Suppression on Particle Movement and Discharge by Nanocomposite Film Coating on DC GIL Electrode Surface

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ABSTRACT The metal particles' movement in DC GIL can easily result in gas-gap breakdown or insulator surface flashover, which will seriously reduce GIL's insulation performance. To suppress the particle movement and discharge, the authors manufactured the colloidal PI/TiO_2 nanocomposite film by the in-situ polymerization method and coated the film on the electrode surface. This paper characterized and tested the film's physicochemical properties and analyzed its influence on the lifting voltage and movement activity of spherical, linear, sheet metal particles. The results show that TiO_2 nanoparticles disperse evenly in the polyimide matrix with excellent compatibility between inorganic and organic phases. As nanoparticles' content increases, the composite film's mechanical performance and electrical strength decrease, and the corona resistance time increases first and then decreases. Nanocomposite films can significantly increase the lifting voltage of metal particles. The lifting voltage is almost the same, whether it is the bottom-electrode coating or dual-electrode coating. Voltage polarity does not affect the lifting voltage; however, as the film thickness increases, the lifting voltage increases. After coating, the metal particles' movement decreases and gradually the particles lie on the bottom electrode's surface. In the meanwhile, the gas-gap discharge process also stops. There is an obvious polarity effect for the movement of metal particles. The bottom-electrode coating method should be adopted for DC positive voltage, while the dual-electrode coating method should be adopted for DC negative voltage.

INDEX TERMS DC GIL, metal particles, lifting voltage, polyimide, nanocomposite film.

I. INTRODUCTION

GAS insulated transmission line (GIL) has a broad development prospect due to its characteristics such as high voltage level, large transmission capacity, little electromagnetic radiation, and substantial laying flexibility [1], [2]. In the actual production, assembly, transportation and operation of the GIL, metal particles such as spherical, linear, and sheet particles will be produced. Attached to the surface of the insulator, distorting the surrounding electric field, causing gas breakdown or flashover along the surface of the insulator, reducing the insulation performance of the GIL, and seriously affecting the safe and reliable operation of the DC transmission system. Under the effect of Coulomb force,

gravity and gas viscosity, particles will move inside the GIL cavity or even adhere to the insulator surface, distorting the electric field and causing' gas-gap breakdown or insulator surface flashover. The research shows that the coating method is an effective solution to increase the lifting voltage of metal particles and reduce metal particles' movement activity [3], [4]. Therefore, it is necessary to study the charging characteristics, lifting characteristics, movement characteristics of metal particles and gas-gap breakdown characteristics caused by particles. Further, the selection of coating materials and coating methods is of great significance for reducing metal particle pollution and improving equipment insulation stability.

Parekh H analyzed the charge characteristics of metal particles after coating, laying a foundation for the study on the suppression of metal particles lifting by coating on the

The associate editor coordinating the review of this manuscript and approving it for publication was Bo Pu [ID].

electrode surface [5]. However, the study object is static microparticles, which lack the charge analysis of the interaction mechanism between particles and electrodes during the collision. Wang established the quantitative characterization model of spherical metal particles with an electrode coated under DC stress based on gas ionization theory and interfacial charge accumulation to quantitatively analyze the effect of the polyethylene terephthalate (PET) films on the lifting voltage of metal particles [6]. However, the effect of space charge on particle movement is not considered. Lu optimized the Parekh model based on the experiments to calculate the spherical particle's surface charge density, considering the effect of the relative dielectric constant of the PET film and space charge [7]. However, PET film has a weak heat resistance and DC corona resistance, poor adhesion with the metal electrode. The simulation only considers the influence of a single factor or some factors on the particle's electrodynamic behavior.

The development of doped nanomaterials provides a new idea for developing new insulating materials [8]–[10]. At present, the research mainly focuses on adding a certain number of inorganic nanoparticles such as TiO$_2$, silicon dioxide (SiO$_2$), aluminum oxide (Al2O$_3$) to the PI, so that organic and inorganic hybrid materials can achieve very excellent properties, such as thermal stability and dielectric properties. Cha prepared the polyimide inorganic nanocomposite film by in-situ dispersion polymerization. The nanocomposite film's dielectric properties and breakdown field strength were analyzed based on the insulation aging mechanism. The correlation between the corona resistance and the nanocomposite film's dielectric constant was established [11]. It provides a theoretical basis for the preparation of the polyimide nanocomposite film suitable for similar working conditions. Huang prepared the phenyl-thioether polyimide film by polycondensation-thermal imidization, characterizing the film's structure and properties [12]. Based on the charged model of metal particles in reference [5], considering the adhesion of metal particles to film materials, the effects of coating on the lifting voltage and metal particle movement were analyzed. The research objects are mostly spherical metal particles; however, the damage of linear and sheet metal particles is more severe than that of spherical metal particles. The research on the lifting, movement characteristics of metal particles and the breakdown process of the gas-gap discharge caused by the particles are mostly qualitative descriptions, lacking quantitative analysis. Besides, different types of metal particles have not been compared and analyzed in the same experimental platform.

According to the references, Srivastava, Wang, Lu and other domestic and foreign scholars are studying the effect of electrode coating under DC, using polyethylene terephthalate (PET) as the coating material, but calculations show that when the current is 3450A, The surface temperature of the DC GIL electrode will reach above 105°C. Taking into account the long-term operational stability of the GIL, the working temperature of the electrode coating material should not be lower than 150°C. The PET film with a long-term operating temperature of less than 120°C cannot meet the heat resistance requirements of the DC GIL electrode coating, and a film material with good thermal stability should be selected.

In this paper, the polyimide/Titanium dioxide (PI/TiO$_2$) nanocomposite film was prepared by in-situ polymerization and tested. The metal particles' movement observation platform was built to quantitatively compared the suppression effects of the PI/TiO$_2$ nanocomposite film coated on the electrode surface on the lifting characteristics and movement characteristics of the spherical metal particles.

II. MANUFACTURE OF PI/TIO2 NANOCOMPOSITE FILM

Polyimide (PI) is a type of high polymer insulation material with thermal stability, corrosion resistance, and excellent insulation performance. It has been widely used in the field of power insulation [13]–[16]. Nano TiO$_2$ has excellent thermal stability, chemical stability as well as superior optical, electrical and mechanical properties, which can improve the aging resistance and high-temperature resistance of materials. The thermal expansion factor of TiO$_2$ matches with that of polyimide. Doping nano-TiO$_2$ in PI can significantly improve nanocomposites' various properties compared with pure PI [17]–[21]. Compared with the solution-gel method and mechanical blending method, the in-situ polymerization method is simple to operate and can effectively reduce nanoparticles' agglomeration. Therefore, in this work, TiO$_2$ nanoparticles were doped into PI by the in-situ polymerization to manufacture PI/TiO$_2$ nanocomposite film.

Inorganic nanoparticles have agglomeration characteristics in the PI matrix. The silane coupling agent KH550 is used to modify TiO$_2$ nanoparticles' surface to reduce the agglomeration and two-phase separation. Mix TiO$_2$ nanoparticles, absolute ethanol, and KH550 to form a mixture solution. Use an ultrasonic cleaner to ultrasonically treat the mixture solution for 0.5h, then use a magnetic stirrer to stir the mixture solution for 6h in a 60° environment to obtain a suspension. After drying and grinding, the coupling agent modified nanoparticles are obtained. Vacuum dry for 0.5 h at 80° before use.

Mix modified TiO$_2$ nanoparticles, Oxydianiline (ODA), and Dimethylacetamide (DMAc) to form a mixture solution. Ultrasonically treat the mixture solution for 1h, then use the mechanical stirrer to stir the mixture solution for 1h in a 50° oil bath environment to disperse the nanoparticles fully. Add Pyromellitic Dianhydride (PMDA) to solution every half an hour for three times to make the reaction more complete. Control nitrogen ventilation rate and stirring rate. Stir the solution for 10h to obtain the PI/TiO$_2$ mixture solution with suitable viscosity.

Use a circulating water vacuum pump to vacuum the mixture solution to remove bubbles, then use an automatic coating machine to uniformly coat the mixture solution on the glass sheet or metal electrode. Use a high-temperature blast drying oven to raise the temperature of the coated glass sheet and metal electrode step by step for 4h. After cooling down to room temperature, the PI/TiO$_2$ nanocomposite film

is obtained. Change the amount of TiO$_2$ nanoparticles to manufacture PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle contents of 0, 2wt.%, 4wt.%, 6wt.%, 8wt.%, 10wt, 12wt.%, 14wt.%, 16wt.%, 18wt.% and 20wt.%. The film's thickness should be limited to reduce the negative effect on the metal electrode's heat dissipation and the spatial electric field distribution. In this paper, the film thicknesses are set to 25 and 50 μm.

III. PERFORMANCE TESTS OF PI/TIO2 NANOCOMPOSITE FILM

A. MECHANICAL PERFORMANCE TEST

Refer to GB/T 13542.2-2009, cut the sample and mark the sample according to the standard; then clamp the two ends of the sample on the AGS-J electronic universal testing machine with clamps, start the button to stretch the sample, and record at the same time Tensile strength and elongation at break when the sample is broken, the moving speed of the clamp during stretching is 0.5 mm/min, 5 samples for each group are measured, and the final result is the average value. The measurement error of the experiment is $\pm$0.5%. The results are shown in Fig. 1. As TiO$_2$ nanoparticle content increases, the tensile strength of the film decreases. The excessive TiO$_2$ nanoparticle content makes the film easier to break.
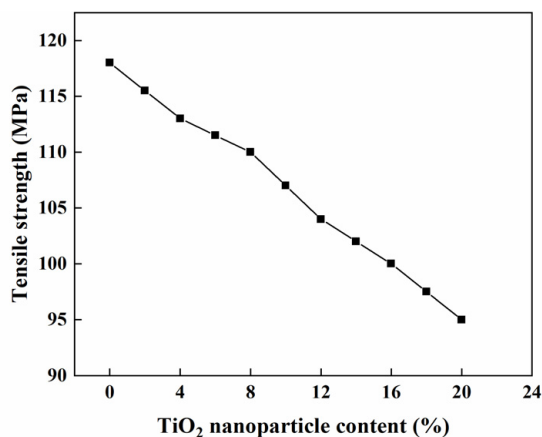

FIGURE 1. Effect of TiO$_2$ nanoparticle content on the mechanical performance of PI/TiO$_2$ nanocomposite film.

B. ELECTRICAL STRENGTH TEST

Refer to GB/T 13542.2-2009, use the HT-5/20 type withstand voltage/breakdown voltage tester to test the DC electrical strength of PI/TiO$_2$ nanocomposite film in the air, obtain the data from "Breakdown Strength = Shock Voltage (V)/Sample Thickness (d)" and record. Measure five times for each mass fraction nanocomposite film and take the average value. The measurement error of the experiment is $\pm$0.5%. The results are shown in Fig. 2.

The electrical strength of PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle content of 20wt.% reduces by 22% compared with that of pure PI film. As the TiO$_2$ nanoparticle content increases, the concentration of impurity ions and the
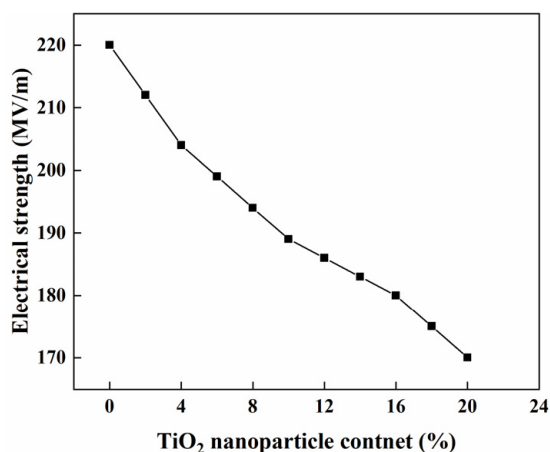

FIGURE 2. Effect of TiO$_2$ nanoparticle content on the electrical strength of PI/TiO2 nanocomposite film.

organic-inorganic interface increase in PI/TiO$_2$ nanocomposite film. Therefore, it is easy to form a through channel and cause breakdown.

C. CORONA RESISTANCE TIME TEST

Refer to GB/T 22689-2008, use the high-frequency pulse voltage tester to test the PI/TiO$_2$ nanocomposite film's corona resistance time. According to the IEC 60034-18-42 standard, select the bipolar pulse square wave as the test voltage. The peak-to-peak pulse voltage is 2 kV, the duty cycle is 50%, and the frequency is 20 kHz. Select the rod electrode with a 6mm diameter and the plate electrode with a 50 mm diameter as the standard test platform. Place the PI/TiO$_2$ nanocomposite film with 25 μm thickness and 4 cm length on the electrode to take the corona resistance accelerated aging test. Measure nine times for each mass fraction nanocomposite film and take the median value as the mass fraction film's corona resistance time. The measurement error of the experiment is $\pm$0.5%. The results are shown in Fig. 3.
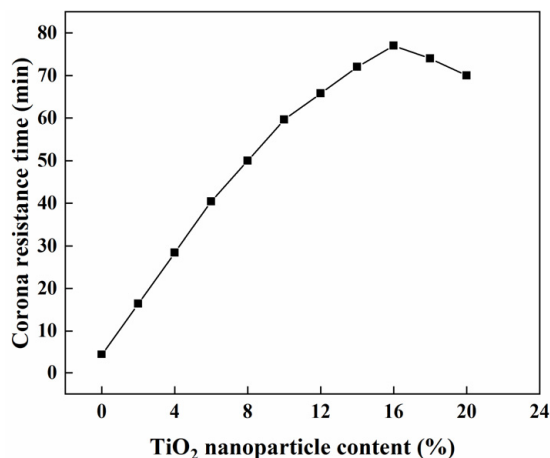

FIGURE 3. Effect of TiO$_2$ nanoparticle content on corona resistance time of PI/TiO$_2$ nanocomposite film.

It can be seen that, as the content of nanoparticles increases, the corona resistance time increases first and then

decreases. The corona resistance time of PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle content of 16wt.% reaches a maximum of 77 min, 17.5 times for the pure PI film with a corona resistance time of 4.4 min, which means the corona resistance performance is significantly improved. During the corona aging, the corona discharge acts on the nanocomposite film's surface and extends to the inside of the film. High-temperature ablation, free radical reaction, and charged particles cause the film to degrade under multiple stresses such as electricity, heat, machinery and environment. The TiO$_2$ nanoparticles in the surface doped layer gradually deposit and form a protective layer composed of inorganic oxides. Since inorganic oxide's bond energy is higher than that of polymer, it has higher oxidation resistance, which can effectively block the damage of corona discharge to the matrix. Therefore, the corona resistance of the material is greatly improved.

Simultaneously, due to the high thermal conductivity of the TiO$_2$ nanoparticles, the nanoparticles overlap each other to form a heat conduction path. The heat accumulated by the corona discharge in the local area can rapidly dissipate along the heat conduction path and reduce the film's damage. Besides, the volume resistivity of TiO$_2$ nanoparticles is lower than that of the matrix resin, which is beneficial to disperse the space charge in the material, reduce or eliminate the stress caused by corona, and weakens the corona strength. The trap structure that can capture the carrier on the surface forms the space-charge electric field. The space charge electric field dramatically reduces the acceleration effect of the charged particles produced by ionization in the electric field and protects the insulating material. However, when the content of TiO$_2$ nanoparticles is too high, the agglomeration phenomenon will destroy the film's stable structure, and the corona resistance time of the nanocomposite film will decrease.

When there are metal particles in the GIL, the corona will appear under the electric field's effect. When using the electrode coating method to suppress the metal particles, the corona resistance performance should also be considered. The above corona resistance time test shows that, when the content of TiO$_2$ nanoparticles in the PI/TiO$_2$ nanocomposite film is 16 wt.%, the film's corona resistance is more prominent, which can effectively avoid the corona damage and improve the service life of the coating. Therefore, PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle content of 16wt.% was selected for morphology, thermal stability, and dielectric properties.

D. SEM ANALYSIS
The scanning electron microscope (SEM) of PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle content of 16wt.% is shown in Fig. 4. The dark area is PI matrix and the light spot is TiO$_2$ nanoparticle. It can be seen that TiO$_2$ nanoparticles are relatively evenly distributed in the PI matrix without obvious boundaries. Two materials with different properties can be sufficiently "coupled" by silane coupling agent. The combined layer of inorganic phase-silane coupling

agent-organic phase is formed. The silane coupling agent is an organosilicon compound with two different reactive groups in the molecule. Its chemical structure can be generally expressed as RSiX3. X is a hydrolyzable group that can react with inorganic materials or adsorb on the materials' surface, thus improving the inorganic materials' affinity. R is an organic functional group, which can react with a polymer. Therefore, due to the coupling effect of KH550, TiO$_2$ nanoparticles are well dispersed. The inorganic phase and organic phase in the nanocomposite film have excellent compatibility.
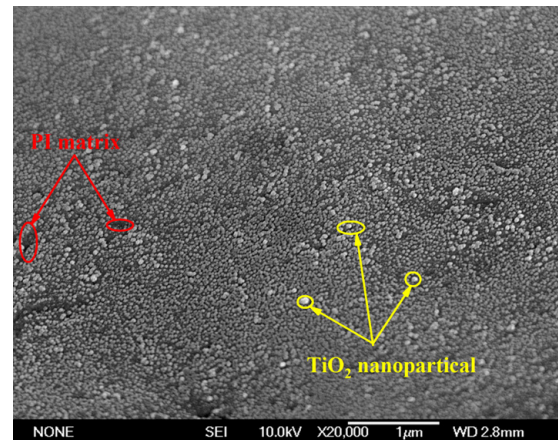

FIGURE 4. SEM of PI/TiO2 nanocomposite film.

E. RESISTIVITY MEASUREMENT
Refer to GB/T 1410-2006, LST-121 volumetric surface resistivity tester is used to test the conductivity of pure PI film and PI/TiO$_2$ nanocomposite film with 16wt.% TiO2 nanoparticle. The results are shown in Tab. 1.

TABLE 1. Film conductivity test results.

Paramter	PI	PI/TiO$_2$
Volume Conductivity(S/m)	1.2×10^{-17}	6.8×10^{-13}
Surface Conductivity (S)	5.3×10^{-16}	1.3×10^{-12}

After doping with TiO$_2$ nanoparticles, stray ions and coincidence interface are introduced, which improves the volume conductivity and surface conductivity of the film. However, the order of magnitude still meets the application requirements.

Therefore, in this work, PI/TiO$_2$ nanocomposite films with TiO$_2$ nanoparticle content of 16wt.% and thicknesses of 25 and 50 μm were selected as the electrode coating materials.

IV. EFFECT OF ELECTRODE COATING ON LIFTING VOLTAGE OF METAL PARTICLES
PI/TiO$_2$ nanocomposite films with 16wt.% TiO$_2$ nanoparticle content were made in the laboratory. And the film had an

excellent performance under actual working conditions by the performance tests. Different kinds of films have different effects on the lifting voltage of metal particles. Moreover, when the same film is coated on a metal electrode by different methods, the experimental results are also different. In this paper, three different electrode coating methods were used to compare the effect on the lifting voltage of metal particles. The first method was to coat PI/TiO_2 nanoparticle mixture on the metal electrode. After heating, PI/TiO_2 nanocomposite film with TiO_2 nanoparticle content of 16wt.% was formed on the electrode surface (defined as Method A). The second method was to use the binder to stick the prepared PI/TiO_2 nanocomposite film on the electrode surface. However, there would inevitably be bubbles between the film and the electrode (Method B). The third method was to use the same binder as Method B to stick the PET film on the electrode surface as a control group (Method C).

A. EFFECT OF BOTTOM-ELECTRODE COATING ON LIFTING VOLTAGE

Coat a film with 25 μm thickness on the bottom electrode. Respectively carry out the experiments on spherical, linear and sheet metal particles. The experimental device is shown in Fig. 5. Under the positive DC voltage, place the metal particles in the middle of the bottom electrode. Raise the voltage slowly, and record the lifting voltage of metal particles. After completing each experiment, use an ion fan to eliminate residual charges and wipe the electrodes and particles with alcohol to maintain the experimental conditions' stability. Change the coating method and the metal particle parameters, and carry out each experiment ten times.
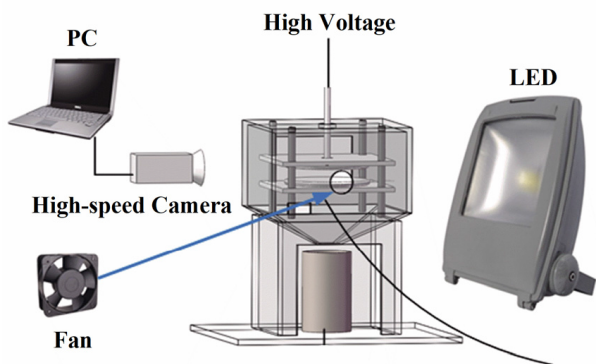

FIGURE 5. Observation platform of metal particles' movement.

1) LIFTING VOLTAGE OF SPHERICAL METAL PARTICLES

The lifting voltages of spherical aluminum metal particles with diameters of 0.5 and 1 mm are shown in Fig. 6.

If the bottom electrode is not coated, the metal particles are instantly charged, and the lifting voltage of the particles is relatively stable. However, if the bottom electrode is coated, the particle charging process is complicated and random. Therefore, there is a range of lifting voltage of metal particles
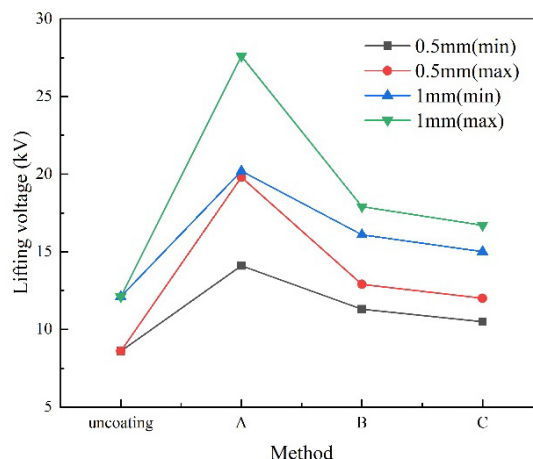

FIGURE 6. Lifting voltage of spherical metal particles.

in different coating methods. The results show that Method A can significantly increase the lifting voltage by 64% to 130% compared with uncoating. However, if using the other two coating methods, the lifting voltages increase by 31% to 50% and 22% to 40%, respectively. Therefore, the coating method of heating and curing the electrode surface mixture can better increase the lifting voltage of spherical metal particles.

2) LIFTING VOLTAGE OF LINEAR METAL PARTICLES

The lifting voltages of linear aluminum metal particles with 0.2 and 0.5 mm diameters and 5 mm length are shown in Fig. 7.
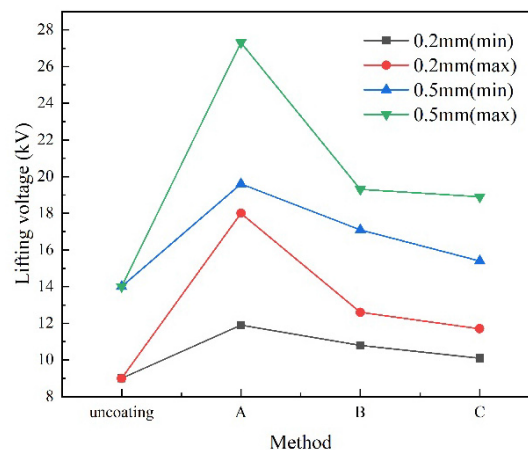

FIGURE 7. Lifting voltage of linear metal particles.

Method A increases the lifting voltage by 32% to 100% compared with uncoating. However, if using the other two coating methods, the lifting voltages increase by 20% to 40% and 10% to 35%, respectively. The effect of Method A on lifting voltage is more prominent.

3) LIFTING VOLTAGE OF SHEET METAL PARTICLES

The lifting voltages of 5×5 mm2 sheet aluminum particles with 0.1 and 0.3mm thickness are shown in Fig. 8.
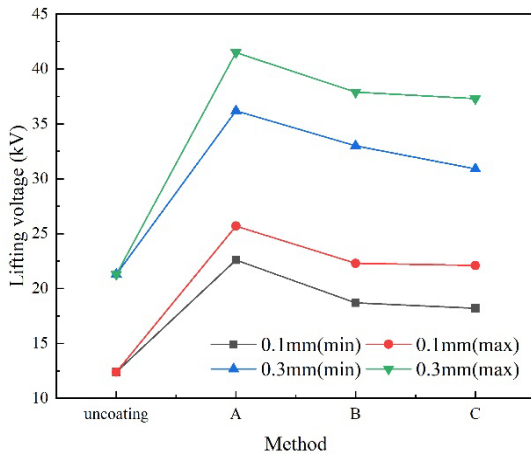
FIGURE 8. Lifting voltage of sheet metal particles.

The lifting voltage of sheet metal particles increases by 70% to 107% with Method A. However, if using the other two coating methods, the lifting voltages of sheet metal particles are increase by 51% to 80% and 45% to 78%, respectively.

The charge exchange between the metal particles and the electrode is instant when the electrode is not coated. The film will affect the charge conduction and micro-discharge process between the metal particles and the electrode. The particle charging process is not smooth, which will affect the particle electric field force. Besides, the film has electrostatic adsorption to the metal particles. Therefore, the film can increase the lifting voltage of metal particles. The experimental data shows that, compared with the common coating methods with the binder, method A presented in this paper has a better effect on the lifting voltage of metal particles.

B. EFFECT OF THE DUAL-ELECTRODE COATING ON THE LIFTING VOLTAGE

Respectively coat the upper surface of the bottom electrode and the bottom surface of the upper electrode with the PI/TiO$_2$ nanocomposite film with 25 μm thickness by Method A. Slowly raise the voltage and record the lifting voltage of metal particles of different shapes to obtain the increasing percentage of the lifting voltage of metal particles by dual-electrode coating. The effect comparison between the bottom-electrode coating and the dual-electrode coating is shown in Tab. 2.

TABLE 2. Effect comparison of bottom-electrode coating and dual-electrode coating.

Metal Particle Shape	Increasing Percentage by Bottom-Electrode Coating	Increasing Percentage by Dual-Electrode Coating
Spherical	64% to 130%	65% to 132%
Linear	32% to 100%	32% to 101%
Sheet	70% to 107%	72% to 107%

When the bottom electrode is coated, the lifting voltage of metal particles is almost the same as the lifting voltage when the dual electrodes are coated. The upper-electrode coating

has a specific distortion effect on the electric field nearby. However, it has little impact on the static metal particles on the bottom electrode due to the distance.

C. EFFECT OF VOLTAGE POLARITY AND FILM THICKNESS ON LIFTING VOLTAGE

The PI/TiO$_2$ nanocomposite film without adhesive coating on the electrode surface can significantly increase metal particles' lifting voltage. With this coating method, keep the parameters of metal particles unchanged and change the DC voltage's polarity to observe the lifting voltage of metal particles of different shapes. The results are shown in Tab. 3.

TABLE 3. Effect of DC voltage polarity on lifting voltage of metal particles after coating.

Metal Particle Shape	Increasing Percentage under Positive Polarity	Increasing Percentage under Negative Polarity
Spherical	64% to 130%	66% to 129%
Linear	32% to 100%	30% to 97%
Sheet	70% to 107%	72% to 105%

After coating, the percentage of the lifting voltage of metal particles is almost the same. Therefore, the polarity of the DC voltage does not affect the lifting voltage of metal particles.

Change the film thickness to 50 μm, and record the increasing percentage of metal particles' lifting voltage. The experimental results are shown in Tab. 4.

TABLE 4. Effect of film thickness on the lifting voltage of metal particles.

Metal Particle Shape	Increasing Percentage with 25 μm Thickness	Increasing Percentage with 50 μm Thickness
Spherical	64% to 130%	85% to 150%
Linear	32% to 100%	49% to 120%
Sheet	70% to 107%	80% to 115%

As the film thickness increases, the increasing percentage of the lifting voltage of metal particles increases. Under actual working conditions, the increase of film thickness will affect the heat dissipation of the electrode. Therefore, the film with 25 μm thickness should be accepted, which can already increase the lifting voltage enough.

D. SUPPRESSION EFFECT OF ELECTRODE COATING ON THE MOVEMENT OF METAL PARTICLES AND GAS-GAP DISCHARGE CAUSED BY PARTICLES

On the one hand, the electrode coating can increase the lifting voltage of metal particles. On the other hand, it can suppress the movement of metal particles and gas-gap discharge. Carry out the electrode coating experiments of metal particles with different shapes, observe the movement and discharge behavior to analyze the suppression effect. The distance between the plate electrodes is 20mm, and the edges are rounded to improve the electric field distribution. Combine aluminum spherical metal particles (Fig. 9.) with a radius of 1mm, aluminum linear particles (Fig. 10.) with a length of 6mm and a radius of 0.25 mm, and aluminum flake particles (Fig. 11.) Place it in the middle of the lower electrode and slowly increase the negative polarity voltage at a rate of 0.1kV/s until
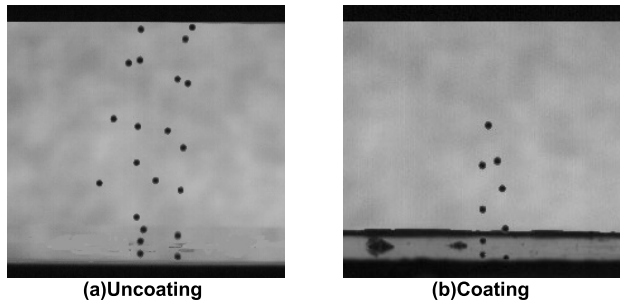
(a)Uncoating   (b)Coating

FIGURE 9. The movement of spherical metal particles.

(a)Uncoating

(b)Coating

FIGURE 10. The movement of linear metal particles.
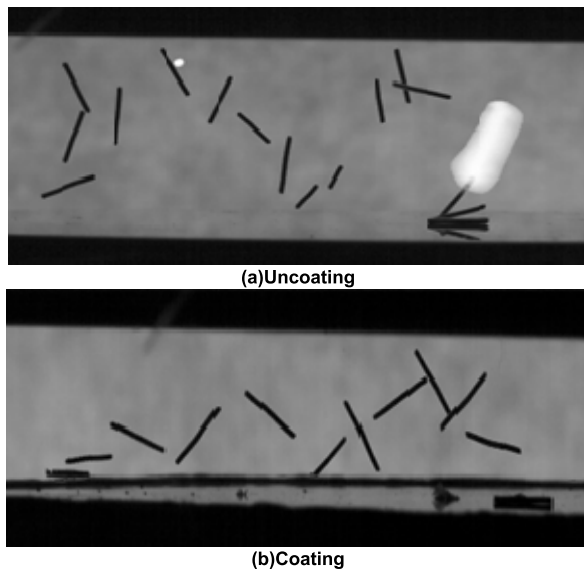

(a)Uncoatinhg

(b)Coating

FIGURE 11. The movement of sheet metal particles.

the metal particles are lifted. The PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle content of 16wt.% and the thickness of 25 μm without adhesive coating on the electrode surface proposed in this paper is used for coating.

When the electrode is not coated, the spherical metal particles continue to reciprocate between the upper and bottom electrodes. However, when the electrode is coated, the dielectric film affects the charge exchange between the metal particles and the electrode. After the spherical metal particles collide with the coated electrode, the movement height will gradually decrease after several reciprocating movements. Finally, it will rest on the surface of the bottom electrode. At the same time, the dielectric film will hinder the gas-gap breakdown process. The breakdown voltage caused by spherical metal particles after the coating is more significant than that without coating.

The movement of linear and sheet metal particles is related to voltage polarity. After coating, the lifting voltage of linear and sheet metal particles increases. Under the DC positive voltage, the particles still move near the bottom electrode, such as rotation and translation. While under the DC negative voltage, the particles will run through the gas-gap and may form the phenomenon of fireflies. The voltage required for particles to move after the coating is higher than that without
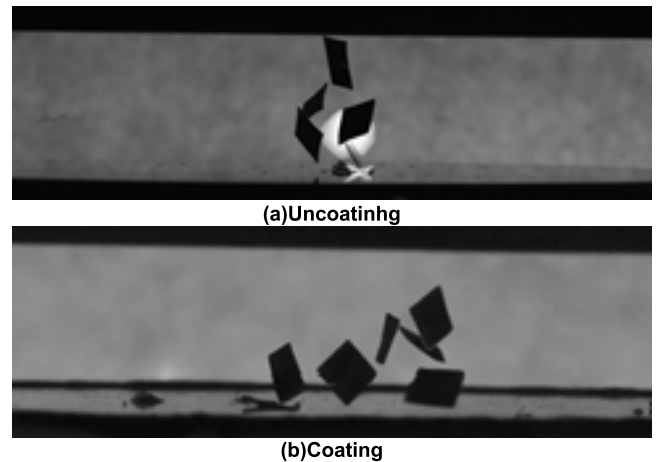
coating. Besides, the linear and sheet metal particles have a substantial effect on the distortion of the electric field. Therefore, when the particles begin to move, there will be a high probability of gas-gap breakdown discharge. If the bottom electrode is coated, the rotation and translation of the particles are suppressed. However, the suppression effect of the firefly is not obvious. The Dual-electrode coating method can suppress the phenomenon of fireflies. If the dual electrode is not coated, the linear and sheet metal particles remain in movement after being lifted, and the gas-gap discharge process is continuous. After coating, the metal particles will rest on the bottom electrode's surface after several discharges and no longer move. The gas-gap discharge process caused by the particles is transient. Therefore, the damage caused by gas-gap discharge after coating will be reduced compared with that without coating.

The experimental results show that electrode coating can suppress the movement ability of metal particles and make the gas-gap discharge caused by metal particles not sustainable so as to reduce the damage caused by metal particles. According to the movement characteristics of metal particles under different polarity voltage, the bottom-electrode coating method should be adopted for DC positive voltage. In contrast, the dual-electrode coating method should be adopted for DC negative voltage.

After coating, the maximum electric field intensity is distributed between the metal particles and the film, and the surface charge density of the metal particles is polarized, making the particles receive a downward polarization force, which decreases as the field intensity increases, and then increases in the opposite direction. According to the improvement of Parekh starting field strength calculation model, if the electric field strength is less than the initial field strength of partial discharge, the starting field strength is calculated, the particle charge is 0pC, and the electric field force received is downward; With the increase of the field strength, the particles are negatively charged and subjected to upward Coulomb force. The combined effect of electrostatic adsorption, Coulomb force and polarization force makes

the force of the particles appear first downwards and then upwards to overcome gravity as the field strength increases. Enlightenment.

V. CONCLUSION

In this paper, PI/TiO$_2$ nanocomposite films with corona resistance were made and the properties were characterized. This paper studied the effect of the electrode coating on the lifting voltage of spherical, linear and sheet metal particles, the suppression effect of movement activity, as well as the gas-gap discharge caused by particles. The main conclusions are as follows:

1) TiO$_2$ nanoparticles are evenly dispersed in the polyimide matrix with excellent compatibility between inorganic and organic phases. As nanoparticles' content increases, the mechanical properties and electrical strength of the composite film decreases, and the corona resistance time first increases and then decreases. If the TiO$_2$ nanoparticle content is 16wt.%, the corona resistance of the nanocomposite film is the best. Moreover, the film's mechanical property, electrical strength, thermal property, and electrical conductivity can effectively meet the actual requirements.

2) Compared with the common coating methods with the binder, the PI/TiO$_2$ nanocomposite film with TiO$_2$ nanoparticle content of 16wt.% and the thickness of 25 μm without adhesive coating on the electrode surface proposed in this paper has a better effect on the lifting voltage of metal particles. The lifting voltage of spherical metal particles increases by 64% to 130%, the lifting voltage of linear metal particles increases by 32% to 100%, and the lifting voltage of sheet metal particles increases by 70% to 107%.

3) When the bottom electrode is coated, the lifting voltage of metal particles is almost the same as the lifting voltage when the dual electrodes are coated. Voltage polarity does not affect on the lifting voltage of metal particles. As the film thickness increases, the lifting voltage of metal particles increases. Considering that the increase of film's thickness will affect the electrode's heat dissipation, the thickness of 25 μm is appropriate. At this time, the effect on the electrode's heat dissipation is little and the lifting voltage of metal particles of different shapes is significantly increased.

4) Due to the film's obstructive effect on the charge transfer process and the electrostatic adsorption force on the metal particles, metal particles' movement is weakened after coating. The metal particles of different shapes rest on the bottom electrode's surface after moving for some time and no longer continue to move. The gas-gap discharge process caused by the moving metal particles is also not continuous, which will stop as the particles rest on the bottom electrode surface. According to the polarity effect of linear and sheet metal particle movement, the bottom-electrode coating method should be adopted for DC positive voltage. In contrast, the dual-electrode coating method should be adopted for DC negative voltage.

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