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RESEARCH ARTICLE

Surface Charge Dissipation Characteristics of Al₂O₃/Silicone Rubber Composites With Different Weight Percentages

ZHIYAO FU¹, ZHENGLONG JIANG¹, DEXIONG HU^{1,2}, FENG WANG^{1,2}, (Senior Member, IEEE),
LIPENG ZHONG^{1,2}, (Member, IEEE), XINGSHUO SONG², AND KAI NING³

¹State Key Laboratory of Disaster Prevention and Reduction for Power Grid, State Grid Hunan Electric Power Company Disaster Prevention and Reduction Center, Changsha 410100, China

²College of Electrical and Information Engineering, Hunan University, Changsha 410082, China

³School of Electrical and Information Engineering, Changsha University of Science and Technology, Changsha 410012, China

Corresponding author: Dexiong Hu (hudexiongthu@163.com)

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ABSTRACT To identify a nanocomposite material capable of mitigating surface charge accumulation issues in silicone rubber composite insulators, this paper investigated the surface charge dissipation characteristics of micron-sized Al₂O₃/silicone rubber composites with different weight percentages under positive dc voltage. Furthermore, this paper investigated the influence of the uncharged and charged silicone rubber on the surface flashover voltage under positive dc voltage. The result show that the addition of micron-sized Al₂O₃ particles effectively ameliorates the severity of surface charge accumulation. In comparison to pure silicone rubber, the reduction in maximum surface charge density and average surface charge density of different weight percentage Al₂O₃/silicone rubber composites ranges from 18.60% to 50.60% and from 33.26% to 57.53%, respectively. When there is no surface charge on the silicone rubber surface, the addition of micron-sized Al₂O₃ particles at different weight percentages results in a decrease in positive dc surface flashover voltage. Conversely, when a positive surface charge is applied to the silicone rubber surface, the greatest reduction in positive dc surface flashover voltage occurs in pure silicone rubber. Furthermore, the positive DC flashover voltage of pure silicone rubber can recover to 86.53% of its value without applied surface charge at a decay time of 60 minutes. In contrast, the addition of micron-sized Al₂O₃ particles at different weight percentages diminishes the impact of surface charge on the surface flashover voltage, allowing it to recover to 92.03% to 94.18% of its value without applied surface charge.

INDEX TERMS Silicone rubber, Al₂O₃, surface charge, surface charge density, positive dc voltage.

I. INTRODUCTION

Silicone rubber composite insulators have emerged as the pivotal equipment for outdoor insulation due to their lightweight nature, robust pollution flashover resistance, and ease of installation [1], [2]. Based on operational experiences within the electrical grid, it has been observed that the predominant operational incidents associated with composite insulators are flashover events. Extensive prior researches have revealed

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that, when subjected to prolonged exposure to unipolar dc voltage as opposed to ac fields, composite insulator surfaces tend to accumulate surface charges more readily and retain them for longer periods [3]. The presence of surface charges not only leads to distortions in the electric field but also serves as seed charges for the initiation and propagation of surface discharges along the composite insulator [4]. Consequently, investigating the surface charge dissipation characteristics of composite insulators holds paramount theoretical significance and engineering value.

Since the initial proposal of nanodielectrics by the British scholar Lewis [5], researchers have made extensive efforts to enhance the surface charge dissipation properties of polymer insulation materials through nanomodification techniques. Li et al. incorporated micron-sized ZnO, known for its non-linear electrical conductivity characteristics, into silicone rubber. Their study focused on the surface charge accumulation and dissipation properties of ZnO/silicone rubber composites under the influence of dc voltage overlaid with pulse voltage. The findings indicated that the addition of ZnO effectively mitigated the accumulation of surface charges in silicone rubber [6]. Dhivakar et al. investigated the surface charge dissipation properties of silicone rubber composites with varying concentrations of nano-sized aluminum trihydrate (ATH). Their research revealed that the introduction of nano-sized ATH improved the interface region between the matrix and the filler. This interface region provided a free pathway for charge carriers to transport into the material's interior [7]. Yan et al. applied both nano and micron-sized SiO₂ coatings to the surface of silicone rubber, resulting in silicone rubber composites with superhydrophobic properties. The study demonstrated that the traps on superhydrophobic surfaces were shallower compared to unmodified surfaces, thereby facilitating surface charge dissipation [8]. Chen et al. investigated the impact of dielectric barrier discharge (DBD) treatment on the surface charge dissipation properties and the surface flashover characteristics of AlN/epoxy resin composites. Their findings revealed an enhancement in surface conductivity and an increase in shallow trap density, leading to accelerated surface charge dissipation and improved the surface flashover voltage [9]. Du et al. employed direct fluorination to treat the surface of silicone rubber materials. Their research showed that the dissipation time of surface charges was influenced by fluorination duration. When the fluorination time exceeded 10 minutes, it introduced chemical defects, resulting in an increased density of deep traps [10]. It is worth noting that Wang et al. used X-ray short-term irradiation on the surface of insulators and found that it can effectively accelerate the dissipation of surface charges [11]. Manufacturers of electrical equipment commonly incorporate significant amounts of micron-sized Al₂O₃ particles into the formulations for epoxy resin basin insulators to enhance their mechanical and insulation properties. On the other hand, adding Al₂O₃ particles to insulating materials may adjust the trap energy level and resistivity, thereby increasing the threshold voltage required for charge injection. Therefore, adding Al₂O₃ particles into silicone rubber composite insulators with the aim of improving their surface charge dissipation properties holds promising practical applications. However, research on the surface charge accumulation and dissipation properties of Al₂O₃/silicone rubber composite materials remains limited.

This study investigates the surface charge dissipation characteristics of micro-sized Al₂O₃/silicone rubber composite materials with different weight percentages under positive dc

voltage. Subsequently, we analyze the mechanistic influence of micro-sized Al₂O₃ particles on the surface charge dissipation properties of silicone rubber by combining the results of surface conductivity and volume conductivity measurements. Finally, we examine the influence of the uncharged and charged silicone rubber on the surface flashover voltage under positive dc voltage.

II. EXPERIMENTAL METHODS

A. SAMPLE PREPARATION

In order to ensure the relevance of our experimental results to practical applications, this study followed the materials formulation and processing parameters for high-temperature vulcanized silicone rubber as outlined for 10 kV composite insulators [12]. The key materials employed in this study include methyl vinyl silicone rubber, ATH, fumed silica, iron oxide, hydroxyl silicone oil, silane coupling agent (KH560), and a vulcanizing agent composition. For this research, micro-sized Al₂O₃ particles with an average diameter of 30 μm were selected. The scanning electron microscopy (SEM) results depicting these particles are presented in Figure 1. Different weight percentages of micro-sized Al₂O₃ were incorporated, specifically 0%, 10%, 20%, and 30%. All silicone rubber samples possessed a diameter of 100 mm and a thickness of 2 mm.

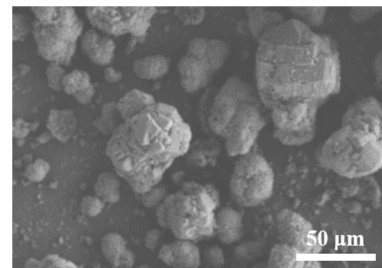


FIGURE 1. The SEM image of micro-sized Al₂O₃ particles.

B. TEST PLATFORM

As illustrated in Figure 2, the surface potential testing platform primarily comprises two modules: the surface charge injection module and the surface potential measurement module. As depicted in Figure 2a, the surface charge injection module is essentially an electrostatic corona charging circuit designed to inject charges onto the surface of the silicone rubber specimen. The silicone rubber specimen is positioned on an aluminum sheet, which is connected to the ground wire. A needle electrode is mounted directly above the central apex of the silicone rubber, maintaining a vertical separation of 20 mm from the surface. The needle electrode is connected to a high-voltage dc power supply HV1, providing a rated voltage of +30 kV and a power output of 30 W.

As illustrated in Figure 2b, the surface potential measurement module primarily consists of an electrostatic capacitance probe, a three-dimensional motion control system, and

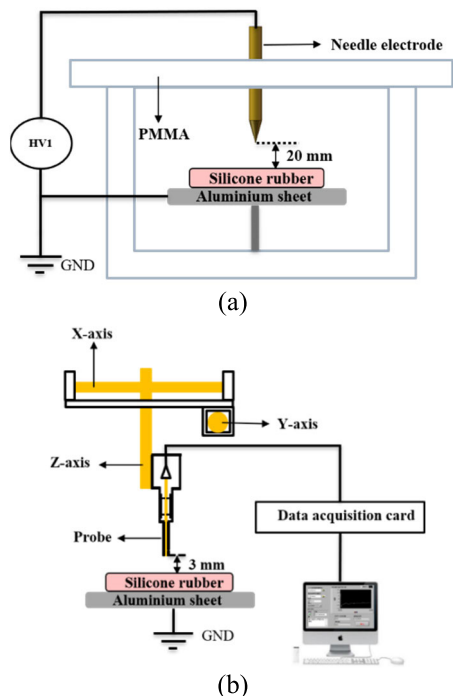


FIGURE 2. The schematic diagram of the surface potential testing platform. (a) The module for applying surface charges. (b) The module for measuring surface potential.

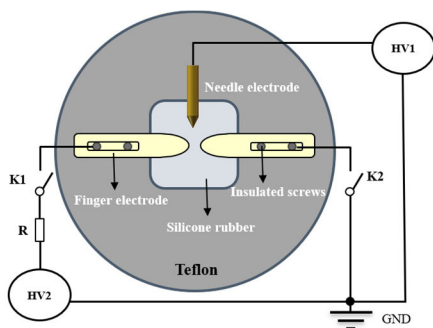


FIGURE 3. The schematic diagram of the surface flashover testing platform.

a data acquisition device. After considering the performance indicators of electronic devices [13], [14], this paper selects ADA-4530 as the electrometer chip. The capacitance probe has a measurement range of -5 V to $+5\text{ V}$, with a measurement precision of 10 mV . The capacitance probe is positioned parallel to the silicone rubber surface, maintaining a vertical separation of 3 mm . It is securely affixed to the Z-axis of the three-dimensional motion control system, allowing the capacitance probe to scan the potential distribution across the silicone rubber surface. Finally, the acquired potential data is transmitted to a computer through a data acquisition device for recording and storage.

As depicted in Figure 3, the surface flashover testing platform is employed. The test specimen of silicone rubber is placed atop a polytetrafluoroethylene (PTFE) layer, which

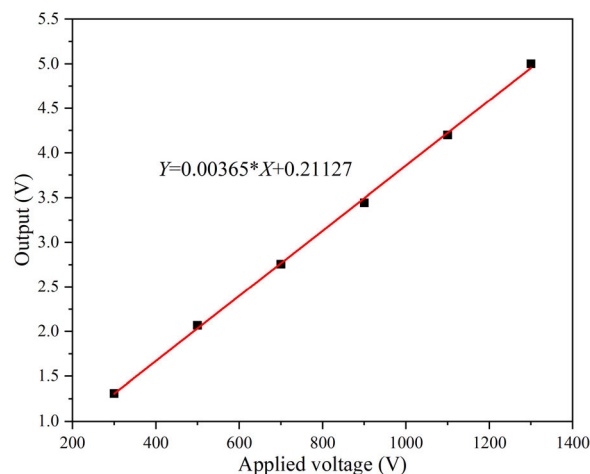


FIGURE 4. The relationship between the input and output of the electrostatic capacitance probe.

is in turn situated on a grounded aluminum sheet. A pair of finger electrodes, composed of brass material, are affixed to the surface of the silicon rubber. The gap between these finger electrodes is set at 10 mm through the adjustment of insulating screws, ensuring intimate contact with the silicon rubber surface. One of the finger electrodes is connected to a high-voltage dc power supply HV2 through switch K1, while the other is grounded via switch K2. The rated voltage of the high-voltage dc power supply HV2 is $+60\text{ kV}$ with a power rating of 300 W . A protective resistor (R) with a resistance value of $10\text{ k}\Omega$ is connected in series within the circuit.

C. TEST PROCEDURE

All tests were carried out at a temperature of $25\text{ }^\circ\text{C}$ and a relative humidity of 50% . Prior to commencing the experiments, the silicon rubber surface is meticulously cleaned with anhydrous ethanol, followed by thorough drying using an ionizing air blower to achieve a near-zero initial surface potential. The experiments are initiated when the initial surface potentials of the silicon rubber consistently fall within the range of $\pm 100\text{ mV}$. During the surface charge injection phase, the high-voltage dc power supply HV1, as depicted in Figure 2a, is smoothly elevated to $+5\text{ kV}$ and maintained at this level for a duration of 5 minutes . Subsequently, the voltage is disengaged. A triaxial motion control system is then employed to precisely maneuver an electrostatic probe, facilitating the measurement of surface potential data at all specified measurement points across the silicon rubber surface. The entire measurement process encompasses a total duration of 5 minutes . Following this, the sequence is recurrently executed at 15-minute intervals for subsequent surface potential assessments. Because it takes 5 min to complete the surface potential measurement of silicone rubber, the actual surface charge dissipation time of silicone rubber is 5 min , 20 min , 35 min , 50 min and 65 min . Figure 4 shows the relationship between the input and output of the capacitance probe. According to the calibration method in reference [15],

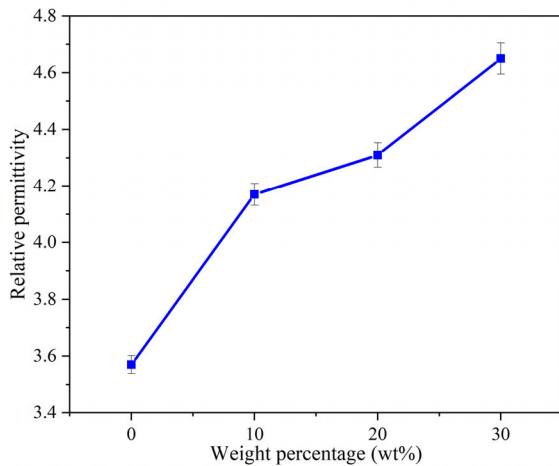


FIGURE 5. The relative permittivity of Al_2O_3 /silicone rubber composites with different weight percentages.

the relationship between surface charge density and the output voltage of probe can be obtained as follows: $\sigma = 0.81 \times U (\mu\text{C}/\text{m}^2)$, where σ is the surface charge density; U is the potential of the measuring point on the silicone rubber surface.

The relative permittivity of Al_2O_3 /silicone rubber composites with different weight percentage are shown in Figure 5. From Figure 5, it can be observed that the growth rate in relative permittivity of Al_2O_3 /silicone rubber composite decreases with the increase of Al_2O_3 content. This may be because when the content of Al_2O_3 particles reaches a certain extent, the interface region of Al_2O_3 particles plays a binding role in the movement of molecular chains, which hinders the polarization process and leads to a decrease in relative permittivity.

In the context of surface flashover voltage testing, as illustrated in Figure 3, the procedure commences by closing switches K1 and K2. Subsequently, the output voltage of HV2 is incrementally raised at a rate of 1 kV/s until flashover occurs. When conducting experiments to investigate the influence of surface charges on the surface flashover voltage, the initial step is to turn on the switches K1 and K2. Following this, an electric potential is applied to the needle electrode, utilizing power supply HV1, to induce surface charges on the silicone rubber. The needle electrode is then removed, and switches K1 and K2 are closed. Ultimately, the output voltage of HV2 is increased at a rate of 1 kV/s until flashover is observed. Once flashover along the surface has occurred, switches K1 and K2 are disengaged, allowing for the natural dissipation of surface charges on the silicone rubber. This entire procedure is repeated at specified intervals of 15 min, 30 minutes, 45 min, and 60 min to conduct the surface flashover tests.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. DISSIPATION CHARACTERISTICS OF SURFACE CHARGE

In ambient air, a dc voltage of +5 kV is applied to the needle electrode, and positive surface charges are introduced

onto the surface of the silicone rubber through the process of corona discharge. Figure 6 presents surface potential distribution for Al_2O_3 /silicone rubber composite materials with varying weight percentages at different dissipation intervals. It is noteworthy that the surface potential polarity remains consistently positive across the spectrum of weight percentages for Al_2O_3 /silicone rubber composites. Furthermore, the maximum surface potential is observed at the central locus of the silicone rubber, with the magnitude of the surface potential diminishing radially from the central point, forming a distinctive bell-shaped distribution pattern. This phenomenon arises from the positioning of the needle electrode directly above the central region of the silicone rubber. Here, electric field lines are most densely concentrated beneath the tip of the needle electrode. Consequently, a substantial proportion of charges, sharing the same polarity as the applied voltage, gravitates along the direction of the electric field towards the central surface region of the silicone rubber [16].

As the needle electrode is removed, the surface charges naturally dissipate under the influence of their own electric field. A comparison of the surface potential distribution characteristics of Al_2O_3 /silicone rubber composites with different weight percentages at different time intervals (5 min, 20 min, 35 min, and 65 min), as illustrated in Figure 6, reveals that the amplitude of the surface potential decreases with increasing time. Regarding the pathways of surface charge dissipation within silicone rubber, researchers have postulated that surface charges primarily dissipate through three mechanisms in insulating materials: along the surface of the insulating material, along the bulk of the insulating material, and recombination with opposite charges present in the ambient air [17], [18]. Typically, all three dissipation mechanisms coexist, and the distribution characteristics of surface charges in insulating materials are primarily determined by the dominant dissipation mechanism in effect. When the predominant pathway is the recombination with opposite-polarity charges from the surrounding air. Because the electric field is strongest at the center of the silicone rubber surface. This high field strength readily attracts a substantial quantity of opposite-polarity charges from the surrounding air for recombination. Consequently, the rate of surface potential decay at the central position of the silicone rubber surface should be the highest, resulting in a transition in the distribution characteristics of the surface potential from a bell-shaped pattern to a cratered one. However, a detailed analysis of Figure 5 does not reveal any transformation of the surface potential distribution characteristics into a cratered pattern with increasing dissipation time for Al_2O_3 /silicone rubber composites of different weight percentages. Therefore, it appears that recombination with opposite-polarity charges from the surrounding air is not the primary mechanism for surface charge dissipation in silicone rubber. Alternatively, if surface charges predominantly dissipate along the silicone rubber surface, the distribution characteristics of the surface potential should extend along the surface as dissipation time increases. However, Figure 6 does not demonstrate significant expansion

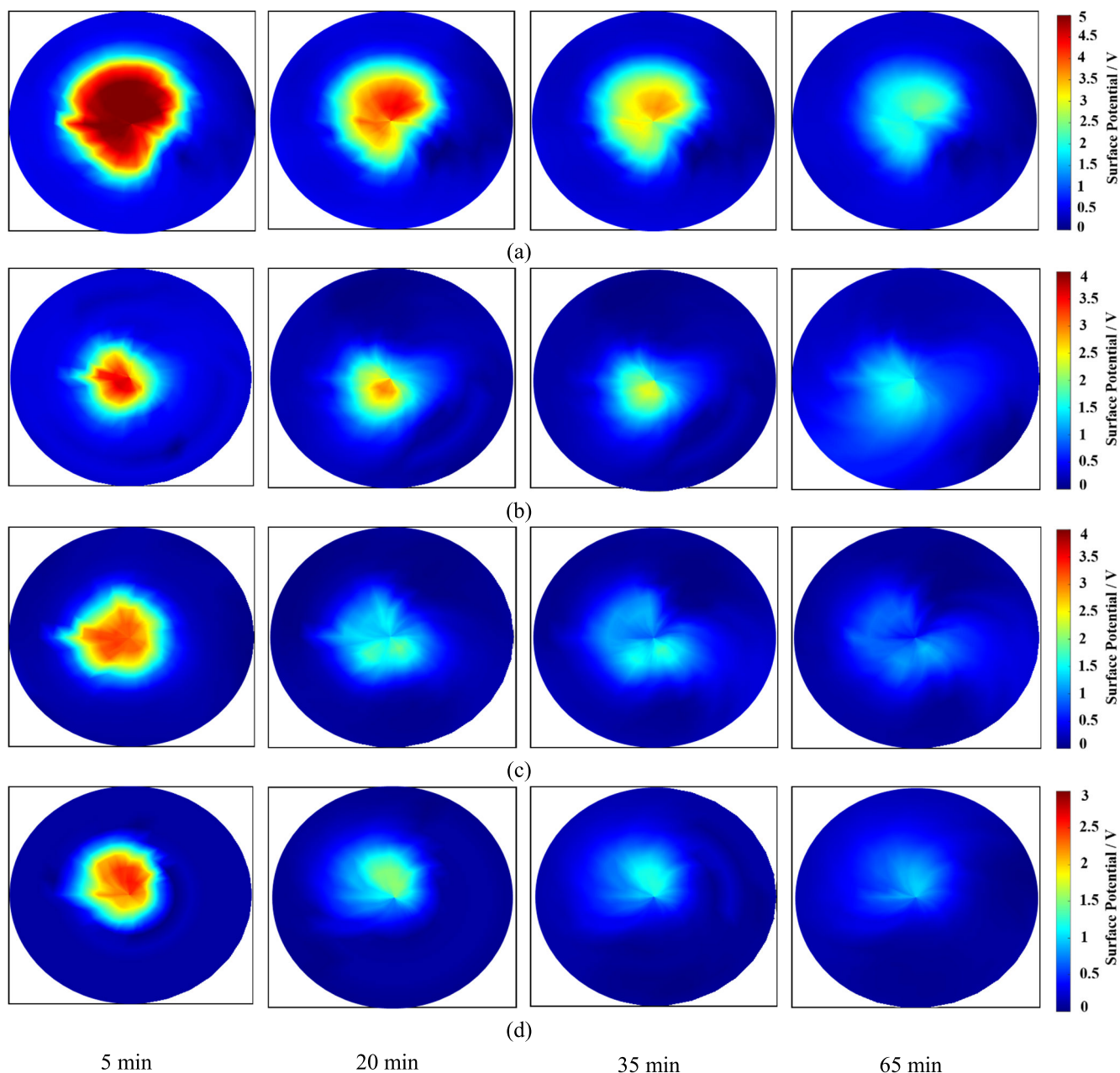


FIGURE 6. Surface potential distribution of Al_2O_3 /silicone rubber samples with different weight percentage under different dissipation time. (a) 0 wt%. (b) 10 wt%. (c) 20 wt%. (d) 30 wt%.

of the surface potential distribution characteristics along the surface with increasing dissipation time for Al_2O_3 /silicone rubber composite materials. Instead, the amplitude of the surface potential decreases while preserving the original distribution characteristics. Therefore, it appears that dissipation along the silicone rubber surface is not the primary pathway for surface charge dissipation. In summary, it is evident that surface charges in Al_2O_3 /silicone rubber composites with different weight percentages primarily dissipate within the bulk of the silicone rubber material itself.

According to the surface potential distribution diagram of Al_2O_3 /silicone rubber composites with different weight percentages in Figure 6a~6d, it can be found that at the initial moment (5 min), pure silicone rubber exhibits the highest magnitude of surface potential and the widest distribution range. When doped with micro-sized Al_2O_3 particles of different weight percentages in pure silicone rubber, it is found that at the initial moment, both the amplitude and distribution range of surface potential are smaller than that of pure silicone rubber. This shows that pure silicone rubber has the strongest ability to accumulate surface charge, and adding different

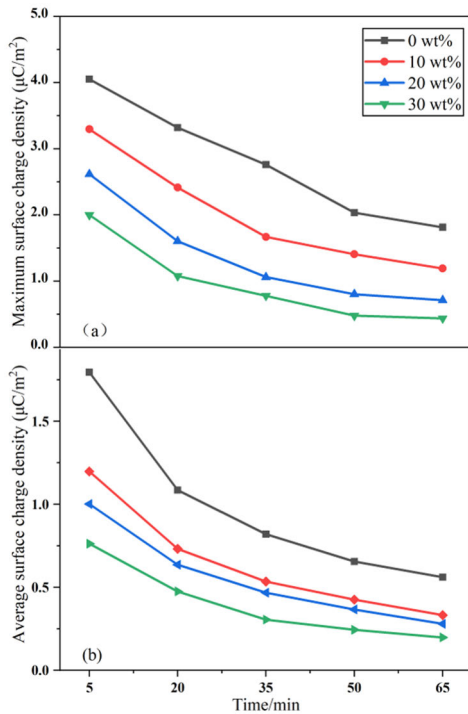


FIGURE 7. The maximum and average surface charge density of Al_2O_3 /silicone rubber composites with different weight percentages under different dissipation times.

weight percentages of micro-sized Al_2O_3 can accelerate the dissipation rate of silicone rubber surface charge, thereby ameliorating the severity of surface charge accumulation in pure silicone rubber. In order to quantitatively compare the ability of Al_2O_3 /silicone rubber composites with different weight percentages to accelerate the surface charge dissipation, the maximum surface charge density and average surface charge density of Al_2O_3 /silicone rubber composites with different weight percentages under different dissipation times were calculated, as shown in Figure 7.

As can be seen from Figure 7, the maximum surface charge density and average surface charge density of pure silicone rubber at 5 min are $4.05 \mu\text{C}/\text{m}^2$ and $1.79 \mu\text{C}/\text{m}^2$, respectively. When the micro-sized Al_2O_3 particles with different weight percentage are added, the maximum surface charge density and the average surface charge density are decreased, and the decrease amplitude increases with the increase of the added weight percentage. Compared with pure silicone rubber, the maximum surface charge density and average surface charge density of Al_2O_3 /silicone rubber composite by different weight percentage decrease in 18.60%-50.60% and 33.26%-57.53%, respectively. The maximum surface charge density and average surface charge density of all samples decrease with the increase of dissipation time. At 65 min, the average surface charge density of pure silicone rubber decreases by 68.79%, while the average surface charge density of 10 wt%, 20 wt% and 30wt% Al_2O_3 /silicone rubber composites decrease by 70.07%, 72.33% and 74.12%

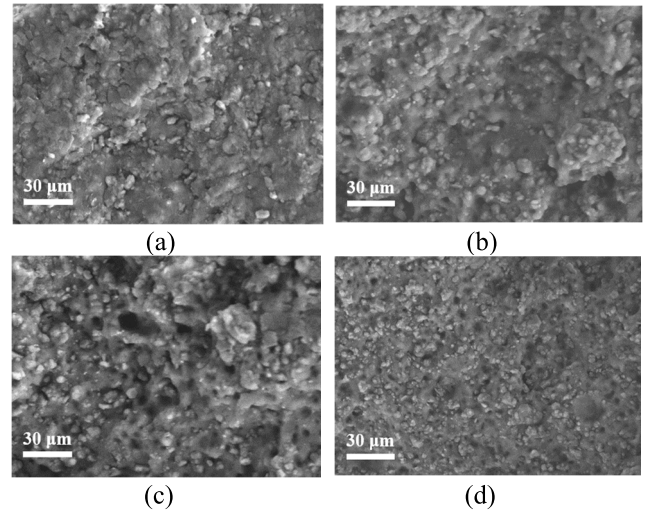


FIGURE 8. SEM images of cross-sections for Al_2O_3 /silicone rubber composite materials with different weight percentages. (a) 0 wt%. (b) 10 wt%. (c) 20 wt%. (d) 30 wt%.

respectively. This indicates that the surface charge decay rate of Al_2O_3 /silicone rubber composites with different weight percentages are faster than that of pure silicone rubber.

Figure 7 also reveals that the most significant reduction in maximum and average surface charge densities occurs within 5-20 min, followed by a gradual decrease within 20-65 min. For example, the average surface charge dissipation rate of 0 wt%, 10 wt%, 20 wt%, and 30 wt% Al_2O_3 /silicone rubber composites within 5-20 min are 39.53%, 38.91%, 37.72%, and 36.58%, respectively. Within 20-65 min, the average surface charge dissipation rate of all samples decreased, with values ranging from 14.49% to 35.72%. The phenomenon can be attributed to the initial accumulation of a substantial amount of charge on the silicone rubber surface, creating a significant electric field within the material. Consequently, many charges trapped by shallow traps are released under the influence of the electric field, leading to a substantial reduction in charge density. As dissipation time increases, most of the charges trapped in shallow traps have dissipated, while those captured by deep traps are less likely to escape, causing a gradual decrease in the rate of charge density reduction [19].

According to research reports, the dissipation process of surface charges in insulating materials is closely related to the internal traps within the material [20]. Physical and chemical defects existing inside insulating materials form localized states within the energy levels of the band gap, known as traps. These traps can be categorized into shallow traps with energy levels ranging from 0.1 to 0.5 eV and deep traps with energy levels generally greater than 1 eV. Comparatively, charges captured by shallow traps are more easily released. Therefore, introducing some shallow traps within insulating materials can facilitate the process of charge trapping and detrapping, thereby accelerating the rate of surface charge dissipation. As reported, shallow traps and deep traps are associated with the physical and chemical defects of

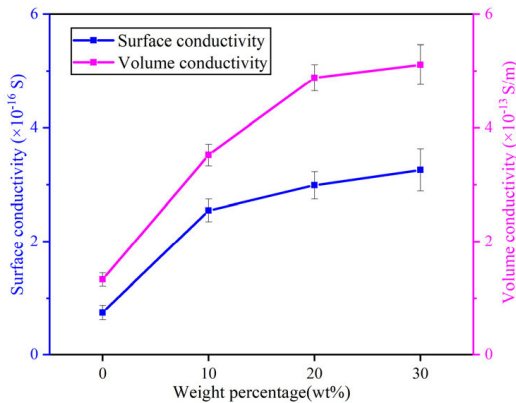


FIGURE 9. Surface and volume conductivity results of Al_2O_3 /silicone rubber composites with different weight percentages.

insulating materials, respectively [21]. The cross-sectional SEM images of different weight percentages of Al_2O_3 /silicone rubber composites are in Figure 8. It reveals that micro-sized Al_2O_3 particles with varying weight percentages exhibit good dispersion without any signs of agglomeration. However, due to the relatively larger particle size of the micro-sized Al_2O_3 particles, their bonding with the silicone rubber is less effective, possibly introducing some physical defects, such as voids, which may lead to an increased abundance of shallow traps. Figure 9 provides results for the surface and volume conductivity of different weight percentages of Al_2O_3 /silicone rubber composites. This paper uses a “three electrodes” conductivity measurement system to measure the conductivity of the sample, and the temperature and relative humidity are 25°C and 50%, respectively. It is evident that the addition of micro-sized Al_2O_3 particles at varying weight percentages leads to an increase in both volume and surface conductivity, with conductivity levels increasing as the concentration of micro-sized Al_2O_3 particles rises. Since a greater number of shallow traps are conducive to electrical conduction, this phenomenon indicates that the introduction of micro-sized Al_2O_3 particles introduces new shallow traps in the silicone rubber. Furthermore, the quantity of shallow traps increases with the higher concentration of micro-sized Al_2O_3 particles.

The dissipation process of surface charges in pure silicone rubber is depicted in Figure 10a. When a positive dc voltage is applied to the needle electrode, free electrons and negative ions in the air migrate towards the needle electrode's tip. A significant number of free electrons undergo collision ionization with neutral molecules in the air, generating new electrons and positive ions. A large number of positive ions will move to the surface of silicone rubber under the action of electric field force and be captured by the surface trap of silicone rubber and become a surface charge [22]. Subsequently, upon removal of the needle electrode, the surface charge in the silicone rubber migrates to the ground electrode from trapped-detrapped mode under the action of its own electric field.

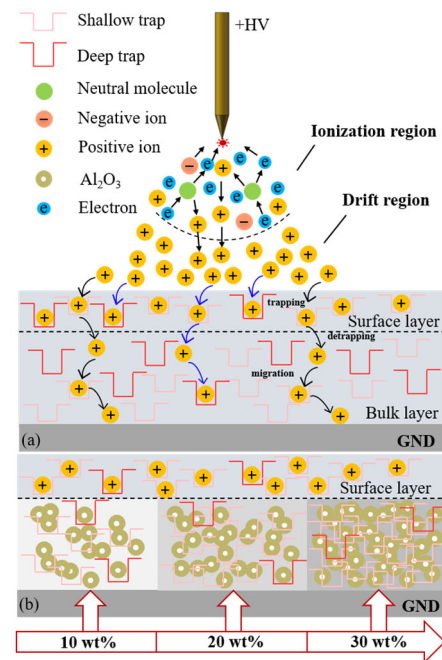


FIGURE 10. Diagram of the surface charge dissipation process. (a) pure silicone rubber. (b) Al_2O_3 /silicone rubber composites with different weight percentages.

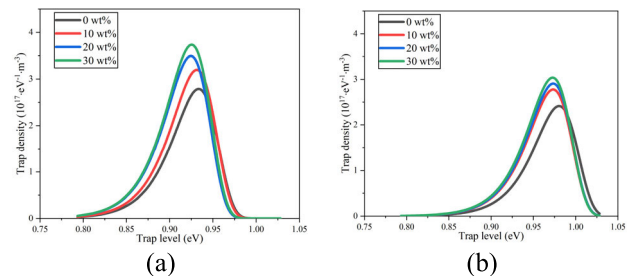


FIGURE 11. The hole trap density of Al_2O_3 /silicone rubber composites with different weight percentages. (a) Shallow traps. (b) Deep traps.

There are primarily two pathways for the migration of charges within the silicone rubber. The first pathway, as indicated by the black arrows in Figure 10a, involves charges initially being trapped by shallow traps within the silicone rubber. Charges trapped in shallow traps are easily detrapped and recaptured during migration, then detrapped again, ultimately leading to their migration towards the ground electrode in a process of trapping and detrapping. The second pathway, as shown by the blue arrows, charges being captured by deep traps in the surface layer, which are not easily detrapping. Or the charge is first captured by the shallow trap and then detrapped, and then in the process of migration is captured by the deep trap inside the silicone rubber, and the charge in the deep traps are not easy to detrapp. In combination with the results of Figure 9 and Figure 11, it can be inferred that the density of shallow traps in all silicone rubber samples is more than that of deep traps. However, the number of shallow traps in pure silicone rubber is relatively small

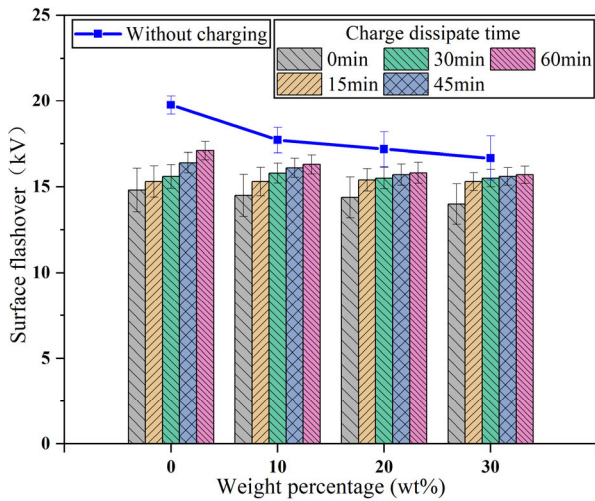


FIGURE 12. The positive dc flashover voltage of Al_2O_3 /silicone rubber composite with different weight percentage under different dissipation time.

compared to Al_2O_3 /silicone rubber composites. Therefore, the probability of charge migrating to the second migration path is relatively large, which makes charges are not easily detrapping, resulting in a slow dissipation rate of surface charge of pure silicone rubber. Due to the fact that the density of shallow traps in different weight percentage of Al_2O_3 /silicone rubber composites increases with the increase of Al_2O_3 content, and compared with pure silicone rubber, the trap energy levels of shallow traps and deep traps are reduced. Therefore, the probability of the charges migrating to the first migration path is relatively large, making the charges are easily detrapping, thereby speeding up the dissipation rate of the surface charge. As can be seen from the schematic diagram in Figure 10b, with the increase of Al_2O_3 addition concentration, the number of shallow traps increases. It leads to a decrease in the spacing between shallow traps and the formation of shallow trap bands among some shallow traps, which is conducive to charge migration and accelerates the dissipation rate of surface charge.

B. SURFACE FLASHOVER TEST

Figure 12 shows the influence of surface charge on positive dc surface flashover voltage of Al_2O_3 /silicone rubber composite with different weight percentages. It can be found that the positive dc surface flashover voltage of uncharged Al_2O_3 /silicone rubber composite decreases with the increase of the weight percentages of Al_2O_3 . Among them, pure silicone rubber exhibits the highest positive dc surface flashover voltage, while the 30 wt% Al_2O_3 /silicone rubber composites display the lowest positive dc flashover voltage, with a difference of 3.09 kV between the two.

On one hand, the introduction of Al_2O_3 particles into silicone rubber may introduce some defects, leading to the formation of centers of charge concentration and consequently a decrease in surface flashover voltage [23]. On the

other hand, the density of shallow traps in pure silicone rubber is relatively low, so the charge involved in the surface flashover may be captured by the deep trap in the process of migration, which inhibits the charge migration process and makes the surface flashover voltage increase. In contrast, due to the relatively high density of shallow traps in Al_2O_3 /silicone rubber composites with different weight percentages, the charge involved in the surface flashover may be captured by the shallow trap in the process of migration. And the charge captured by the shallow trap is easy to detrapping under the action of the electric field, which is conducive to the migration process of the charge, resulting in a drop in the surface flashover voltage.

When applying a positive dc corona to inject surface charges onto the center of the silicone rubber's surface, it is observed that the surface flashover voltages of all samples are lower compared to the scenarios without applied surface charges. This phenomenon occurs because when the polarity of the applied surface charges aligns with the polarity of the power source, the surface charges provide seed charges for the initiation of the flashover, leading to a decrease in the surface flashover voltage [24], [25]. Among them, the pure silicone rubber exhibits the most significant decrease in surface flashover voltage, with a reduction of 4.95 kV. In contrast, the surface flashover voltage reduction for different weight percentages of Al_2O_3 /silicone rubber composites falls within the range of 2.67 to 3.21 kV. This indicates that the addition of varying weight percentages of micro-sized Al_2O_3 can mitigate the reduction in surface flashover voltage. As can be seen from Figure 12, with the increase of dissipation time, the influence of surface charge on the surface flashover voltage of Al_2O_3 /silicone rubber composites with different weight percentages decreases, resulting in an increase in the surface flashover voltage. Due to the surface charge dissipation rate of different weight percentage Al_2O_3 /silicone rubber composites is different, the influence of surface charge on the flashover voltage during the dissipation process is also different. In the case of the pure silicone rubber sample, with its slow surface charge dissipation rate, the increase in surface flashover voltage grows with the increase in dissipation time. However, after adding Al_2O_3 , the increase in surface flashover voltage is less pronounced. This is because, as shown in Figure 6, the average surface charge density of Al_2O_3 /silicone rubber composites with different weight percentages decreased significantly within 5-20 min, and gradually decreased within 20-65 min. Therefore, the surface charge has little influence on the flashover voltage of Al_2O_3 /silicone rubber composite with different weight percentage after 20 min. When the dissipation time is 60 min, the surface flashover voltage of pure silicone rubber is 17.81 kV, which reaches 86.53% of that uncharged silicone rubber. The flashover voltage of Al_2O_3 /silicone rubber composite with different weight percentage can be restored to 92.02%-94.18% without applying surface charge. This shows that adding different weight percentage of micron Al_2O_3 can reduce the influence of surface charge on the flashover

voltage. Therefore, subsequent research in this paper may focus on optimizing the distribution characteristics of shallow and deep traps in silicone rubber. This work aims to simultaneously improve the surface flashover voltage and surface charge dissipation rate of silicone rubber.

IV. CONCLUSION

In this paper, the surface charge dissipation characteristics of micron Al_2O_3 /silicone rubber composites with different weight percentages under positive dc voltage are studied. Some important conclusions are listed as follows:

1. The surface potential of Al_2O_3 /silicone rubber composites with varying weight percentages exhibits a positive polarity and follows a bell-shaped distribution pattern. The surface charge primarily dissipates along the internal pathways within the silicone rubber body.

2. Adding micro-sized Al_2O_3 particles can increase the dissipation rate of surface charge. At 65 min, the average surface charge density of pure silicone rubber decreases by 68.79%. The average surface charge density of 10 wt%, 20 wt% and 30 wt% Al_2O_3 /silicone rubber composites decreased by 70.07%, 72.33% and 74.12%, respectively.

3. When no surface charge is applied to the silicone rubber, adding micro-sized Al_2O_3 particles will lead to a decrease in positive dc surface voltage. When the positive surface charge is applied to the surface of silicone rubber, the influence of surface charge on the flashover voltage can be reduced by adding micro-sized Al_2O_3 particles with different weight percentages, and the flashover voltage can be restored to 92.02%-94.18% of the uncharged silicone rubber.

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ZHIYAO FU was born in China. She received the Ph.D. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2021. Since 2021, she has been with State Grid Hunan Electric Power Company Disaster Prevention and Reduction Center. Her research interests include disaster prevention and mitigation technology of transmission and distribution lines and nonlinear dielectric materials.



ZHENGLONG JIANG was born in China. He received the M.S. degree in high voltage technology from Huazhong University of Science and Technology, Wuhan, China, in 1996. Since 1996, he has been with State Grid Hunan Electric Power Company. His research interests include power system overvoltage and disaster prevention and mitigation technology of transmission lines.



LIPENG ZHONG (Member, IEEE) was born in Hunan, China, in 1990. He received the B.Sc. and Ph.D. degrees in electrical engineering from Xi'an Jiaotong University, Xi'an, China, in 2012 and 2017, respectively. He is currently an Associate Professor with Hunan University, Changsha, China. His research interests include air discharges, high-voltage insulation, and online monitoring for power equipment.



DEXIONG HU was born in Fujian, China, in 1995. He is currently pursuing the Ph.D. degree with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His current research interest includes the study of surface charge accumulation and dissipation characteristics of outdoor insulating materials.



XINGSHUO SONG was born in Shandong, China, in 1999. He received the B.E. degree from Shandong University of Technology, Zibo, China, in 2021. He is currently pursuing the master's degree with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His current research interest includes the study of new environmentally friendly gases.



FENG WANG (Senior Member, IEEE) was born in Liaoning, China, in 1972. He received the B.Sc. degree in electrical engineering from Xi'an Jiaotong University, Xi'an, China, in 1994, the M.Sc. degree in electrical engineering from Shenyang University of Technology, Shenyang, China, in 1999, and the Ph.D. degree in electrical engineering from Xi'an Jiaotong University, in 2003.

He is currently a Professor with the College of Electrical and Information Engineering, Hunan University, Changsha, China. He is also a Visiting Professor with the School of Electronics and Information Engineering, Yili Normal University, China. His current research interests include surface charge behavior under dc voltage, online monitoring, and fault diagnosis of power equipment.



KAI NING was born in Hunan, China, in 1993. He received the master's degree from Xiangtan University, China, in 2019. He is currently pursuing the Ph.D. degree with Changsha University of Science and Technology, China. Subsequently, he is receiving joint training with State Grid Hunan Electric Company Disaster Prevention and Reduction Center, China. His research interests include multi-stress aging of outdoor insulating materials, the development of better-performing silicone rubber, and new electrical materials.

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