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Surface Charging Phenomenon on HVDC Spacers in Compressed SF_6 Insulation and Charge Tailoring Strategies

Chuanyang Li[1], Yuan Xu[2], Chuanjie Lin[3], Geng Chen[4], Youping Tu[4], Yao Zhou[3], Zhipeng Lei[1], Tao Han[1], Simone Vincenzo Suraci[1], Jian Wang[4], Weidong Liu[3], M. Tariq Nazir[5], Shun He[6], Andrea Cavallini[1], Giovanni Mazzanti[1], Davide Fabiani[1,*], Jinliang He [3,*]

[1] Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi", University of Bologna, Viale Risorgimento 2, Bologna, 40136, Italy

[2] China Electric Power Research Institute, Haidian District, Beijing 100192, China

[3] State Key Laboratory of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China

[4] Beijing Area Major Laboratory of High Voltage and Electromagnetic Compatibility, North China Electric Power University, Beijing 102206, China

[5] School of Mechanical and Manufacturing Engineering, University of New South Wales Sydney, NSW 2052, Australia

[6] Electric Power Research Institute, Yunnan Electric Power Grid Co., ltd., Kunming, Yunnan, 650217, China

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Abstract: Surface flashover of spacers is a key factor limiting the application of HVDC GIS/GIL, while the charge accumulation on the surface of the spacer could have a potential adverse effect on the surface flashover voltage. This paper discusses the laws regarding distribution patterns of surface charges and the related mechanism. The field-dependent property is discussed in detail to comprehensively illustrate the charge transport mechanism and explain the research differences regarding different surface charge patterns obtained by previous researchers. In addition, the main surface charge control methods for epoxy resin are summarized and discussed. The potential research directions of charge control methods and key points in manufacturing of spacers used in HVDC GIS/GIL are also prospected.

1. Introduction

Spacers are key components that are used in gas insulated switchgears (GIS) or gas insulated power transmission lines (GILs) to separate high voltage conductors from grounded enclosures [1-3]. However, the spacer is the weakest component mainly because of its presence introduces a gas-solid-insulation triple junction [4, 5]. This triple junction causes inevitable local electric field distortion, which greatly affects the reliability of the spacer. More importantly, residual charges would stay on the spacer surface for a long time under a dc electric field, or after a dc voltage was applied to the spacer. These surface charges affect the local electric field distribution and may have an adverse influence on the reliability of the spacer, depending on the property of these charges and the polarity of the applied voltage [6, 7]. Due to the invisibility of charges and the difficulty in direct surface charge measurement, assessing charge transport phenomena and their influence on the electric field distortion have always been a tricky problem.

Numerous studies have been done by previous researchers regarding surface charge accumulation and charge suppression methods [8,9]. Surface charge patterns of different materials under different voltage waveform are considered, and various forms of material modification methods are used to suppress charge accumulation and to improve surface charge dissipation [1, 3-6]. In our recently-published paper, important studies on surface charge transport models were summarized, and the correlation between surface charge accumulation and the surface flashover phenomenon was concluded [1]. We further introduced a field-dependent charging model to explain the charge accumulation patterns on spacers under DC application [3]. This paper can be considered as a further extension of the content of the previous researches. However, the focus of this paper goes deeper on the surface charge pattern interpretation, based on a comprehensive understanding of charge transport mechanism. More accurately, using the field-dependent charging theory, we illustrate the surface charge transport mechanism to explain the different surface charge features obtained by former researchers. After that, the main surface charge control methods for epoxy resin in recent years are summarized. We hope that this article could provide researchers with a new perspective to understand the charging mechanism and interpret the surface charge accumulation patterns obtained in their own measurement. Meanwhile, it is also our expectation that this article could offer a useful tool for readers to understand and reference the surface charge tailoring methods.

2. Surface Charging Mechanism

2.1. Physical basis of surface charging

The surface charging phenomenon is a complicate process which involves electric conduction inside the dielectrics (i.e. both on the surface and in the volume) and surface charge trapping in gas phase. This conclusion has been

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accepted by former researchers [8-12]. Depending on the local electric field applied to the spacers, different charge transport mechanisms must be considered separately before interpreting surface charge patterns.

Surface charges injected from volume are related to the leakage current which follows a power law: $I = I_0 \times E\alpha$ (I_0 is a function of the temperature only) [13]. At low field, the value of α is close to a range between 1.04 and 0.99 for the filler-free and particle-filled resin, respectively, which is corresponding to an ohmic conduction [13]. At high fields, similar interpolations yield α value changes from 2.00 to 2.47 for the unfilled and particle filled epoxy resin, respectively. The lines of interpolation intersect at threshold fields E_{th} delimiting the two conduction modes: E_{th} = 17 kV mm^{-1} for the filler-free resin and E_{th} = 13 kV mm^{-1} for the particle filled resin [13], as shown in Figure 1. For the interface of a spacer operating under HVDC, the electric field should be far less than 17 kV/mm [14]. Therefore, the conduction model inside the bulk follows the ohmic conduction. However, it should be noted that the contribution of surface potential measurement value from volume injection is not directly related to the value of leakage current. Under the premise of power-off surface potential measurement, only the charge trapped in the volume and the charge that migrates along the normal electric field to the gas-solid interface can contribute to the surface potential measurement.

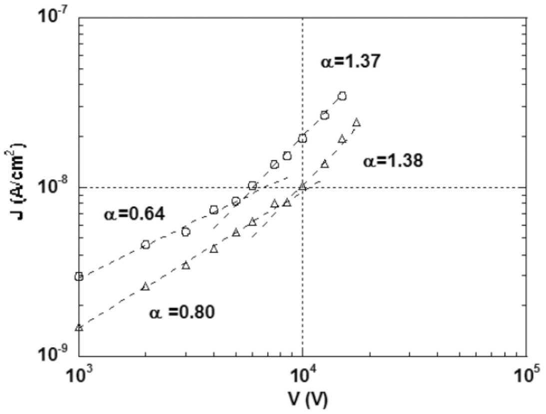

Fig.1. *Quasi-steady-state current densities J versus applied voltage V at 55 °C. Filler-free resin (○). Filled-resin (∆).[13]*

The physical process of the charge accumulation from the gas side is more complicated. We would like to start the discussion with the variation of the gas current measured between two parallel plate electrodes that firstly been studied by Townsend [15] as a function of the applied electric field, as shown in Figure 2. When the electric field is lower than a certain value, i.e. in zone I and zone II, natural ionization from cosmic radiations and natural radioactivity would be dominate factors accounting for charge carriers migration. In the ideal case (i.e., the insulator is defect-free and there is no micro-discharge on the gas side), the surface charge originated from the gas phase could be explained by charge carrier migration in zone I and zone II [16]. That is to say, at relative lower local electric field (from a micro perspective considering electric field strength near micro defects), charges accumulated on the spacer from the gas phase are generally attributed to the natural ionization which results from cosmic radiations and natural radioactivity.

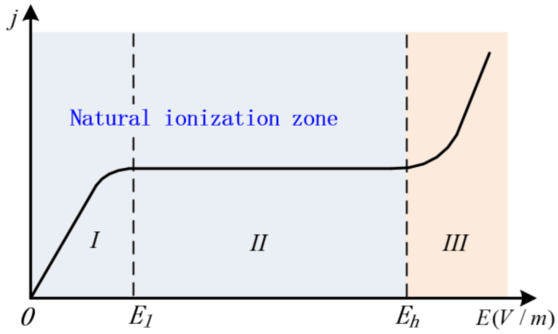

Fig.2. *The current density v.s. electric field strength curve using a plane to plane gap in air. (I: the ohmic conductance section; II: the current saturation section; III: the current surge section, new charge source.)*

When the electric field exceeds the ionization threshold electric field (i.e. in Zone III), the current increases quickly following an exponential law [15]. This can be explained by Townsend law that the ionization of the gas by electron collisions and ionization [15]. It is reported that the ionization of SF_6 and N_2 due to a corona discharge can generate electrons which involves the ionization (dissociation), electron attachment (dissociation), electron-impact dissociation, and recombination [17]. The generated negative charges include electrons, SF_6-, SF_5-, SF_4-, SF_3-, SF_2-, F-, and F_2-, while the generated positive charges include N_2+, SF_6+, SF_5+, SF_4+, SF_3+, SF_2+, SF+,S+, and F+ [17]. In this case, the charges accumulated on the spacer surface are mainly positive or negative ions due to ionization in SF_6.

2.2. Field-dependent surface charge patterns-Literature classification

Based on the analysis of the dominant charge physical process under different electric fields in Section 2.1, as well as in our original paper [3], we classify the previous research results according to: low electric field (L), moderate electric field without temperature gradient (M), high electric field (H), the electric field in the overlap regions (LM and MH), and the moderate electric field with temperature gradient (M-TG), as shown in Figure 3. The previous researches on surface charge accumulation patterns and models at different regions are also listed in Table 1.

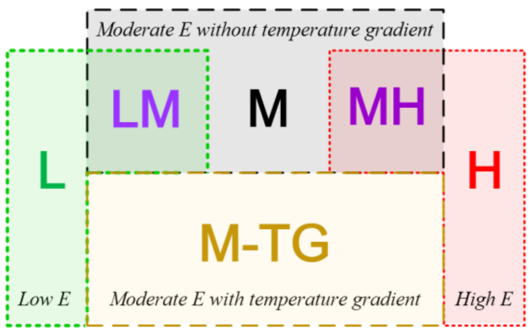

Fig.3.*Classification of research conclusions based on electric field region. (L: low electric field; LM: overlap zone between low electric field and moderate electric field; M:*

moderate electric field; MH: overlap zone between moderate electric field and high electric field; H: high electric field; M-TG: moderate electric field with temperature gradient.)

Tab.1*. The characteristics of surface charge patterns at different regions and the corresponding references.*

Zone	Charge distribution characteristics	Literature
L	Very low charge amount which seldom changes with increasing of voltage application time.	[18]
LM	Uniformly distributed homo-charges; locally distributed hetero-charges.	[19, 20]
M	Uniformly distributed homo-charges in domination; very little charge with hetero polarity.	[19, 20, 17, 21]
MH	Uniformly distributed homo-charges in domination; locally distributed charges with hetero polarity.	[19, 22-27]
H	hetero-charges in domination.	[28-30]
M-TG	Uniformly distributed homo-charges in domination; very little hetero-charges.	[31-33]

There are very few research results showing a surface charge pattern in Zone L. The surface charge pattern in this zone usually presents a low amplitude due to a very low electric field. If the electric field was increased, the increase in leakage current introduces a significant injection of homo-charges and these charges migrating through the bulk are pushed by the electric field line and reach the surface where there is an electric field component perpendicular to the surface. As a result, the charge distribution pattern falls into Zone LM, whose property shows a uniform distribution of charges with the homo polarity, and localized hetero-polar charges. Ma *et al*. applied a voltage of -50 kV to a 550 kV AC spacer (equivalent to an electric field of about 0.25kV/mm) [18]. The surface charge distribution shown in Figure 4 does not change much with the the voltage application time, which implies a surface charge pattern of Zone L. However, when the voltage was increased to -150 kV, a significant change in surface charge distribution is found with the increase of voltage application time. The pattern of uniformly distributed homo-charges with locally distributed hetero-charges implies that under -150 kV, the surface charge pattern has developed to Zone LM [18]. The authors believe that the non-uniform charge distribution is induced by the uneven distribution of the dielectric material under relative low voltage, which corresponding to the "unclear factors" under low electric field that are discussed in our original paper [3]. Meanwhile, under relative high voltage application, the surface charge pattern is dominated by the electric conduction through the volume [18].

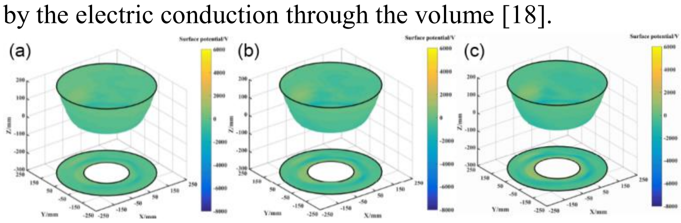

Fig.4*. Surface potential on the 550 kV cone type spacer under DC voltage U=-50 kV for 20h, 40h and 60h. [18]*

If the electric field continue to increase, the ion migration on the gas side would be saturated (referring to the stable section of the natural ionization zone shown in Figure 2). However, the bulk conduction current still increases with the increasing of electric field linearly [3]. This results in a surface charge accumulation pattern which is dominated by the bulk injected charges with homo polarity. At this time, the charge distribution pattern falls into Zone M. If the electric field was further increased, new ionization would be induced in the gas phase. As a result, the homo-polar charge would be detected uniformly (due to the bulk injection) on the convex surface, with a distinct hetero-polar charge locally distributed due to an ionization in the gas phase. At this time, the charge distribution pattern transitions to Zone MH. When the local electric field strength exceeds a certain value, due to strong ionization from the gas, the charge distribution pattern follows Zone H and the feature in this region is presented by a surface covered by hetero-charges [3].

Suda [19] and Zhang [20, 22] used experimental setups that are similar to each other to measure the surface charge in different gas environments. Their experimental conclusions are mutually corroborating and the surface charge patterns from their results cover the above mentioned three surface charge pattern zones (Zone LM, M, and MH). In Zhang's research, the applied voltage rises from -10 kV to -40 kV, and the surface charge pattern is shown in Figure 5. It can be seen that as the voltage increases from -10 kV to -30 kV, charges with the same polarity uniformly distributed near the high voltage electrode was less dominant compared with that after the voltage is increased to -35 kV (Figure 5 a-e). The unevenly distributed hetero-polar charge gradually increased with the applied voltage. The above phenomenon corresponds to a transition from Zone M to Zone MH. When the test voltage was raised to -35 kV and -40 kV (Figure 5 d and e), the surface of the spacer was substantially all covered by hetero-charges, and in this case the charge pattern enters Zone H. Similar conclusions can also be found in Qi's research [27]. He used a 220 kV spacer as experimental sample. When the voltage was increased from 38 kV to 43 kV, the hetero-polar charge gradually increased, indicating that the gas ionization factor gradually increased, corresponding to a surface charge pattern transition from Zone M to Zone MH.

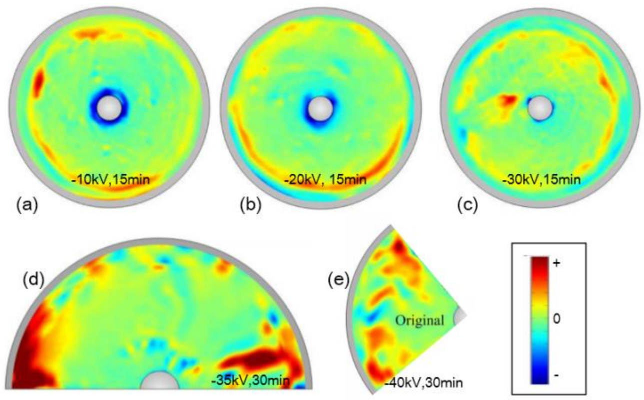

Fig.5*. Surface charge distribution on the sloping surface of the spacer after different voltage application.[20, 22]*

The surface charge patterns from the research conducted by Suda [19] are more representatively classified that is transitioned from Zone M to Zone MH. The related test results are shown in Figure 6. At -30 kV, the surface of the spacer was completely covered by homo-charges, indicating that the bulk injection dominates, and the related surface charge pattern strictly falls into Zone M. At -60 kV, hetero-charges were detected, which accounted for an

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ionization from the gas phase. Correspondingly, the charge distribution pattern transitions to Zone MH. When the voltage was increased up to -90 kV, the surface of the insulator was mostly covered by hetero-charges, indicating that a large part of the gas was ionized, corresponding to Zone H. However, his experimental results shows a voltage hysteresis compared to Zhang's results. It is because in Suda's experiment, the gas atmosphere is 0.5 MPa SF_6. The ionization is not easy to occur at low voltages (-10 kV~ -40 kV). However, Zhang uses an air atmosphere of 0.1-0.12 MPa. Thereby, the charge pattern transition to Zone H at a lower voltage can be understood.

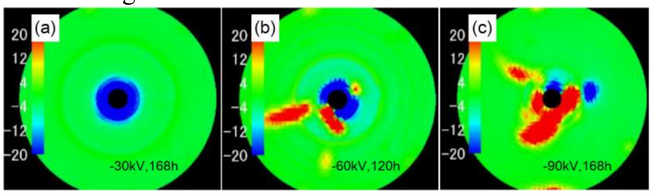

Fig.6. *Surface charge distribution on the sloping surface of the spacer after different voltage application.[19]*

Xue *et al.* used a spacer with similar shape and size compared to that of samples used by Zhang and Suda. The difference is that Xue uses four spacers with different surface roughness levels. The surface charge patterns in his experiment are shown in Figure 7. After applying ± 40 kV to the insulator, they found that the surface was essentially covered by charges with the same polarity [17]. However, with the increase of surface roughness level, the hetero polar charges begin to increase, which is due to a gas ionization that is easier to take place at a rougher surface. Similar conclusions can also be found in literature [21], where it is believed that surface leakage current would be the main factor affecting surface charge accumulation. These studies all attributed to Zone M.

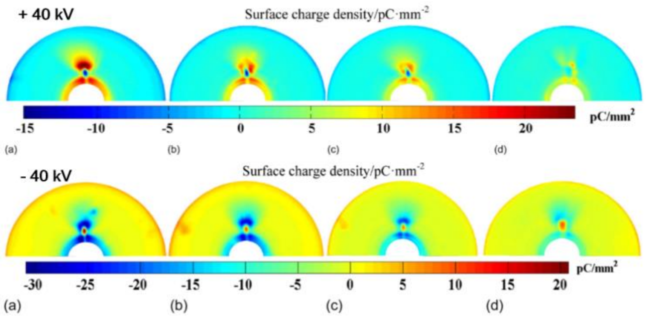

Fig. 7. *Surface charge distribution under ±40 kV DC voltage, with spacers of different surface roughness levels: (a) 0.58 µm; (b) 5.19 µlm; (c) 7.48 µm; (d) 9.24 µm.[17]*

For the charge distribution pattern of Zone MH, Cooke pointed out in his article published in 1982 that the surface charge of the insulator under the electric field comes from the bulk injection and the gas side ionization [23]. However, the amount of the bulk injected charge is much lower than that compared with the amount of gas side ionization, especially when there is a local tip ionization process. The surface charge from the gas side has the following features: charge can be formed more rapidly with larger charge amount compared to that from the volume. Figure 8 shows the surface charge distribution of the insulator after + 600 kV for 1 hour [23]. It can be seen that there is a slight charge of the same polarity near the high-voltage side electrode. This result proves that the trapping of charges due to ionization phenomena in the gas is simultaneously with the same polarity charge injection from the volume, but the hetero-charge is dominant when there is a local tip ionization process (Zone MH).

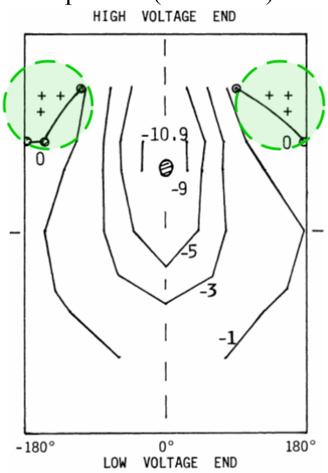

Fig.8. *Surface charge distribution of test insulator after +600 kV for 1 hour.[23]*

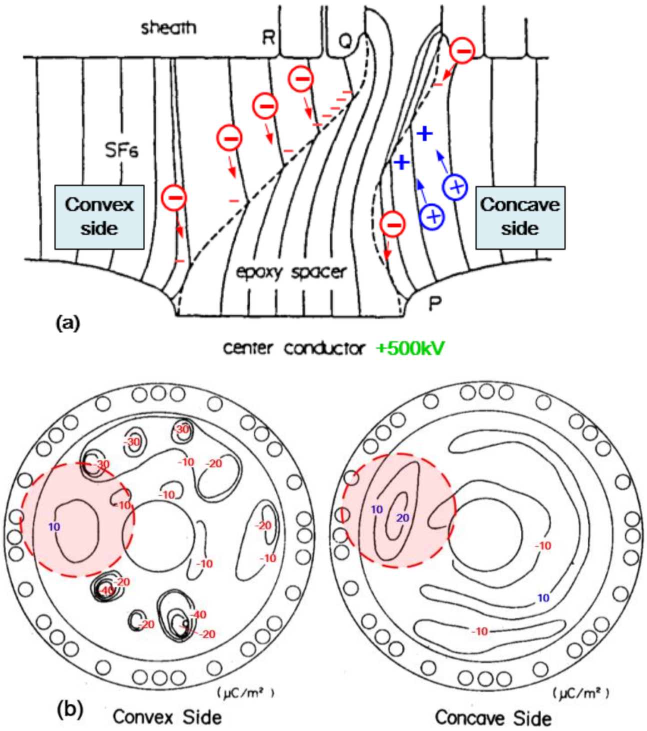

Fig.9. *Typical example of charge distributions on the cone-type spacer (+ 500 kV, 30 min). Figures in the map are charge densities in pC/cm². Electric field lines at the cone-type spacer. [25]*

For surface charge pattern regarding Zone MH, representative cases can be found in the research results obtained by Japanese researchers using a 550kV spacer [25, 26]. The surface charge measurement results by Ootera *et al.* are shown in Figure 9. It can be seen that the surface charge distribution of the convex and concave surfaces is basically obeyed by the law of gas side discharge due to intrusions. That is, hetero-charge is dominant on the convex surface side. Homo-charge dominates on the concave surface side. However, a small amount of homo-charges can be found also on the convex surface. We believe that it is because the

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large amount of the homo-charge in the same region on the concave surface affects the surface measurement results on the convex surface side. Relevant theoretical analysis and argumentation can refer to our previous research [34]. However, it is still difficult to determine barely from this figure that whether the charge pattern is into Zone LM or the Zone MH, without combining the work of Nitta *et al.* , which will be discussed in detail in following contents [26].

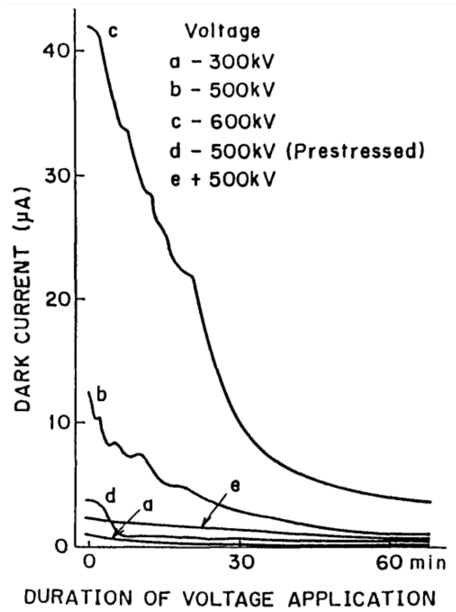

Fig.10. *Measurement of dark current during dc voltage application. [26]*

Nitta *et al.* repeated the measurement using Ootera's test system and analyzed the leakage current at different voltage applications. Together with Nitta's work, we can further determine the charge pattern obtained by Ootera. Figure 10 shows the leakage current measurement results under different voltage applications. When a voltage of -300 kV is applied, the leakage current basically show a linear trend with time, indicating that ionization does not take place in the gas phase, which is similar presented in our previous research results [3]. When -500 kV and -600 kV were applied, nonlinear leakage current curves could be found (a, b, and c), which indicates that an ionization was taking place in the gas. Combined with the conclusion of the convex surface potential measurement shown in Figure 11, we can further explore the physical phenomena behind their experiment: When the voltage was -500 kV, some negative charges of the same polarity appeared on the surface of the spacer, which was apparently derived from bulk conduction (Figure 11 convex curve 1). When the applied voltage was -900 kV, the entire convex side was completely covered by the positive polarity charges (convex curve 3 of Figure 11). This indicates that with the voltage application of -900 kV (the electric field is about 4.7 kV/mm), a corona discharge occurred on the surface of the ground electrode, and a large amount of positive charges (hetero polarity) were introduced. At this time, the charge distribution pattern falls into Zone H.

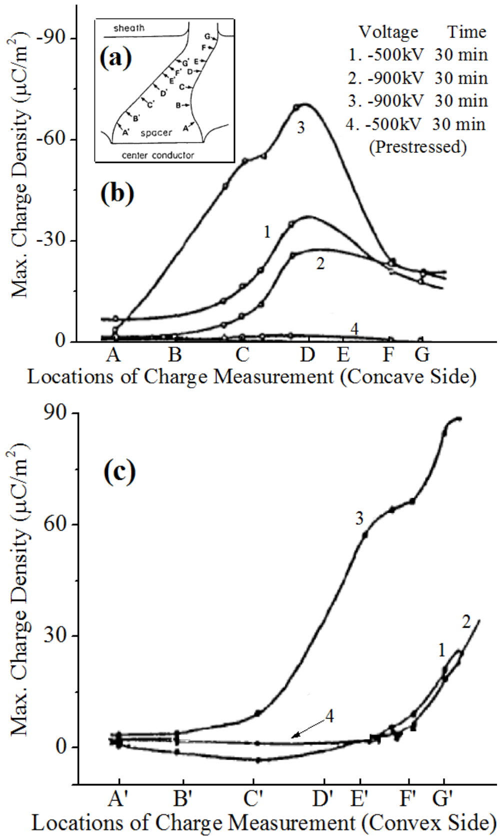

Fig.11. *Surface charge density measurement results: (a) Shape of the cone-type spacer and locations for probe measurement, (b) surface charge distribution along the radial direction of the concave side of the spacer, and (c) surface charge distribution along the radial direction of the convex side of the spacer.[26]*

The research conclusions of Nakanishi *et al.* also falls into the Zone MH [24]. They used post insulators to study the surface charge distribution characteristics under different electric fields and they pointed out that "The hetero-charge accumulation is because an electrode attracts the charge of opposite polarity. The charge density ought to depend on the intensity of radial electric field." Also, they proposed that the factors that have a great influence on surface charges should be field emissions and partial discharges [24].

Related research results that follow the Zone H include: research by Fujinami *et al.* using a post insulator model in 1989 [28], and researches by Li *et al.* using a spacer model in 2018 [29, 35, 36]. The commonality between these studies is that the applied electric field is relatively high, and the charge pattern appears to be dominated by the hetero-charge. Among them, Fujinami *et al.* applied an electric field of about 5 kV/mm, while Li *et al.* applied a field strength of more than 3.5 kV/mm. In addition, Vu-Cong *et al.* tested a 170 kV spacer and found only hetero-charge accumulated on the surface. They believes that the leakage current in SF_6 gas is the main mechanism for surface charge accumulation [30]. This result can also be explained by the charge pattern model in Zone H.

However, it should be noted that when there was a temperature gradient on the spacers, the surface charge distribution can change accordingly even at a low electric fields, and the surface charge pattern falls into Zone M-TG. The related surface charge pattern has the following features:

uniformly distributed homo-charges with very little hetero-charges. In this case, Lutz mentioned in his research paper that higher temperatures lead to lower volume resistivity values and thus to enhanced volume conduction through insulators [31]. In order to minimize surface charge accumulation within their investigated gas insulated system, insulating materials with a volume resistivity close to $5x10^{17}$ Ωcm should be chosen [31].

Meanwhile, it is also found by our former researches that the surface potential increases significantly under an applied temperature gradient because of electron injection and migration near the high-voltage electrode [32]. An "analogous ineffective region" was proposed to explain the shift in the surface potential. The results suggest that charge migration in the regions with high temperature near the high-voltage electrode plays a crucial role in creating the analogous ineffective region. The expansion of this region is equivalent to the high voltage electrode being stretched, which results in a large voltage drop across the area near the ground electrode. Under these conditions, positive streamers can be triggered at the triple junction of the ground electrode more easily [32].

Similar evidences can be found in the work of Ma *et al.* They proposed a simulation result on heat transfer and surface charge accumulation model foundation [33]. In their work, a heat transfer model of operating DC-GIL including the gas convection, radiation and heat conduction in the gas-solid insulation system was developed. A surface charge accumulation model was built including the nonlinearly relationship between volume current, electric field, and the space charge in the insulator induced by conductivities dependent on temperature profiles [33].

2.3. Field-dependent surface charge patterns-mechanism

Under low electric field (referring to a related surface charge pattern into Zone L), there are many unclear factors (i.e.electrostatic charges introduced during installation, homo-charges injected into the dielectric from the conductor, partial discharge due to particles on the surface of the conductor or local particles introduced during installation, homo- and hetero-charged ions in the gas environment, the hetero-charges generated by the local polarization, and the polarization charge due to a discontinuity of material conductance, etc.) and it is very difficult to separate a single or several influencing factors in dominate that most affect surface charge distribution patterns. Therefore, it is impossible to obtain a unified model that can illustrate all the experimental results obtained under low electric field.

For experimental results obtained under moderate electric fields (referring to a related surface charge pattern in Zone M) or under temperature gradients (referring to a related surface charge pattern into Zone MTG), the obtained surface charge patterns are dominated by the homo-charge from volume injection. This phenomenon can also be explained partially by the expansion of “analogous ineffective region”, which has been discussed in our previous research [32].

High electric field (providing a surface charge pattern into Zone H) is usually found where local defects exist. In this case, the dominant charge behavior depends on the local roughness of conductors and metal particles. This can be explained by the factor regarding the gas side ionization enhancement, as well as the donut-shaped charge cluster effect in local high field, which we will verify in detail in the upcoming article [41]. It should be noted that if a cone type spacer is subjected to a high electric field, due to the distribution of the electric field lines, hetero-charges can be detected on the convex surface side. The concave surface only accumulates homo polarity charges, which are contributed by the injected charge in the bulk and the homo-charges from gas ionization. However, it must be emphasized that the electric field range discussed in this letter is obtained at an already defined temperature and test setup. Changes in temperature, gas pressure or surface roughness of conductors can absolutely affect the division of the electric field range.

For the overlap regions, i.e. Zone LM and Zone MH, the surface charge pattern shows a characteristic similar to adjacent Zones. For example, the charge distribution of the low field and the moderate field (referring to a related surface charge pattern in Zone LM) is represented by uniformly distributed homo-charges with locally distributed hetero-charges, while the charge distribution of the moderate field and high field overlap region (referring to a related surface charge pattern in Zone MH) is featured by uniformly distributed homo-charges in domination, with locally distributed charges with hetero polarity. Therefore, it is difficult to find the difference between surface charge patterns in Zone LM and Zone MH, due to very much similarities in charge patterns. However, it is suggested that one can increase the applied voltage and see if the surface charge pattern transition to a pattern of Zone M or Zone H.

2.4. Key points and difficulties in future model development

In this chapter, the electric field strength applied to the insulator is classified, and the dominant charge behaviors under different electric field strength are discussed. The distribution law of the surface charge pattern is reasonably explained. However, there are still works to be done before refining of models in the future:

1) Due to the fact that surface charge measurement must be carried out after turning off the voltage, the dissipation of the surface and bulk charge during the interval between removing the voltage and starting the surface potential measurement can affect the result of surface potential measurement. This can in turn affect the division of the electric field ranges due to the reason that the bulk decay current is usually higher than that of the surface. Verification test done by authors show that the bulk charge dissipation rate was much faster than that of the surface charge dissipation rate: It was found that after the moderate electric field was applied, the surface potential of the spacer is detected to be homo polarity. However, after the spacer was being stored for a few minutes, the surface potential polarity gradually changed from its initially homo-polarity potential to a surface potential with the opposite polarity.

2) The field ranges during each experiments are determined to a large extent by the surface condition of the high voltage conductor, the enclosure, and even the surface roughness of the sample due to the reason that surfaces with

different roughness can result in different discharge inception voltages. In addition, other factors such as the temperature (or temperature gradient), gas composition and gas pressure can also affect the division of the electric field during the experiment. The presence of a temperature (or temperature gradient) increases the surface potential decay rate due to an increasing of the conductivity of tested samples. Meanwhile, the relationship between the leakage current and the injected charges that contributes to surface potential measurement needs to be further clarified.

3) During the curing stage, to decrease the additional surface energy caused by the sudden disruption of atomic periodic arrangement, micro cracks and bulges can be created in the surface layer of the insulator, and this would result in a bumpy surface whose structure is different compared with that of the bulk physical composition. That is to say, the surface state is totally different from that of the bulk property. However, it is very difficult, while it is of vital important, to give a corresponding relation between the charge amount passing through the volume and along the surface, before obtaining accurate surface charge calculations. Direct measurement of surface leakage current is almost impossible which is due to the the unavoidable electric field distortion caused by the combination of insulation and electrode of the measuring system, especially the electric field distortion near the triple junction region.

4) The limitation in the measurement of the surface potential amplitude makes it much difficult to further study the surface charge distribution under high electric fields. As far as we know, the surface potential measuring device currently available on the market has a maximum measurement voltage amplitude of ± 20 kV. It is impossible to measure a surface with a voltage potential higher than 20 kV. The surface potential for a spacer with operating voltage under SF_6 could be much higher than the experimentally applied voltage, and many physical processes may only be observed under the high electric field (i.e. in some cases nonlinear materials are introduced into manufacturing of spacers[29, 35, 36] as well as the donut-shaped charge clusters [41]).

3. Charge tailoring methods

At present, there are three types of charge decay paths that have been generally accepted: through gas conduction, by bulk conduction, and by surface conduction [34-46]. For an untreated epoxy surface, charge dissipates primarily through bulk conduction and gas side conduction, which has been discussed extensively in Section 3 and in previous literature [47, 48]. From the perspective of suppressing surface charge accumulation, modification methods could be divided into two groups: 1) Suppressing charge injection from the conductor; 2) Increasing dissipation rate of accumulated surface charges, as depicted by Figure 12. It is the aim of this chapter to review important researches over the past 10 years. Suggestions regarding modification methods of spacers are also made and the potential research directions are discussed.

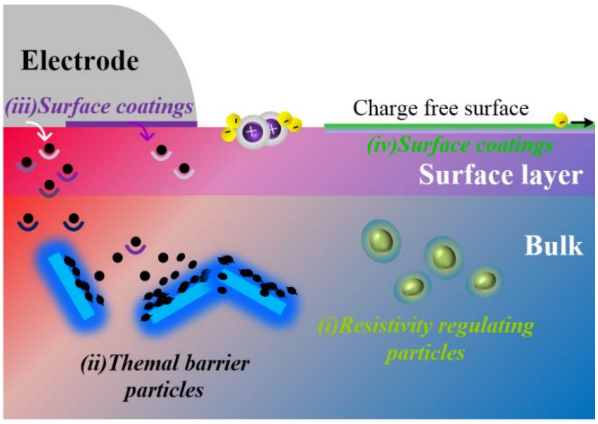

*Fig.12. Route map for surface charge tailoring methods in the interface of HVDC spacer (**i** is to suppress charge injection; **ii** and **iii** are to restrain charge migration in the bulk; **iv** is to increase surface charge decay).[58]*

3.1. Increasing surface charge decay rate

Table I in appendices lists the research conclusions and related charge tailoring mechanism of dielectric surface treatment methods over the past 10 years. It can be found that the mainstream of surface treatment methods for dielectrics includes fluorination, plasma treatment, surface coating, etc.. Most of these treatment methods control the time duration and environment during treatment process, and the surface conductivity, morphology and surface trap of dielectrics are parameters that are most investigated in relative with the decay of surface charge accumulation.

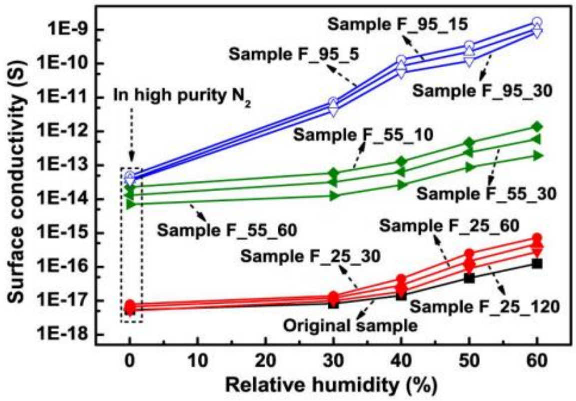

Fig.13. Surface conductivity change with relative humidity using samples treated under different conditions.[53]

An *et al.* conducted a systematic study on the property of epoxy before and after direct fluorination [49-55]. Their research begins with the discovery of some characteristic changes of epoxy by fluorination [49]. After that, their studies focus on establishing the correlation between physical parameters and surface charge dissipation property [50-53]. They proposed that the surface properties of epoxy-based insulating materials can be controlled by changing the reaction temperature and time during the fluorination process, as shown in the Figure 13. Further, they applied fluorination treatment to improve the electrical performance of epoxy model insulators, and positive results were achieved [54, 55]. A detailed summary of his researches can be found in **Table I**, which is not repeated in the text.

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Chen *et al.* also modified the epoxy with fluorination treatment [55] and they found that with the introduction of fluorinated substituent onto the surface of the epoxy resin sample, the conductivity of the dielectric surface could be increased [55]. Li *et al*. conducted similar researches on fluorinated plate, cylinders and cone type insulators characterized by various methods (electroluminescence, electrical conductivity, surface potential scanning, DC surface flashover voltage in air and SF_6, etc.) [57, 58]. They further verified the controllability of epoxy characteristic parameters by fluorination and proposed that surface fluorination could have the potential as a surface treatment method of products in industrial large-scale epoxy insulation [59, 60].

Plasma treatment is also an effective approach to increase surface charge dissipation rate. Li *et al.* found that the surface conductivity of epoxy sample increased by at least one order of magnitude after plasma treatment [61]. They attributed the change in surface conductivity to the synergistic effect of change in surface morphology and surface chemical composition change. Shao and Zhang have done a series of research on the plasma treatment of epoxy-based alumina materials [62-64]. Figure 14 shows the schematic diagram of their APPJ treatment setup. They believed that the surface conductivity, the surface chemistry and the surface topography of the epoxy resin can be controlled by changing plasma treatment time duration. They further proposed that the increase of surface conductivity can promote the dissipation of electric charge, and thereby improve the electrical resistance of the insulator under direct current [64]. They further expanded the plasma treatment to the application of surface coating. A SiO_x coating on the surface of epoxy resin was developed to control surface charge accumulation and dissipation, which have shown positive results [65, 66].

Tu *et al*. developed a SiO_2 coating and a TiO_2 coating on the surface of the epoxy resin by spraying on the matrix using an air brush [67, 68]. They believed that nano SiO_2 (TiO_2)/epoxy composite coatings can increase shallow trap density and carrier mobility. As a result, surface charge accumulation can be suppressed. At the beginning of the 21st century, Messerer *et al.* studied the regulation of the solid-gas interface charge by surface coatings with different conductivity. They pointed out that the charge accumulated on the surface of the insulator after coating can be reduced, and the flashover voltage can be improved [69, 70].

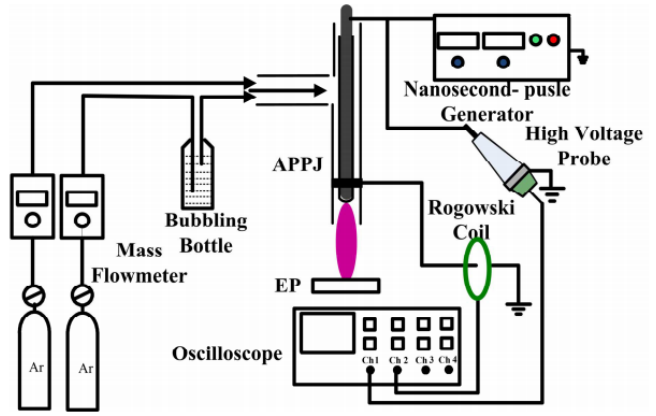

Fig.14. *Schematic diagram of the APPJ treatment setup.[62]*

Min *et al*. treated the epoxy using electron bombardment and ozone, respectively [71, 72]. They found that the surface conductivity of epoxy after the two treatment methods is different. The surface conductivity of the sample treated by electron bombardment decreased while it increased after ozone treatment. However, the flashover voltage value for samples under two treatment methods both increased. They believed that the combined effect of changing in energy and density of deep traps, as well as increasing of surface conductivity by electron beam irradiation and ozone treatment can explain the increase in surface flashover value [71, 72]. Gao *et al.* treated the epoxy with gamma-ray irradiation. They found that the decay rate of the charge is promoted by increasing of the irradiation time. Such promotion for negative charge is more remarkable than that compared for positive charges [73, 74].

Meanwhile, Du *et al.* proposed a wide range of surface treatment methods on the epoxy insulator to suppress surface charge accumulation and modify electric field distortion [75-82]. Based on the relationship among the carrier mobility, trap distribution and flashover voltage of epoxy insulator, they developed a novel cone-type insulator with a gradient surface conductivity based on direct fluorination. [75, 76]. Meanwhile, they believed that a surface functional graded materials (SFGM) could be adopted to insulators, which showed a more uniform electrical field distribution in their experiments, due to the charge suppression effect [77]. Their researches are also involved in interfacial E-field self-regulating insulator with nonlinear conductive coating [78,79].

3.2. Suppressing bulk charge injection

In the ideal case (i.e., the insulator is defect-free and there is no micro-discharge on the gas side), the accumulation of surface charge on the insulator is mainly due to the current in the bulk. Inorganic nanoparticle doping is one of the most common modification methods for dielectric materials. A large number of studies showed that doping a small amount of inorganic nanoparticles can effectively reduce the volume conductivity of polymers [83].

Chu introduced nano SiO_2 particles to epoxy matrix and the bulk conductivity of the epoxy was decreased [84]. He attributed the decrease in conductivity to the introduction of alkyl groups and few hydroxyl groups. Zhang *et al.* also reduced the volume conductivity of epoxy resin by doping a small amount of C_{60} fullerene and similar results were obtained [85].

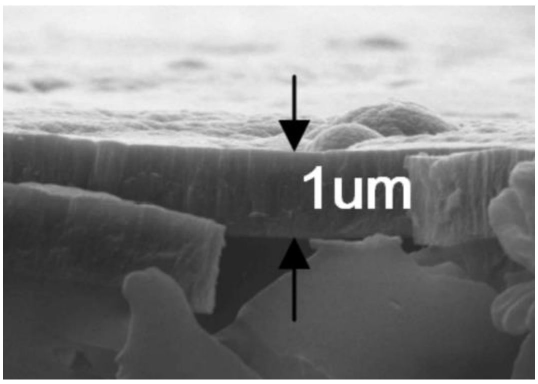

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Fig.15. *SEM image of a Cr_2O_3 coating.[78]*

He *et al.* applied a Cr_2O_3 coating (Figure 15) to the epoxy surface and a large number of deep traps were introduced [86]. They found that the charge injection was effectively restrained by the reversed electric field formed by a lot of charges trapped in Cr_2O_3 coatings. In addition, they found that the charge injection from the electrode can be restrained, especially under temperature gradient when the epoxy matrix was doped with $K_2Ti_6O_{13}$ particles [87].

3.3. Other Methods

Conventional strategies for surface charge suppression usually emphasize on improving of surface charge dissipation rate and suppressing of bulk charge injection. However, Li *et al.* introduced a novel HVDC spacer concept from a new perspective [29]. In their recent works, a combination of structural improvement and material modification was approached. The idea is to force charges to accumulate within a specific area (charge adoptively controlling region). The conductivity of the intelligent material in this area can be changed according to the charge amount in this region [29]. Thereby, the accumulated surface charges can be restricted below a certain value. Figure 16 shows a picture of the charge adoptively controlling spacer, as well as the surface potential measurement result of this spacer.

Tenzer *et al.* proposed an insulator using oriented fillers [40, 88]. Through a special casting process, the MFF filler is randomly doped inside the insulator material. The MFF filler is horizontally aligned in a direction consistent with the bulk. This structure effectively increases the surface conductance in the tangential direction without affecting the bulk conductivity in the normal direction.

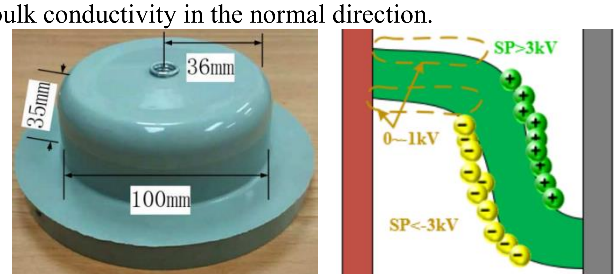

Fig.16. *(a) Picture of a charge adoptively controlling spacer; (b) Surface potential measurement result of this spacer. [29]*

Meanwhile, it has been reported in recent years that a radical scavenger can mop up surface radicals, which can help the surface charge decay very effectively without affecting the surface resistivity [89]. However, the charging mechanism of contact electrification or triboelectrification and electrification owing to electric fields or corona discharge treatment are probably very different from each other. One involves material transfer, surface oxidation, and the reorientation of polar molecules, while the other involves mainly oxidation and potentially reorientation. In addition, the molecules or chains at the surface of epoxy-based materials may differ significantly from those of an elastomer-based material, which makes it difficult to neutralize free radicals at the surface [1].

3.4. Selection basis and some suggestions

The operation stability of the spacer under HVDC can be increased by appropriately increasing the surface conductivity and decreasing the volume conductivity. However, attention should be paid especially to the durability and stability of the dielectrics after treatment. In particular the aging properties of the modified surface or bulk under long time application. In our recent research, we found that the conductivity of the fluorinated layer has a negative correlation with the temperature increase (Figure 17). This means that when the temperature rises, the conductivity of the fluorinated layer will decrease, which can reduce the rate of charge dissipation [90]. In this case, the surface charge decay rate would be affected. Meanwhile, the water contact angel of the plasma treated surface would change after the experimental samples were treated at different temperatures. This changing could also affect the charging property in the gas/solid interface and is an important issues that are to be investigated in future studies. In addition, the industrial feasibility of the treatment method should also be carefully considered, including the cost, whether the treatment process is highly dangerous, or toxicity.

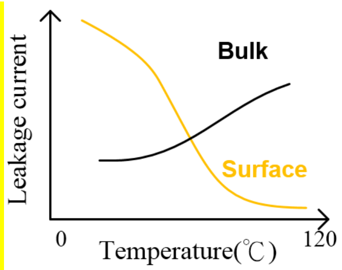

Fig.17. *Trend of stable surface leakage current and bulk leakage current for a short time fluorinated spacer treated at different temperatures.*

Most of the current research focused on the treatment of the insulating material itself. It is recommended to look for the charge source and block it from the root, especially charge generated from the gas phase. Japanese scholars have done some researches and they painted the conductors and enclosure with a semi-conductive coating to reduce the carriers introduced by local high-field ionization. In addition, bulk injected charges can be suppressed by a Cr_2O_3 coating between the conductor-insulation interface as reported by our former research [59].

In our research, it was found that most of the flashovers under DC occurred on the convex surface side of the insulator, while the flashover under AC did not have such obvious convex surface side dependence. We believe that this is directly related to the accumulation of hetero-polar charges on the convex surface side under high field strength, since it has been verified by researchers that the hetero-polar charge accumulation greatly reduces the flash voltage under HVDC [1]. Therefore, surface treatment (such as plasma, fluorination, sanding, etc.) on the convex surface to appropriately improve the conductivity of the convex surface may be an optional way for effectively improving the operational stability of the DC insulator.

4. Conclusion

This paper is a further extension of the content of the previous one [3]. A field-dependent charging theory based on dominant charge behavior is discussed to comprehensively illustrate the surface charge transport mechanism and explain the surface charge patterns obtained by previous researchers. The main surface charge control methods for epoxy resin in recent years are summarized. Relevant research recommendations and conclusions have been given at the end of chapter 3 and chapter 4, respectively. Here we summarize some of the key points in future research directions and some key points based on our experience in the manufacturing of HVDC GIL.

The operating environment of gas-solid interface inside DC GIL involves high electric fields, high SF_6 pressure, and complex electrical and physical processes. The related mechanism of DC flashover on the interface requires further exploration. At present, most of the existed research only focus on the stage regarding the phenomenon “charge accumulation leads to an increase in electric field, and electric field rise induces flashover on the surface.” That is true, however, this is only a conclusion, but not a disclosure of a physical process. The internal physical processes regarding charge accumulation-surface flashover needs to be further explored. Our previous study introduced the "analogous ineffective region" to characterize the effect of dominant charge behavior on the surface flashover under temperature gradients. However, flashover under steady-state conditions and surface flashover triggered in the presence of localized charge concentrations need more attention and to be further explored [41].

In addition, increasing the cleanliness of the DC GIS/GIL installation process is a step that is too harsh to be overemphasized. Any metal particles and dielectric particles that may be present would pose a threat to the electrical physical environment within the pipeline. Regarding the insulator modification methods, we still prefer a spacer produced by casting without post-treatment. Any subsequent process may destroy the integrity of the spacer, introducing a potentially unevenly distributed charge. Anyway, there is still a long road ahead into manufacturing of the HVDC spacer.

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Appendices

Table I. Important research classification of dielectric surface treatment to decay surface charge over the past 10 years.

No.	Date/ Author	Surface Modification Type	Results and *Charge Control Mechanism*	Significance
1	2011/ Liu, Y.Q. and An, Z.L.	Fluorination	Surface conductivity of epoxy dramatically increases from 10^{-17} S to 10^{-14} S after fluorination. *A very likely decrease in charge trap depth and the adsorbed water on the surface in air are responsible for the high surface conductivity.*	Preliminary study of fluorination on epoxy. The results have an important potential application in enhancing reliability of epoxy insulation.
2	2012/ Liu, Y.Q. and An, Z.L.	Fluorination	The fluorination for only 10 minutes can effectively suppress surface charge accumulation. *The suppress of surface charge accumulation is due to a very likely substantial decrease in trap depth of the surface layer or an intrinsic increase in surface conductivity.*	A first attempt to chemically modify the surface layer of epoxy insulation by direct fluorination to suppress surface charge accumulation.
3	2013/ Liu, Y.Q. and An, Z.L.	Fluorination	The increase in fluorination temperature can enhance the surface conductivity (10^{-17} S up to 10^{-13} S). *Increasing of surface conductivity is due to not only the compositional and concomitant structural changes, but also a structural change caused by the chain scission that occurs more easily at elevated temperatures.*	An epoxy insulator with surface conductivity high enough to completely suppress the charge accumulation may be obtained by fluorination at elevated temperatures for a short time.
4	2015/ An, Z.L. and Yin, Q.Q.	Fluorination	Surface conductivity of epoxy insulators can be modulated over a wide range by changing fluorination temperature and fluorination time. A quantitative link between surface conductivity and the surface morphology is difficult to be established, *because of the combined influences.*	Temperature and time duration are two important factors controlling the fluorination process, and the modulating role of fluorination temperature on surface conductivity is more significant in comparison with fluorination time.
5	2017, 2018/ Que, L.K. and An, Z.L.	Fluorination	DC flashover voltage on cone type samples and sheet samples is improved, *due to dispersion of surface charge caused by an improvement of surface conductivity after fluorination.*	These works prove that the degradation or tracking resistance of the epoxy insulator to surface discharge can be significantly improved by fluorination.
6	2013/ Mohamad and Chen, G.	Fluorination	There is a clear trend of increasing surface breakdown strength as the fluorination time increases, *due to the incorporation of fluorinated surface layer on epoxy improves the conductivity.*	With the introduction of fluorinated substituent onto the surface of epoxy resin sample, the conductivity along the dielectric surface is increased.
7	2016/ Li, C.Y. and He, J.L.	Fluorination	Lower EL is found after fluorination, which indicates greater degradation inhibition property. A more compact surface layer is obtained, *due to the replace of C-H bonds by C-F structures*.	The results provide important founding in improving aging inhibition property and dc performance of epoxy based insulators used in HVDC applications.
8	2015, 2016/ Li, C.Y. and He, J.L.	Fluorination	A decrease of surface charge level and an increase of dc surface flashover voltage are achieved, *due to the synergistic effect of change in surface morphology and surface conductivity*.	
9	2018/ Yue, and Li, S.T.	Plasma	Plasma treatment changes surface trap distribution and increase surface flashover voltage of epoxy resin. *The change of surface trap distribution is considered to be caused by the surface chemical composition (More O atoms were introduced in the surface of sample).*	Surface chemical composition of EP/Al_2O_3 micro composite can be changed by plasma treatment.
10	2017/ Shao, T. and Liu, F.	Plasma	The dissipation of surface charge can be accelerated and the epoxy surface insulation performance can be enhanced obviously after plasma treatment. The surface trap becomes shallow after plasma treatment *by the introduced carbonyl groups.*	Plasma treatment of epoxy can be used to prevent surface flashover caused by surface charge accumulation. Plasma treatment can be used to protect the electrical and electronic equipment.
11	2017/ Zhang, C. and Shao, T.	Plasma	After the plasma treatment, both the surface conductivity and bulk conductivity significantly increase, almost 40 times and 32 times compared with their original values. *These changes are mainly attributed to a change in the surface nanostructure, and a decrease in the depth of energy level.*	The results contribute to the methods to suppress the surface charge accumulation and accelerate the surface charge dissipation.
12	2018/ Shao, T. and Kong, F.	Plasma	A treatment time of 3 min can increase the surface conductivity up to 3 orders of magnitude, which is critical to the dissipation of surface charge. *The increase in conductivity is due to the binding capability change of the material.*	It suggests that plasma treatment can suppress the accumulation of the surface charge and can be a useful tool in insulators operating under DC application.
13	2017/ Wang, R.X. and Shao, T.	Coatings	The SiOx film with a thickness of 50-200 nm increases the surface conductivity, which in turn reduces surface charge level. *The improvement of epoxy property is due to the introduction of a lower density of shallow traps.*	AP-DBD is an effective and environmental friendly method for SiOx thin films deposition to accelerate the surface charge decay.

No.	Date/ Author	Surface Modification Type	Results and *Charge Control Mechanism*	Significance
14	2019/ Zhang, C. and Shao, T.	Plasma	Deposited samples keep a stable surface charge dissipation in five-day storage. However, the plasma etched samples shows a significant ageing effect because the reorientation of the oxygen-containing functional groups to the interface.	DBD deposition can provide an effective and clean approach for accelerating surface charge dissipation on the Al_2O_3-ER surface without ageing effect.
15	2018/Tu, Y.P. and Zhou, F.W.	Coatings	Surface charge accumulation is suppressed by *increasing the shallow trap density and carrier mobility*, which is achieved by a coating with micron and nano SiO_2 (TiO_2)/epoxy composites.	The coating with a nano-TiO_2 particle content of 5% shows the most significant effect on restraining charge accumulation.
16	2002/ Messerer, F. and Finkel, M.	Coatings	A special coating with the resistance varied from 10^8 -$10^{14}\Omega$ can withstand an electrical field stress up to 30 kV/cm.	High resistance surface coating of solid insulating components in highly ‘stressed HVDC insulation systems have been investigated.
17	2017/ Zhang, B.Y. and Cao, Y.	Coatings	A superior nano laminate dielectric barrier coating can increase surface charge dissipation rate due to *the release of energies of hot electrons by the abundant interfaces within nanocoatings.*	A superior nano laminate dielectric coating has a potential to be used in insulators inside DC GIL to restrain surface charge accumulation.
18	2017/ Li, S.T. and Huang, Y.	Electron beam irradiation	*Increase in the energy and density of deep traps enhances the progress of trapping primary emitted electrons*, suppressing the development of surface flashover of epoxy.	The increase in energy and density of deep traps by electron beam irradiation, as well as the increase of surface conductivity by ozone treatment, can both be effective ways to modify surface condition of epoxy and improve surface flashover voltage.
19	2017/ Min, D.M. and Huang, Y.	Ozone treatment	*The large dissipation rate of surface charge* after ozone treatment can reduce the electric field distortion at the cathode triple junction, thereby improving the surface flashover voltage.	
20	2010-2011/Gao, Y. and Du, B.X.	Gamma-ray irradiation	With the increase of radiation dose, charge dissipation time decrease. Such promotion for negative charge is more remarkable, *which is due to changes in charge traps.*	Gamma-ray irradiation can be a useful tool to change surface trap distributions, which is effective to increase surface charge dissipation.
21	2019/ Li, J. and Du, B. X.	Fluorination	Under the superimposed voltages, the initial surface charge density and carrier mobility are affected by both pulse voltage and fluorination modification time. *The electric field distortion near the high voltage electrode can be effectively suppressed with increasing the thickness and conductivity of the fluorinated layer.*	It is indicated that surface modification is an appropriate method which can significantly inhibit the surface charge accumulation, and improve the flashover characteristics of epoxy sample by increasing carrier mobility and release the electric field distortion with graded design.
22	2019/ Li, J. and Du, B. X.	Magnetron Sputtering	A functional surface can be fabricated by magnetron sputtering ZnO onto the epoxy resin surface forming a surface conductivity gradient, namely surface functional graded materials (SFGM). U*niform electrical field distribution can be obtained and charge accumulation can be suppressed.*	It is a novel method to realize the electric field uniforming and charging suppression simultaneously with SFGM concept.
23	2019/ Liang, H. C. and Du, B. X.	Nonlinear Conductive Coating	A concept of an interfacial E-field self-regulating (IER) insulator was proposed. *When the SiC content in the coating layer is increased, the surface charge migration process accelerated because of the reduction in volume resistivity.*	An epoxy insulator coated with nonlinear conductivity not only uniforms the electric field distribution and also accelerates transient process, whose dielectric loss is within an acceptable range.
24	2018/ Xue, J.Y. and Zhang, G.J.	Surface roughness treatment	The declination of surface charge is *owing to both the increased surface conductivity and the introduced deep traps*. The surface insulation strength improvement is *ascribed to the combination of the declination of surface charges, the prolonged path of surface discharge, and the block of electron avalanche development by the rough surface.*	Roughing the surface can suppress surface charge accumulation and improve surface flashover performance.

Table II. Important research content of dielectric surface treatment to restrain bulk injection over the past 10 years.

No.	Date/ Author	Surface Modification Type	Results and *Charge Control Mechanism*	Significance
1	2016/ Li, C.Y. and He, J.L.	Cr_2O_3 coatings	The Cr_2O_3 coating can introduce a large number of deep traps, which can prevent charge injection *through a reversed electric field formed by intensive trapped charges in the Cr_2O_3 coatings.*	Charge injection of epoxy can be greatly prohibited by a Cr_2O_3 coating, as well as $K_2Ti_6O_{13}$ whiskers. The expansion of the “analogous ineffective region” can be restrained as a result.
2	2018/ Li, C.Y. and He, J.L.	Doping $K_2Ti_6O_{13}$ particles	Doping of $K_2Ti_6O_{13}$ whiskers can restrain the heat propagation of epoxy and further restrain the charge transport under temperature gradient. It is *attributed to the excellent thermal barrier property of $K_2Ti_6O_{13}$ whiskers.*	

3	2017/ Chu P.F.	Doping SiO_2 particles	*Low-polarity nanoparticles have a large amount of highly insulating alkyl groups and few hydroxyl groups and/or absorbed water molecules, which form charge carriers (ions) under electric field* and promoting electrical conductivity.	A nano doping of SiO2 to epoxy matrix can decrease the bulk conductivity of the epoxy, restraining charge injection from the electrode to the dielectric.
4	2018/ Zhang B.Y.	Doping nano C_{60}	*C_{60} has a special hollow cage structure* that enables a strong electrophilic properties and can effectively capture free electrons in the polymer matrix.	A nano doping of C_{60} to epoxy matrix can decrease the bulk conductivity of the epoxy and decrease charge accumulation amount.
5	2013/ Tarik Baytekin H.	Radical scavenger	*The radical scavenger (DPPH) can mop up surface radicals*, which can help the surface charge decay very effectively.	Antioxidants remove surface free radicals and increase charge dissipation rate without affecting surface conductivity.