The conduction current is determined



(a)

by the volume conductivity of the insulator. For conical insulators, charges of the same polarity accumulate on the insulator surface near the inner conductor [36]. Since space charges are easily generated due to the uneven distribution of volume conductivity, the space charge migrates to the insulator surface, resulting in surface charge accumulation. That is to say, it follows the volume conductivity model proposed by Cooke et al. [12].



Figure 6. Surface potential measurement system under a temperature gradient [91].

The conduction current through the gas is affected by the generation rate, recombination coefficient, mobility, diffusion coefficient, and other factors [7]. Insulation defects are inevitable within a DC GIL, such as protrusions on the electrode, metal particles on the insulator surface, and the gas-electrode-insulator tri-junction, since the corona discharge of insulation defects is the main cause of surface charge accumulation. The randomly distributed charge spots and charge bands are shown in Figure 7 [18]. This means that the insulator surface charge distribution is uneven [18]. Furthermore, a normal electric field model was proposed by Knecht et al. [93]. It showed that the normal electric field on the insulator surface is the cause of charge accumulation.



Figure 7. Surface charge distribution pattern: 1. uniform distribution, 2. charge spots, 3. charge clouds [18].

The conduction current along the surface is closely related to the surface conductivity of the material [94]. For insulators with surface modification, the surface charge distribution depends on the conduction current along the surface. The tangential electric field model was proposed by Nakanishi et al. [95]. This model points out that there is an exponential relationship between surface conductivity and tangential electric field, resulting in uneven material surface. Therefore, the discontinuity of conducting current along the surface is the main cause of surface charge accumulation.

The three accumulation pathways of surface charges exist simultaneously. However, the proportion of each part varies significantly under different tests [28]. For the vacuum, corona discharges from the tri-junction of the cathode are the main source of insulator surface charges [96]. Yu et al. pointed out that the surface charge density is closely related to the secondary electron energy emission curve [97]. When the partial discharge in the gas is ignored, the conduction current through the insulator volume is the main accumulation pathway for surface charges [87]. For high-resistivity insulation systems, the accumulation of surface charges is determined by the conduction current in the gas side. The main accumulation pathway gradually changes from the gas to the insulator when the volume resistivity is less than $5 \times 10^{17} \Omega \cdot \text{cm}$ [22]. Furthermore, the generation rate of ion pairs in the gas is one of the key factors. The accumulation pathway changes to the conduction current in the gas with the increase in the ion pair generation rate [48,98].

For basin insulators, a unified surface charge accumulation mechanism was proposed by Li et al. The electric field is divided into three levels based on the leakage current, as shown in Figure 8 [99–101]. For the low electric field, there are many factors, such as residual static charges on the surface, bulk charges inside the insulator, and charged particles in the gas. Each factor may become the core. Thus, charge accumulation under low electric fields can occur in a variety of ways. Under a medium electric field, charges of the same polarity injected through the insulator are the main source. Since the ionization in the gas side is enhanced due to insulation defects under a high electric field, the influence of charged particles in the gas on the surface charge accumulation increases. Therefore, the source of the surface charge is electric-field-dependent.



Figure 8. Field-dependent surface charge accumulation model [101].

5. Surface Charge Suppression Strategy

The methods to reduce the surface charge include inhibiting the accumulation of surface charges and promoting the dissipation of accumulated charge, for example, by doping modification, structural optimization, and surface treatment [102]. Since the surface charge accumulation is determined by the conduction current flowing through the insulator when the volume resistivity of the insulator is lower than the critical value of

the system [103], increasing the volume resistivity of insulators is an effective method to inhibit surface charge accumulation. The volume conductivity of epoxy resin was reduced through doping with fullerene C60 by Zhang et al. The surface charge on the C60-epoxy composite insulators was reduced due to the hollow cage structure of C60 [104]. That is to say, C60 has extremely strong electrophilic properties. Free electrons in the polymer matrix could be captured.

Nanoparticle doping is the most commonly used modification method for insulation materials, such as Al₂O₃, TiO₂, SiO₂, BN, and AlN [105–112]. This is because a charge accumulation center is introduced by nanoparticles, and the carrier concentration is reduced. As a result, the material conductivity is decreased [113]. Since the surface charge is usually derived from partial discharge in gas for Al₂O₃ epoxy resin insulators [114–116], the normal electric field should be reduced as much as possible during the optimization of insulator shape [87]. For example, a conical insulator was adopted, and the flat bottom was basically parallel to the electric field line. As a result, there was only a small charge on the bottom [36]. Furthermore, a bowl-shaped insulator was designed by He et al. The normal electric field on the insulation area was designed to be negligible in order to reduce the surface charge, as shown in Figure 9 [7]. Therefore, the surface charge accumulation could be reduced by doping modification and structure optimization. However, the influence of the insulation surface is usually ignored. This is because the surface resistivity of GIL insulators is greater than the volume resistivity. The conduction current along the insulator surface is negligible.



Figure 9. Electric field distribution around insulators: (a) cone, (b) bowl-type [7,36].

For accumulated surface charges, surface treatment is used to promote dissipation and reduce the surface charge. The main dissipation pathways include: recombination with charged particles in gas, dissipation through the insulator volume, and dissipation along the insulator surface [117]. As partial discharges are random, there is usually little recombination between heteropolar charged particles in gas. For GIL epoxy insulators, the volume conductivity is in the order of 10^{-17} S/m [118]. A surface conductivity of 10^{-18} S has been measured on epoxy resin insulators. As a result, it is impossible for the surface charge to dissipate autonomously for a long period of time. For example, the dissipation curve of the surface potential within 1200 s is approximately horizontal. The dissipation of charge is negligible [119].

The dissipation of surface charges through an insulator material is promoted by the increase in the volume conductivity. However, the insulation size needs to be increased due to the decrease in insulation strength. Therefore, an ideal charge dissipation strategy is to increase the surface conductivity through surface treatment. The surface treatment of insulator materials is used to increase the surface conductivity by 1–2 orders of magnitude, including through surface fluorination, plasma surface treatment, and coating. Thus, the amount of surface charge is reduced by accelerating the dissipation rate.

5.1. Fluoridation

An epoxy resin sheet was fluorinated in a gas mixture of $12.5\%F_2/87.5\%N_2$ by An et al., as shown in Figure 10. A fluorinated layer of micron size was formed. The mobility of the carrier was improved when the fluorination reaction time was less than 60 min. That is to say, the rate of surface charge dissipation along the surface was accelerated [120].



Figure 10. SEM images of the cross-section of fluorinated samples [73].

5.2. Plasma Surface Treatment

Plasma was used by Shao et al. to improve surface conductivity. According to Figure 11, an atmospheric plasma injection device deposited SiOx on the surface of the epoxy resin. Inorganic groups were introduced, such as Si-O-Si and Si-OH [121,122]. Therefore, plasma treatments could also result in shallow trap energy levels on the surface. As a result, the surface charge could rapidly dissipate along the insulator surface [123].



Figure 11. Atmospheric pressure plasma jet device [121].

5.3. Coating

Non-uniform coatings are also functional gradient materials. A functional gradient coating was prepared by Li et al. [124]. The surface conductivity with a gradient was formed by magnetron sputtering ZnO or fluoridation on the epoxy resin surface, as shown in Figure 12.



Figure 12. Functional gradient coating on the insulator surface: (**a**) magnetron sputtering, (**b**) fluorination [124,125].

The effect of the concentration and particle diameter of the SiC in the coating on the surface charges was analyzed by Tang et al. [50]. The results showed that the surface trap density was increased due to the SiC/EP coating. Therefore, more surface charges accumulated. Since the surface trap energy level could also be decreased by the coating, the dissipation rate of charges was accelerated. This indicates that the regulation of SiC/EP coatings is attributed to the interaction between the trap density and trap energy level.

6. Conclusions and Suggestions for Future Work

The surface charge measurement methods, charge accumulation mechanisms, and suppression measures for DC GIL insulators were summarized. In order to measure the insulator surface potential, dust patterns, the Pockels effect method, and the electrostatic probe method can be implemented. Then, a surface charge inversion algorithm should be adopted to calculate the surface charge density. Based on the surface charge distribution characteristics, many factors (such as the applied voltage, insulation gas, insulator shape, and temperature) have an impact on the surface charge accumulation. For surface charge suppression, the main solution is inhibiting the accumulation of surface charges and promoting the dissipation of accumulated charges. Finally, suggestions for future research in this area are as follows:

(1) With regard to surface potential measurement, Kelvin electrostatic probes have a high accuracy. However, the application of Kelvin electrostatic probes in online measurements is limited by their lower measurement range. Furthermore, capacitive electrostatic probes have a simple structure and lower cost. Capacitive probes are expected to be applied for the online monitoring of insulator surface charges after the measurement accuracy is further improved.

(2) Focusing on the surface charge inversion algorithm, the environmental noise during the data acquisition cannot be ignored. For online measurement, the changes in the original electric field caused by the probe should be considered to ensure the accuracy of the measurement. Furthermore, a 3D display of the insulator surface charge distribution could be established by the surface charge inversion algorithm combined with data transmission, storage, and image processing.

(3) For the surface charge accumulation mechanism, the proportions of the three pathways of charge accumulation should be clarified. The dominant pathway of charge accumulation should be revealed to provide a theoretical basis for the suppression of surface charges. For the surface charge transport model, the influence of partial discharges in the gas and the surface trap distribution on the insulator cannot be ignored. Additionally, the type of carrier in the gas must be further distinguished rather than simply dividing it into positive ions, negative ions, and free electrons.

(4) In terms of surface charge suppression, the application of coatings on the GIL insulator surface needs to be further tested in terms of adhesion strength and material aging. The effect of coating detachment on insulation should be paid more attention.

Since the material doping modification of an insulator is limited by the casting techniques available, the interface due to the curing properties of different materials should not be ignored. Therefore, understanding the transition region between different doped materials will be one of the challenges for subsequent research.

Author Contributions: Writing—original draft preparation, F.L. and H.L.; writing—review and editing, X.F.; visualization, X.L. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under grant No. 51677061.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to thank Jiayi Liu from Hunan University for the help with the writing.

Conflicts of Interest: The authors declare no conflict of interest.

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