Surface Potential Decay and DC Conductivity Characteristics of Epoxy Composite Materials Postprint

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Abstract

Gas-insulated transmission line (GIL) insulators are typically cast from epoxy resin/Al2O3 composite materials. Under DC voltage and load-induced temperature rise, charges easily accumulate on the insulator surface, causing electric field distortion and subsequently initiating surface flashover. To investigate the influence of nonlinear ZnO fillers on the insulation performance of epoxy resin/Al2O3/ZnO composite materials, this paper measured the surface potential decay of epoxy composites with different ZnO contents under DC voltage, analyzed the effect of different temperatures on surface charge characteristics, and obtained the variation pattern of nonlinear conductivity based on charge dissipation. The research results indicate that under DC voltage, ZnO particle doping can significantly promote surface charge dissipation in epoxy composites; with increasing temperature, charge carrier mobility increases, and the surface charge dissipation rate accelerates; when ZnO content exceeds a certain threshold, the conductivity exhibits nonlinear characteristics under high electric fields, thereby suppressing surface charge accumulation in epoxy resin composites. The relevant results provide a reference for the application of nonlinear conductivity composite materials in regulating the surface charge characteristics of DC gas-insulated transmission line insulators.

Full Text

Preamble

Surface Potential Decay and DC Conductivity Characteristics of Epoxy Composites

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Abstract

Gas-insulated transmission line (GIL) insulators are typically cast from epoxy/Al O composites. Under DC voltage and load-induced temperature rise, charges readily accumulate on insulator surfaces, causing electric field distortion and potentially triggering surface flashover. To investigate the influence of nonlinear ZnO fillers on the insulating properties of epoxy/Al O /ZnO composites, this study measured surface potential decay of epoxy composites with varying ZnO content under DC voltage, analyzed the effects of different temperatures on surface charge characteristics, and obtained nonlinear conductivity variation patterns based on charge dissipation. The results demonstrate that ZnO particle doping significantly promotes surface charge dissipation in epoxy composites under DC voltage. As temperature increases, carrier mobility increases and surface charge dissipation accelerates. When ZnO content exceeds a certain threshold, conductivity exhibits nonlinear characteristics under high electric fields, thereby suppressing surface charge accumulation in epoxy composites. These findings provide references for the application of nonlinear conductivity composites in regulating surface charge characteristics of DC GIL insulators.

Keywords: Gas-insulated line, epoxy insulator, operating temperature, surface charge, nonlinear conductivity

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1. Introduction

DC gas-insulated transmission lines offer advantages including large transmission capacity, high voltage withstand levels, minimal electromagnetic environmental effects, and high reliability, making them the preferred alternative to overhead lines in special environments. In recent years, the necessity of this technology has become increasingly prominent, showing rapid growth in ultra-high voltage transmission applications. In practical GIL composite insulation systems, disc insulators are typically cast from epoxy/Al O composites, and the gas-solid interface represents the weakest region in the system, seriously threatening the safe operation of DC transmission systems. Under long-term DC voltage, surface charge accumulation caused by partial discharge and electrode injection leads to electric field distortion and reduced interface dielectric strength, ultimately resulting in surface discharge or flashover. Studies have shown that surface charge accumulation can cause the surface flashover voltage of disc insulators to decrease significantly, by as much as 23%. Therefore, surface charge regulation has become a key research focus in DC GIL technology development.

Research indicates that materials with nonlinear conductivity characteristics can effectively regulate surface charge accumulation and improve local electric field distribution. By doping polymer matrices with inorganic fillers to obtain field-dependent conductivity, these materials exhibit high conductivity under high electric fields to accelerate surface charge dissipation, enabling intelligent regulation of non-uniform electric fields. Studies on ZnO varistor/silicone rubber composites show that when filler volume fraction exceeds 20%, the composites exhibit obvious nonlinear conductivity characteristics that can suppress non-uniform electric fields. Research on adding ZnO to polyester resin found that when ZnO filler doping concentration exceeds 30wt%, the composites show distinct nonlinear characteristics while also affecting surface charge and electrical treeing properties.

This paper investigates the nonlinear conductivity characteristics of epoxy composites under DC voltage. Al O and ZnO particles were doped into an epoxy matrix, and the surface charge dynamic characteristics of epoxy/Al O /ZnO composites with different ZnO contents and at different temperatures were measured using the surface potential decay (SPD) method. Based on the model relating surface potential decay to material conductivity, the variation patterns of composite conductivity were studied.

2.1 Sample Preparation

To investigate the role of ZnO particles in epoxy/Al O /ZnO composites, alumina particles with approximately 12 m diameter and ZnO particles with approximately 40 m diameter exhibiting nonlinear characteristics were selected as fillers. Liquid bisphenol-A type epoxy resin was used as the matrix. Considering the low viscosity of the epoxy resin used, physical blending could be directly employed to prepare microcomposite dielectrics. The mixing ratio of filler particles, epoxy resin, and curing agent was 300:100:33. The mixture was poured into a mold and hot-pressed using a plate vulcanizing machine. Five types of epoxy/Al O /ZnO composite samples were prepared with ZnO contents of 0, 12.5wt%, 25wt%, 37.5wt%, and 50wt%, with a sample thickness of 0.5mm.

2.2 Surface Potential Decay Measurement Setup

The surface potential measurement system is shown in [Figure 1: see original paper]. The main system is installed in a sealed container. In this experiment, humidity was set at 30%. To investigate the effects of different DC voltages and temperatures, DC voltage was set at 4kV, 5kV, and 6kV, while temperature was set at 30℃ and 60℃. Temperature was controlled by a heater beneath the grounded electrode, with a layer of insulating material placed between them to stabilize the circuit. After corona charging, the sample was quickly translated via guide rail to beneath the electrostatic probe, and surface potential values were measured using a surface potential meter. The experimental data reflect the variation of surface potential over time after applying different DC voltages and the resulting surface charge accumulation.

2.3 Conductivity, Carrier Mobility, and Trap Density Calculation

Surface potential decay is a natural process controlled solely by material properties and ambient environment. During experiments, conditions such as humidity and temperature were kept constant to minimize environmental effects, while surface conduction effects were neglected. The surface potential decay method can obtain electric-field-dependent conductivity. The model relating surface potential decay to material conductivity is as follows [15-16]:

$$Kv(VS) =!VS(t)dVS(t)$$

where $Kv(VS)$ is conductivity (S/m), ε is permittivity (F/m), VS is surface potential (V), and t is time (s).

Surface potential decay is closely related to charge trapping and detrapping processes. Carrier mobility and trap density can be calculated from the surface potential decay process [17-18]. Assuming the average transport time for charges from the sample surface to ground is t_T, carrier mobility can be expressed as:

$$\mu = \frac{L^2}{t_T \cdot V_0}$$

where μ is carrier mobility ($\mathrm{m}^2 \cdot (\mathrm{s} \cdot \mathrm{V})\ ^1$), L is sample thickness (m), and V_0 is the corresponding absolute initial potential (V).

If charge neutralization is assumed not to occur during transport from the upper surface to ground, and all charges can eventually reach the grounded electrode, trap density and trap energy level can be calculated as:

$$N_t(E) = \frac{eL^2}{kT}\frac{dVS(t)}{dt}$$

$$E_t = kT\ln(\nu t)$$

where N_t is trap density (eV ^{1}m ^{3}), E_t is trap energy level (eV), T is thermodynamic temperature (K), σ is trap capture cross-section (m^2), v_T is free electron thermal velocity (m/s), N is effective density of states in conduction or valence band (m ^{3}), ν is electron detrapping frequency (s ^{1}), and k is Boltzmann constant (J/K).

3.1 Effect of DC Voltage on Surface Charge Dynamic Characteristics

In this study, a high-voltage DC power supply was used for corona discharge through a needle electrode to generate charges. Under the electric field, one portion of charges moved to the needle electrode while the opposite polarity portion moved to and accumulated on the sample surface.

Surface charge dissipation characteristics of epoxy/Al O /ZnO composites with different ZnO contents are shown in [Figure 2: see original paper]. After corona discharge injection, some charges become trapped. Charges in shallow traps with lower energy levels can more easily detrap, and as time progresses, charge dissipation causes the sample surface potential to decrease. In [Figure 2: see original paper]a, samples with low ZnO content show relatively gentle overall potential decay trends. Under 4kV DC voltage, the remaining charge quantity after 600s is still considerable, with surface potential exceeding 1300V. As applied voltage increases, initial potential rises significantly and potential decay speed increases slightly. When ZnO particle content increases to 25% and 37.5%, as shown in [Figure 2: see original paper]b and 2c, higher corona charging voltage provides more potential energy for carriers to reach the sample surface, further accelerating surface charge accumulation during charging and resulting in higher initial surface potential. Meanwhile, surface charge accumulation leads to increased electric field strength, accelerating the surface potential decay process.

[Figure 2: see original paper]d shows the surface potential decay characteristics of samples with 50% ZnO content. At 6kV, due to high conductivity, the initial surface potential decreases by more than 2700V. The local conductive network formed by high-content ZnO particles significantly promotes surface charge decay. The surface potential curve under 5kV rapidly decreases to near the level of the 4kV curve within 300s, with the two curves nearly coinciding at 600s. This indicates that although increasing corona voltage enhances charge injection, charge dissipation speed plays a crucial role in the charge accumulation process. The high conductivity of samples with 50% ZnO content can almost offset the surface charge accumulation effect caused by higher corona voltage.

lists the average surface potential decay rates within the first 60s of the SPD process for different samples, calculated using:

$$R = \frac{V_0 - V_{60}}{\Delta t}$$

where R is decay rate (V/s), V_{60} is surface potential at 60s (V), and Δt is time interval (s).

The results show more intuitively that as DC voltage increases or ZnO content rises, sample surface charge dissipation accelerates. When DC voltage increases from 4kV to 6kV, the surface charge decay rate for samples with 12.5% ZnO content increases by 245.71%, while the other three sample types show increases of 49.52%, 76.98%, and 92.96%, respectively. Due to excessively slow surface potential decay for the 12.5% ZnO sample at 4kV, this case is excluded from discussion. As ZnO content increases, the initial surface potential decay rate of samples increases. The high surface potential caused by high DC voltage leads to more pronounced surface charge dissipation, likely due to more significant nonlinear characteristics of high ZnO content composites under high fields.

3.2 Effect of Temperature on Surface Charge Characteristics

Studies show that temperature rise at the GIL center conductor creates temperature gradients along insulator surfaces, affecting surface charge and flashover characteristics of insulating materials. To investigate the influence of different temperatures on surface charge accumulation in epoxy/Al O /ZnO composites, considering temperature rise caused by insulator load, surface potential decay characteristics of epoxy composite samples were tested at 60℃. The initial surface potentials of different samples are shown in [Figure 3: see original paper]. The average decay rates within the first 60s for different samples were calculated, with results shown in [Figure 4: see original paper].

For epoxy/Al O /ZnO composites, as DC voltage increases, initial surface potential rises and surface charge dissipation accelerates. Under the same DC voltage, as ZnO content increases, sample initial surface potential decreases slightly while surface potential decay rate increases. Among these, the sample with 50% ZnO content can suppress surface charge accumulation caused by increased corona voltage due to extremely fast surface charge dissipation, resulting in significantly reduced surface potential.

Comparing experimental results for samples with the same ZnO content at 60℃ and 30℃, under the same DC voltage, initial surface potential remains essentially unchanged at higher temperature, indicating temperature has little effect on surface charge accumulation. However, the initial surface potential decay rate of samples increases significantly, with obvious acceleration of surface charge dissipation, demonstrating that the charge dissipation process is influenced by both electric field and temperature.

Based on surface potential decay of composite samples with 12.5% ZnO content, carrier mobility and trap characteristics under different experimental conditions were calculated, with results shown in . At the same voltage, when temperature increases, carrier mobility improves and trap depth and density also increase. This indicates that high temperature can promote charges in deeper traps to gain sufficient energy for detrapping, thereby accelerating surface charge decay.

3.3 Nonlinear Conductivity Characteristics

For epoxy/Al O /ZnO composites with the same ZnO content, the variation patterns of conductivity during surface potential decay for samples with different ZnO contents under DC voltages of 4kV, 5kV, and 6kV at 30℃ are shown in [Figure 5: see original paper].

When ZnO content is 12.5%, sample conductivity under different DC voltages remains low with little variation. When ZnO content increases to 25%, conductivity decreases slowly as surface potential decreases, with similar conductivity values under different DC voltages. However, as ZnO content increases further, for samples with 37.5% and 50% ZnO, conductivity changes by 2-3 orders of magnitude during surface potential decay. At higher surface potentials, conductivity increases more rapidly. The sample with 50% ZnO content shows the greatest difference in conductivity variation patterns under different DC voltages: at 4kV, conductivity increases relatively uniformly with surface potential; while at 5kV or 6kV, conductivity values are larger and increase significantly at higher potentials, showing a very obvious nonlinear upward trend.

The field-dependent conductivity variation pattern corresponds to the surface charge dissipation process, proving that when ZnO content exceeds a certain threshold, conductivity changes significantly depending on the electric field. Under high electric fields caused by high surface potential, conductivity shows a nonlinear rapid increase. This occurs because at higher ZnO particle concentrations, the average distance between particles decreases, allowing adjacent particles to form local conductive channels for direct carrier passage, which further promotes conductive network formation, leading to significantly accelerated surface potential decay and enhanced surface charge dissipation.

At 5kV DC voltage, the conductivity at maximum surface potential for composite samples with 12.5% ZnO content under different experimental conditions is shown in [Figure 6: see original paper]. At 60℃, as ZnO content increases, sample conductivity increases, similar to the pattern at 30℃. For samples with the same ZnO content, temperature increase leads to higher carrier mobility and significantly increased conductivity.

4 Conclusions

This study investigated surface potential decay characteristics of epoxy/Al O /ZnO composites under DC voltage, analyzed their nonlinear conductivity variation patterns, and discussed the influence mechanisms of ZnO content and temperature on surface charge and conductivity characteristics. The conclusions are as follows:

1. As DC corona voltage increases, the initial surface potential of epoxy/Al O /ZnO composites with the same ZnO content increases, and charge accumulation enhances the built-in electric field, promoting carrier migration. As ZnO content increases, a percolation network gradually forms within the epoxy resin, accelerating surface charge dissipation under the same voltage. Increased ZnO doping concentration can suppress surface charge accumulation caused by increased corona voltage.
2. When temperature rises to 60℃, the effects of DC voltage and ZnO content on material surface charge characteristics are similar to those at 30℃. Temperature's influence on material surface charge dynamic characteristics is mainly manifested in the carrier detrapping process. At 60℃, carrier mobility increases, while charges in deeper traps can gain sufficient energy for detrapping, further accelerating surface charge dissipation.
3. When ZnO content exceeds a certain threshold, epoxy/Al O /ZnO composites exhibit nonlinear conductivity characteristics. Sample conductivity is relatively low under low electric fields but increases rapidly under high electric fields, with the nonlinear growth trend becoming more pronounced as ZnO content increases. This nonlinear conductivity characteristic can effectively promote material surface charge dissipation to achieve electric field regulation.

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