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Influence of charge emission behaviors of semi-conductive shielding layer on charge accumulation properties of insulation layer for HVDC cable

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Abstract

Space charge accumulation is one of the key factors restricting the manufacture and application of high-voltage direct current (HVDC) cables. Semi-conductive shielding layer plays an important role in uniform electric field in HVDC cable, and its own emission properties directly affect the space charge behaviours in the insulation material. In the paper, charge injection property from semi-conductive layer to insulation layer have been focused emphatically based on experiment and simulation. The charge injection characteristics of semi-conductive layer under two typical electrode configurations of 'Metal-Insulation layer-Metal' (M-I-M) and 'Semi-conductive layer-Insulation layer-Metal' (S-I-M) have been studied. The conductive current and depolarization current of the insulation layer are compared. Finally, effect of particle size and concentration of carbon black (CB) in the semi-conductive layer on the interfacial electric field has been studied by electric field simulation. The experimental results show that the charge injection from the semi-conductive layer is more obvious under the action of low electric field of 5 kV mm$^{-1}$ due to effect of CB particles. It can be seen from the depolarizing current curve that the charge injection quantity with S-I interface is greater than that of M-I interface. Further calculation results show that the maximum distortion electric field increases slightly with the increase of CB size. When CB content is 25%, the electric field distortion caused by interface CB particles is about twice of the average electric field (5 kV mm$^{-1}$), increasing from 9.61 kV mm$^{-1}$ at 10 nm to 10.15 kV mm$^{-1}$ at 50 nm. The reduction of CB size in the semi-conductive layer within a certain range is conducive to the reduction of the interface electric field. The maximum distortion field gradually decreases with the increase of CB content at a certain range.

1. Introduction

As a key power equipment for high voltage direct current (HVDC) transmission, high voltage cables play an important role in long-distance power transmission, cross-sea power transmission and grid connection of renewable energy. However, with the rapid development of manufacturing technology of high voltage cable, the development of high voltage cable material lags seriously. At present, only a few companies in the world have mastered the preparation technology of the semi-conductive shielding material above 110 kV. Compared with AC cable, HVDC cables are faced with space charge accumulation problem in insulation layer is one of the key problems restricting the development of HVDC cables [1–5]. Space charge accumulation of cable insulation material will accelerate material aging and seriously affect cable life.

For a long time, the research on space charge accumulation of HVDC cable mainly focused on the charge injection from conductor wire core into the insulation layer in the cable structure [6–10], while the charge injection from the carbon black-polymer semi-conductive shielding layer into the insulation layer was
neglected. Semi-conductive layer as an indispensable part of the HVDC cable, it can improve electric field distribution effectively by tightly connecting with conductor wire core and insulation layer \[11\]. Meanwhile, Semi-conductive layer has great influence on the space charge accumulation in the insulation layer as a direct way of charge injection into the insulation layer \[12–16\]. In recent years, with the occurrence of faults in HVDC cables, many scholars have realized the importance of charge emission problem from the semi-conductive shielding layer to the insulation layer for the safe operation of the whole high-voltage cable \[17\]. Currently, most studies on semi-conductive shielding layer of HVDC cable mainly focus on two aspects, the modification of semi-conductive composites \[13, 14, 17–20\] and interfacial discharge properties \[15, 16, 21–23\]. Such as the influence of CB content or the secondly filled materials on its resistivity and charge injection \[20–26\], the relationship of the microstructure of semi-conductive interface and breakdown strength of the insulation layer \[13, 14, 18, 19\]. Until now, mostly studies are aiming to solve the problem of space charge accumulation in HVDC cables from the source. But the measurement structure adopted is the ‘Metal upper electrode—the insulating layer—metal bottom electrode’ (M-I-M) whatever it is the interface discharge characteristic or the charge inhibition effect after modification of shielding material. It is considered that the charge only comes from the metal electrode injection. While the semi-conductive layer direct contact with insulation layer in actual cable structure, ignoring the charges injected from the semi-conductive shielding layer.

In the work, the charge injection characteristics of the inner semi-conductive shielding layer of the high voltage cable was studied. Firstly, samples were prepared using commercial HVDC cable materials (internal semi-conductive shielding material and insulting material), and the semi-conductive layer and composite interface were characterized by observing microscopic morphology. Secondly, the charge injection properties of the semi-conductive layer with different field intensity was analysed by comparing the conduction current and depolarization current of the electrode structure of M-I-M and electrode structure of ‘Semi-conductive layer—the insulating layer—metal bottom electrode’ (S-I-M). Finally, the mechanism of charge injection into the insulting layer was discussed by simulating the carbon black particle size of the semi-conductive layer.

2. Preparation and characterization

2.1. Preparation of semi-conductive composite and morphology characterization

In this work, the commercial insulation materials and semi-conductive shielding materials for HVDC cables were prepared. The insulation materials were cross-linking polyethylene (XLPE), and the semi-conductive composites were including CB, ethylene-vinyl acetate copolymer (EVA)/Ethylene-ethyl acrylate (EEA). The semi-conductive composites and insulation samples with thickness of 0.2 mm and 0.3 mm, respectively, were prepared by the melt blending method. Firstly, the raw materials were dried in a vacuum chamber at 60 °C for 6 h, and the dried raw materials were set in the mold separately during the preparation process. In order to remove bubbles generated in the vulcanizing process, melting molding and exhausted samples were fabricated at 130 °C, 10 Mpa using plate vulcanizing machine. And then, the cross-linked process was implemented at 180 °C for 15 min. Finally, the specimens were obtained by cooling at 10 Mpa for 10 min. In addition, the semi-conductive layer and the insulation layer were combined at 120 °C by means of hot fusion to form the semi-conductive layer/insulating layer composite structure, considering the co-extrusion temperature of the three layers in cable production process.

The microstructure of semi-conductive layer and semi-conductive/insulating layer composites were obtained by scanning electron microscope (SEM) and surface roughness of the semi-conductive layer was observed by atomic force microscope (AFM), as shown in figure 1. The semi-conductive/insulating composite sample was cooled in liquid nitrogen and then quickly quenched, which was observed by SEM. Figures 1(a) and (b) shows the SEM images of the semi-conductive layer surface and the cross-section of the semi-conductive layer/insulation layer respectively. Figure 1(c) is AFM image of semi-conductive layer surface.

It can be clearly seen from figure 1(a) that CB particles were highlighted in white under SEM with uniformly distributed and formed conductive pathways. As can be seen in figure 1(b), the interface was closed contact without obvious bulge. The side of the semi-conductive layer was not smooth and obvious carbon black particles can be seen. In comparison, the surface of the insulating layer was smooth. Because the semi-conductive layer contains a lot of tiny CB particles, the surface roughness changes, resulting in the field distortion, which has a great impact on charge injection. As shown in figure 1(c), the surface roughness was obtained through AMF scanning, which was about 13.9 nm.

2.2. Test method

Currently, most researches paid more attention on metal electrode structure of M-I-M, which was used to study charge injection properties of HVDC cable, as shown in figure 2(a). The source of charge injection was metal electrode, in which the contact interface was ‘Mental upper electrode-Insulation layer’ (M-I). In actual cable,
however, semi-conductive layer was located between the metal core and the insulation layer, which directly
connected with insulation layer. That was the interface of ‘Semi-conductive layer-Insulation layer’ (S-I),
therefore, the traditional mental electrode structure was not suitable for the study of the charge injection of
semi-conductive layer.

As shown in figure 2(b), a kind of new electrode structure of ‘Semi-conductive-Insulation layer-Metal
down electrode’ has been designed, in which the semi-conductive composites as high voltage electrode. Metal
ring equipment was designed as the upper electrode, which applied voltage on semi-conductive composites, so
as to realize the charge injection from semi-conductive layer to insulation layer. In order to tightly connected
between semi-conductive layer and insulation layer, polytetrafluoroethylene (PTFE) material of the same quality
as the metal electrode is pressed above the semi-conductive layer. The test region was chosen directly below the
polytetrafluoroethylene material, which away from the metal ring electrode to reduce the influence of the charge
injection from metal ring device, which can ensure that charge injection mainly comes from semi-conductive
layer injection.

In the experiments, the conduction current and thermally stimulated depolarization current (TSDC) of the
insulation layer were measured to synthetically characterized the charge injection of insulation layer from semi-
conductive layer, and compared these two results of two kinds of electrode structures of M-I-M and S-I-M. The
steps of experiment can be seen in figure 2(c). Firstly, the conduction current of insulation layer were carried out
using the traditional three electrode structure of M-I-M and S-I-M, and the system is including measuring
electrode, high voltage electrode, guard electrode, electrometer 6517B and data acquisition computer. The
current data was obtained by two typical electric field of 5 kV mm⁻¹ and 20 kV mm⁻¹ during the applying
voltage time of 20 min. After that, removed the applied voltage, the insulation sample was taken out and placed in the TSDC testing system (Novocontrol Concept 40). The injected charge of the electrode to the insulation layer was reflected by measuring the TSDC. The depolarization current was acquired by means of electrometer 6517B. The heating condition changes from 25 °C to 80 °C, the heating rate is 1 °C min⁻¹.

3. Experimental results and analysis

The charge injection characteristics of the semi-conducting layer were characterized by measuring the conduction current of the insulation layer with high voltage and the TSDC after removing voltage. The results are shown in figures 3 and 4.

It can be seen from figure 3 that the conduction current of insulation materials have different time to reach equilibrium under different electrode structures. Figure 3(a) shows the conductive current of the insulation layer when the applied electric field is 5 kV mm⁻¹. The time for the current to reach equilibrium under M-I-M electrode structure is about 400 s, and that for S-I-M electrode structure is about 900 s. When the applied electric field is 20 kV mm⁻¹, the current equilibrium time was 700 s and 500 s respectively, as shown in figure 3(b). The time for the current to reach a stable state was related to various polarization types and dynamic processes such as charge injection and migration. It is worth noting that conduction current exists in both electrode structures, and the steady state time of current in S-I-M electrode structure is much higher than that of M-I-M at 5 kV mm⁻¹.

Figure 4 shows the depolarization current of the insulation layer under different electrode structures. It can be seen from figure 4 that depolarization current existed in both electrode structures under 5 kV mm⁻¹ and 20 kV mm⁻¹. Especially for the depolarization current under low field, as shown in figure 4(a), the maximum current value of S-I-M electrode structure was about $7 \times 10^{-13}$ A, and that of M-I-M was about $5 \times 10^{-13}$ A. According to the references, the electric field threshold of charge injected into the insulation layer by metal
should be greater than 10 kV mm\(^{-1}\), but the measured current under the M-I-M structure in Figure 4(a) indicated a small amount of charge injection, which should be related to the interface state. Similarly, at a low field of 5 kV mm\(^{-1}\), the current in the S-I-M structure indicated that charges were emitted from the semiconductive layer. It can be seen from the above phenomenon that the polarization current of different electrode structures were mainly related to contact interface at low electric field. Figure 4(b) shows that the depolarization current was measured under both electrode structures at 20 kV mm\(^{-1}\), and the current value of M-I-M electrode structure was greater than that under S-I-M structure, which is because when the electric field is high, electrons can overcome the M-I interface barrier and inject into the insulation layer.

Simultaneous analysis of figures 3 and 4, it can be seen that, to a certain extent, the charge injection existed both in these two electrode structures with low and high electric field. Moreover, the charge injection at low electric field is mainly affected by the interface, especially for S-I interface.

### 4. Simulation analysis and discussion

In order to further analyze the interfacial charge injection characteristics of 'Semi-conductive layer-Insulating layer', the finite element method was adopted to calculate the electric field distribution caused by interfacial CB particles. Based on the structure shown in figure 2(b), the interface model of 'Semi-conductive layer-Insulating layer' was established. The thickness ratio of the semi-conductive layer and the insulation layer of the HVDC cable is about 1:15. To simplify the calculation, the structure of the HVDC cable was scaled down in the same scale. The thickness of the semi-conductive layer was set as 16 nm and the insulation layer as 240 nm. The width of the semi-conductive layer and the insulation layer was set as 400 nm, and the CB content in the semi-conductive layer was set as 25% and 50% respectively. Based on the AFM results shown in figure 1, the CB particle size of the interface between the semi-conductive layer and the insulation layer was designed as 10–50 nm. In order to keep consistent with the experimental conditions, the electric field distortion caused by interface CB was simulated at external applied electric field, 5 kV mm\(^{-1}\). The calculation results were showed in figure 5.

It can be seen from figure 5 that CB particle content and particle size of the interface between the semi-conductive layer and the insulation layer have a significant influence on the electric field distribution. Compared with figures 5(a), (c) and (d), when CB content was 25%, the electric field distortion caused by interface CB particles was about twice of the average electric field (5 kV mm\(^{-1}\)), and with the increase of particle size, the maximum distortion electric field showed a small increase trend, from 9.61 kV mm\(^{-1}\) at 10 nm to 10.15 kV mm\(^{-1}\) at 50 nm. It was indicated that reducing the size of CB particles in the semi-conductive layer was beneficial to reducing the interfacial electric field. Compared with figures 5(a) and (b), the interface electric field...
decreased with the increase of CB content, and the maximum distorted electric field was 8.74 kV mm\(^{-1}\) when CB content was 50%. That was because the distance among CB particles became smaller with the increase of CB content at a certain range, and the electric field between adjacent particles will interact with each other. Since the electric field along the horizontal direction was opposite, a certain weakening effect will occur, leading to the decrease of the maximum distorted electric field.

For the interface of ‘Metal-Insulating layer (M-I)’, schottky theory was often adopted to analyze the charge injection from metal into the insulated layer. The experimental results showed that the threshold field of charge injected by metal into polyethylene was about 10 kV mm\(^{-1}\). However, it was difficult for the metal to inject charge into the insulation layer at low applied electric field (<5 kV mm\(^{-1}\)) for tightly contacted interface of M-I. Because it was difficult to obtain sufficient energy for the electrons in the metal electrode to overcome the interface barrier between the metal and the insulation material. The situation of the interface between semi-conductive layer and insulating layer (S-I) was different. As shown in figure 4, when the applied electric field is 5 kV mm\(^{-1}\), the internal depolarization current of the insulation layer is more obvious, which is consistent with the calculation results. The calculation results show that although the applied electric field is low, the S-I interface caused by CB particles will have obvious electric field distortion caused by these tiny bump structures, and the maximum distorted electric field is about twice the average electric field, which will cause the charge within the semi-conductive layer injected into the insulation layer.

Further analysis shows that the distortion electric field of S-I interface gradually decreases with the decrease of CB particle size or the increase of CB content in the semi-conductive layer. This indicates that for the semi-conductive composite material of HVDC cable, under the condition of satisfying the preparation process, the S-I interface electric field distortion can be weakened by reducing CB particle size in a certain range or increasing CB filling amount, thus reducing the charge injection from the semi-conductive layer into the insulation layer.

5. Conclusions

In conclusion, the charge injection characteristics of semi-conductive layer were studied and the specimens were prepared adopted commercial semi-conductive materials and insulation materials of HVDC cable. The conclusions were drawn as follows:

1. Both in the low field and high field with two electrode structures, charge injection phenomenon exists due to many carbon black particles existed in semi-conductive composites. And the effect of charge injection mainly affected by the interface state, especially the charge injection value of the S-I interface is greater than that of the M-I interface.

2. For the same content of CB, the maximum distortion electric field increases slightly with the increase of particle size, and reducing the particle size of CB within the semi-conductive layer was beneficial to reducing the interface electric field. In a certain range, the maximum distortion field decreases with the increase of carbon black content.

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