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RESEARCH ARTICLE

Study on the Capture Effect of Particle Trap in 1000 kV AC GIL

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ABSTRACT In this paper, a 1000 kV gas insulated transmission line (GIL) prototype with a basin insulator and a three-post insulator structure was designed and developed to study the particle motion behavior in an ultra high voltage (UHV) GIL. Particle traps were arranged on the convex side of the basin insulator and near the three-post insulator. Aluminum and copper particles were arranged in front of and on the surface of the traps. A short-time voltage application procedure and a graded long-time voltage application procedure were designed to investigate the difference in the capture effect of the traps on the two types of particles when the test voltage was applied to the prototype through these two voltage application procedures. The results of the study show that the particle motion behavior is complex under AC voltage. The placement of the particles, their own properties and the voltage application procedure all affect the motion behavior of the particles. The trap with the grid structure is effective in capturing particles near both the convex side of the basin insulator and the three-post insulator. At the end of the test, some of the particles went inside the trap and some of them gathered at the edge of the trap. The graded long-time voltage application procedure with a small voltage application gradient and a long duration enables the particles to move sufficiently at a lower voltage to be trapped.

INDEX TERMS Particle trap, particle motion, trap capture, UHV GIL.

I. INTRODUCTION

Gas insulated transmission line (GIL) has the advantages of small footprint, high transmission energy, good insulation performance and environmental friendliness, and is widely used in the field of ultra high voltage (UHV) transmission [1], [2], [3]. However, metal particles are inevitably generated in stages from production to operation of GIL [4]. When metal particles are subjected to multiple forces within the GIL, the phenomenon of free motion may occur. The moving particles may even attach to the electrodes or insulators to trigger partial discharge phenomena, which can seriously damage the insulation performance of the GIL and affect the safe and stable operation of the system [5], [6], [7]. Therefore, it is important to be familiar with the movement characteristics of metal particles in GIL and take relevant suppression measures to suppress the movement of particles to improve the insulation performance of GIL and ensure its safe and reliable operation.

The movement of metal particles inside the GIL is complex, and factors such as the material of the particles, their shape and the applied voltage all affect their movement characteristics. The literature [8] used the finite element method to study the particle characteristics, the frequency and amplitude of the applied voltage and the influence of shielding ball shapes on the particle motion. The literature [9] established a linear particle motion simulation model to study the motion characteristics of linear particles in the GIL. The results showed that the lifting voltage of linear particles increases with the increase of particle radius, and when positive or negative polarity voltage was applied to the high voltage conductor, the particles exhibited standing or ''firefly'' motion

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behaviors on the shell, respectively. In the literature [10], the effect of diameter on the motion characteristics of spherical particles was investigated by combining simulation analysis and validation tests. The results showed that an increase in particle diameter led to a decrease in the radial acceleration of the particles and an increase in the collision period. The dispersion of the particle motion distribution increased and then decreased with the increase in diameter. The literature [11] studied the motion and distribution characteristics of metal and semiconductor particles with different particle sizes by constructing a scaled-down GIL model, and a trapping coefficient was proposed to characterize the trap trapping effect.

In order to reduce the harm of particles to GIL, the research on particle phenomena in GIL has gradually turned to particle suppression measures. The commonly used suppression measures include particle traps, pre-buried electrodes or insulator surface coating [12], [13], [14]. Among them, particle traps is one of the most common particle suppression measures in GIL systems by constructing localized low electric field regions to achieve particle trapping [15].

The study of particle traps has been started as early as in the 1970s [16]. Recent studies on particle traps have mainly focused on studying their parameters and structural optimization. The literature [17] analyzed the motion characteristics of the particles located in front of the particle trap by simulation. The effect of trap parameters on the capture effect was investigated and the optimal thickness and height applicable to the trap with a grid structure were proposed. In the literature [18], a three-dimensional simplified simulation model of GIL was established to simulate the particle motion near the basin insulator. A trap optimization scheme was proposed in three aspects: electric field regulation, trap capture effect and trap placement. In the literature [19], based on the particle deactivation mechanism, a wedge-shaped particle trap was proposed. A particle capture probability simulation model was further developed to optimize the trap design with the trap slot width and tilt as variables. In the literature [20], the effects of trap slot width, number of slots and trap thickness on the trap capture effect were analyzed by simulation. A trap parameter optimization model was established based on the whale optimization algorithm, and a metal particle capture test platform was built to verify the feasibility of the model.

The above studies are mainly conducted by building simulation models or simulating experiments to investigate the motion behavior of particles and the effect of particle traps on particle capture. Due to the high cost and time consuming nature of testing with a real GIL prototype, there are relatively few studies have been conducted to verify the effectiveness of particle traps in capturing particles through tests with real GIL prototypes. However, due to the complexity of the particle motion inside the GIL in real situations, tests with a real GIL prototype can provide a more realistic picture of the metal particle motion.

In this paper, according to the design requirements of 1000 kV GIL, a 1000 kV real GIL test prototype was developed, two voltage application procedures were designed. The motion behavior of metal particles and the trapping effect of the traps on the particles under different voltage application procedures were studied. The voltage interval suitable for particle motion is found. In the 1000 kV GIL sophisticated test, it is advantageous to extend the time appropriately in this interval. The research results of this paper can provide some guidance for the application of particle traps in UHV GIL and the improvement of their application effect. It can also provide some suggestions for the optimization of the voltage application procedure of UHV GIL sophisticated test.

FIGURE 1. Particle trap used in the test.

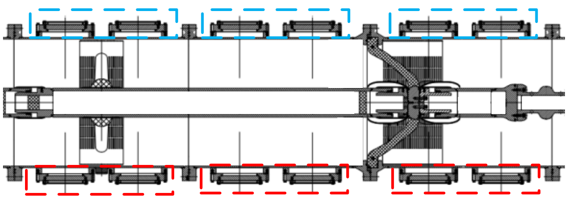

FIGURE 2. The specific structure of the cavity near the basin insulator and the three-post insulator.

II. GIL METAL PARTICLE MOTION TEST PLATFORM

A. UHV GIL TEST PROTOTYPE

The UHV GIL test prototype designed in this paper contains structures such as basin insulator and three-post insulator. In order to observe the motion characteristics of particles near the insulators and the effect of particle traps on particle suppression, the test uses high-speed cameras to observe the motion behavior of metal particles. To meet the needs of the observation, six observation windows were reserved on the side of the barrel wall of the GIL near the basin insulator and the three-column insulator. The six Plexiglas windows on the opposite side of the observation windows are used to arrange the fill light to supplement the light environment inside the chamber and facilitate the observation of particle movement. Particle traps are installed on the convex side of the basin insulator and at the three-post insulator. The particle trap used in this paper is a particle trap with a grid structure, and a 4 mm gap is left between the trap and the inner wall of the cavity. The specific structure of the particle trap used is shown in Fig. 1. The specific structure of the cavity near the basin insulator and the three-post insulator is shown in Fig. 2.

B. TEST CIRCUIT

The GIL test platform in this paper is shown in Fig. 3, which mainly consists of three parts: power supply system, test

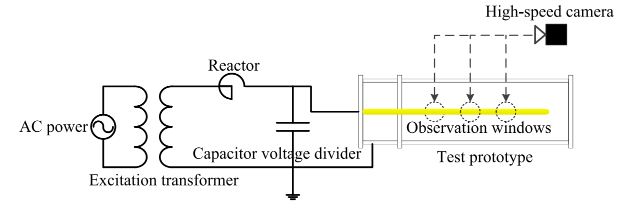

FIGURE 3. Diagram of the test circuit.

prototype and recording system. The power supply system consists of PFTS-450 inverter power supply, WJFB-L450 excitation transformer, YKDTK-3000/300 resonant reactor and ZGSF-A1200kV capacitor divider. The recording system is used to observe and record the motion of the particles during the test. The model of the high-speed cameras was Sony PXW-FS5M2 with a frame rate of 960 fps. The lights were placed at the supplementary light windows on the opposite side of the observation windows to provide suitable light conditions for shooting. The data captured by the cameras was transferred and stored to a laptop.

C. TEST PROCEDURE

In order to simulate as much as possible the movement behavior of the particles in the real GIL cavity, the test particles should be selected as close as possible to the real situation of the GIL project. Through the material and morphological analysis of the particles collected during the operation of the UHV GIL, it was found that the particles in the GIL were mainly made of copper and aluminum. The shape of the particles was irregular and nearly spherical, with the diameter concentrated around 0.5 mm. Therefore, in this paper, spherical particles made of aluminum and copper with a diameter of 0.5 mm were chosen to simulate the metal particles that may appear in the UHV GIL.

Prior to the start of the test, tick marks were drawn on the inner wall of the prototype cavity for particle placement and subsequent observation. The particles were arranged on the trap surface and on the inner wall of the cavity near the insulator in the area shown in Fig. 4. The area of the inner wall of the prototype cavity where the particles were arranged is a rectangular area of 100 mm in length and 10 mm in width at a distance of 5 mm from the trap edge. For each test, 15 g of copper particles and 5 g of aluminum particles were weighed and arranged evenly in the rectangular area. After arranging the particles, the prototype was capped and the camera system was adjusted to allow for proper shooting. Then, the prototype was pumped and inflated. The pumping and inflation process avoided the placement of the particles and controlled the pumping and inflation rate to avoid the particles moving during the process. The voltage of the prototype was then increased using a preset voltage application procedure with a voltage rise rate of 4 kV/s. In order to study the effect of different voltage application procedures on the particle motion characteristics, two voltage application procedures with different gradients by referring to the relevant standards such as IEEE Std C37.122.4-2016 and IEEE Std C37.122-2010 and the voltage application procedures of the 1000 kV GIL field AC withstand voltage test were set up in this paper, as shown in Fig. 5. By studying the motion characteristics of the particles under different voltage application procedures, the results of the tests in this paper can provide some guidance for the optimization of voltage application procedures for the UHV GIL sophisticated test procedures.

During the test, the movement of particles was recorded in real time by the camera. After the test, the gas inside the cavity was recovered, and the distribution of particles inside the cavity and the surface state of the insulators were photographed and analyzed.

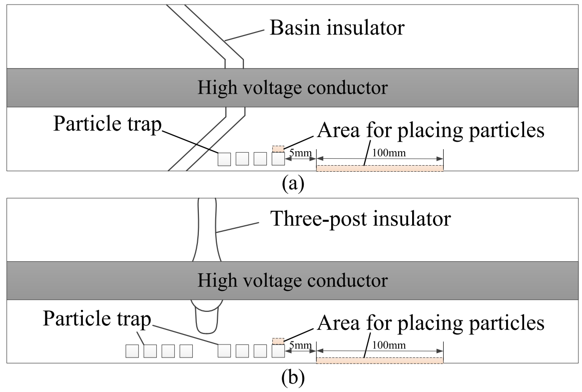

FIGURE 4. Areas for particle placement. (a) Particle arrangement area near the basin insulator. (b) Particle arrangement area near the three-post insulator.

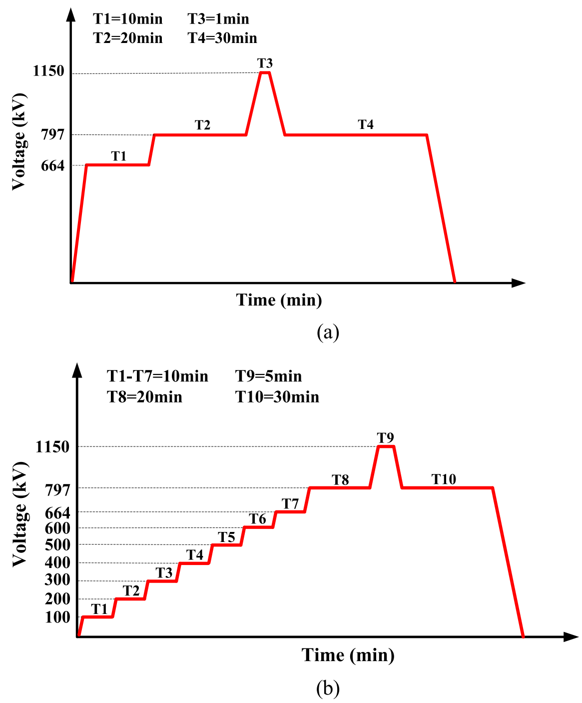

FIGURE 5. Graph of voltage application procedures. (a) Short-time voltage application procedure. (b) Graded long-time voltage application procedure.

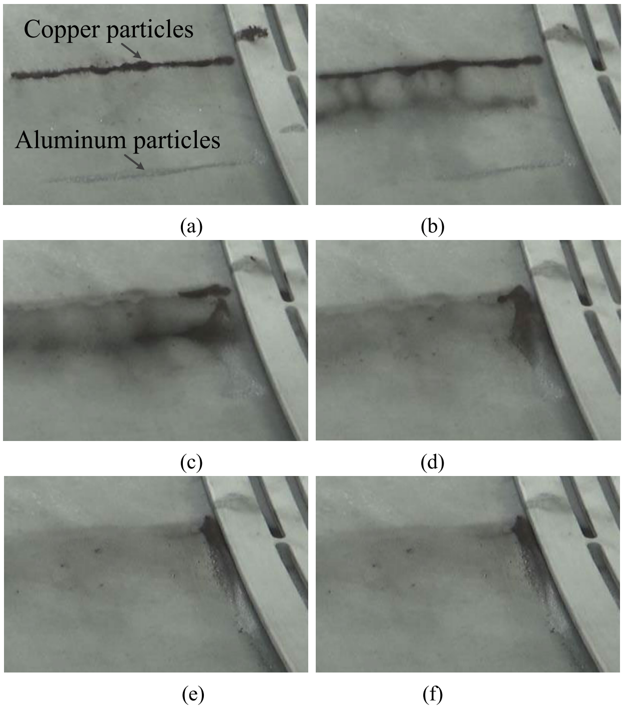

FIGURE 6. **The distribution of the particles on the convex side of the basin insulator at different test voltages. (a) 100kV. (b) 200kV. (c) 300kV. (d) 400kV. (e) 664kV. (f) At the end of the test.**

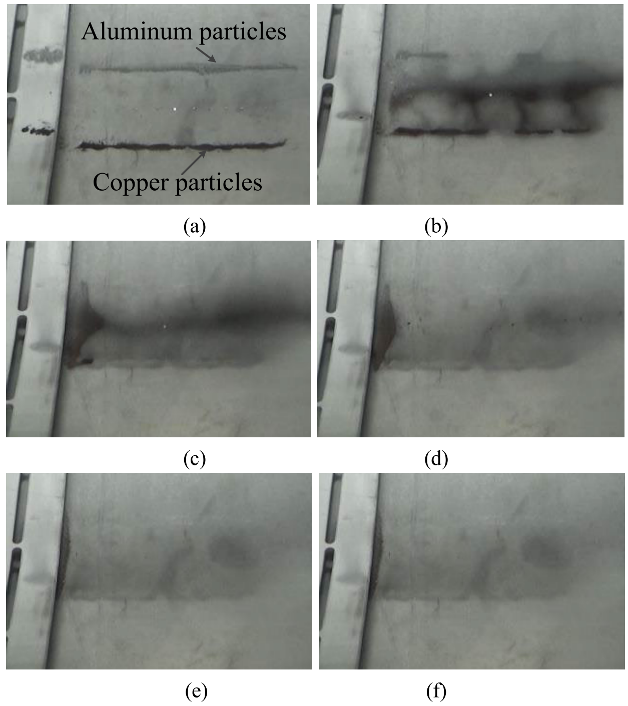

FIGURE 7. **The distribution of the particles near the three-post insulator at different test voltages. (a) 100kV. (b) 200kV. (c) 300kV. (d) 400kV. (e) 664kV. (f) At the end of the test.**

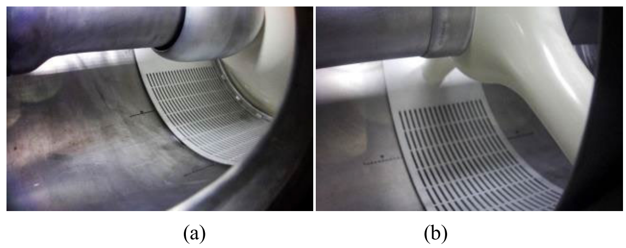

FIGURE 8. **Surface condition of the insulators. (a) Surface condition of the basin insulator. (b) Surface condition of the three-post insulator.**

III. TEST STUDY OF PARTICLE MOTION CHARACTERISTICS

Three tests were conducted for each of the above two voltage application procedures. In order to avoid the influence of the previous test on the next test, alcohol was used to wipe the inner wall of the GIL cavity and the insulator surface before each test. The results of the three tests were similar under the same voltage application procedure, and one of them was taken as a typical test result for the following analysis.

A. PARTICLE MOTION CHARACTERISTICS UNDER THE SHORT-TIME VOLTAGE APPLICATION PROCEDURE

1) MOTION CHARACTERISTICS OF PARTICLES ON THE CONVEX SIDE OF THE BASIN INSULATOR

With the increase of the test voltage, the particles gradually started to move. The distribution of particles at different test voltages and at the end of the test were analyzed to summarize the effect of different voltage application procedures on the particle motion. The distribution states of the particles on the convex side of the basin insulator at different test voltages are shown in Fig. 6.

Fig. 6 shows that in the process of test voltage rising from 0 to 100 kV, the particle movement was not obvious. When the time reached 50 s, the test voltage was 200 kV, some of the particles had obvious movement, and most of the particles placed on the surface of the trap have entered the trap. While the particles placed on the surface of the cavity were moving towards the trap, there was also irregular movement in the radial direction, and the amount of aluminum particles entering the trap was greater than that of copper at this time. As the test voltage continued to increase, the particles continued to move toward the trap. When the voltage increased to 400 kV, all the particles placed on the surface of the trap had entered the trap, and the particles placed on the surface of the cavity moved to the edge of the trap. Thereafter, the particles moved slowly during the voltage increase. When the voltage increased to 664 kV, the particles had no significant movement. At the end of the test, most of the particles entered the trap and some of them gathered at the edge of the trap. Since the particles at the edge of the trap had no significant motion during the subsequent voltage increase, they were also considered to be captured by the trap.

2) MOTION CHARACTERISTICS OF PARTICLES NEAR THE THREE-POST INSULATOR

The distribution states of the particles near the three-post insulator at different test voltages are shown in Fig. 7. During the test, the motion characteristics of the particles near the

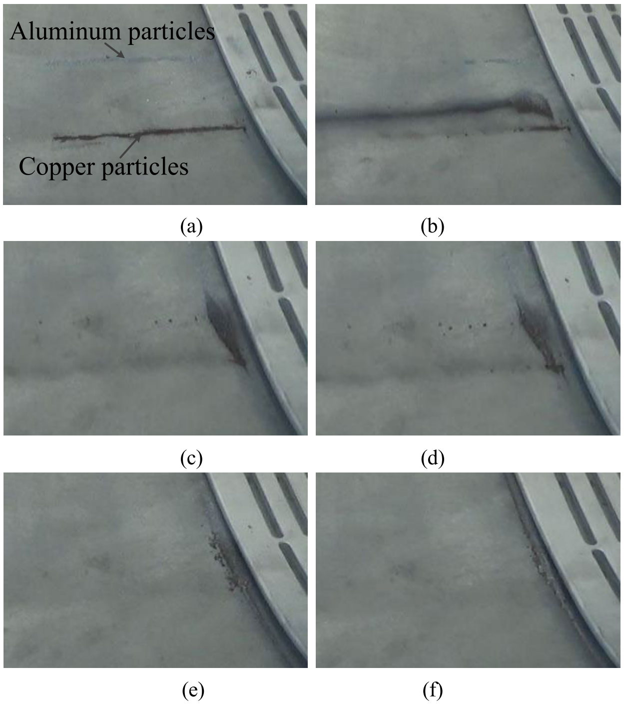

FIGURE 9. The distribution of the particles on the convex side of the basin insulator at different test voltages. (a) 5min at 100kV. (b) 5min at 200kV. (c) 5min at 300kV. (d) 5min at 400kV. (e) 5min at 664kV. (f) At the end of the test.

three-post insulator were similar to those of the particles on the convex side of the basin insulator. However, the particles arranged on the trap surface entered the trap faster, and when the voltage increased to 200 kV, almost all the particles on the trap surface had already entered the trap. At the same voltage, the particles near the three-post insulator moved more vigorously in the radial direction than the particles arranged on the convex side of the basin insulator. At the end of the test, there were fewer particles gathered below the trap edge.

After the test, the surface condition of the basin insulator and the three-post insulator were observed and the surface of the insulator was wiped with lint-free paper, and no particles were found on the lint-free paper. The surface condition of the insulators after the test is shown in Fig. 8.

B. PARTICLE MOTION CHARACTERISTICS UNDER THE GRADED LONG-TIME VOLTAGE APPLICATION PROCEDURE

1) MOTION CHARACTERISTICS OF PARTICLES ON THE CONVEX SIDE OF THE BASIN INSULATOR

Since the obvious difference between the two voltage application procedures is that graded long-time voltage application procedure has a duration of 10 min at several lower test voltages. In order to investigate the effect of the duration on the particle motion, the particle state at the same test voltage of 5 min as the short-time voltage application procedure in the previous section was selected for analysis. The distribution of particles on the convex side of the basin insulator at different test voltages is shown in Fig. 9.

Fig. 9 shows that when the test voltage increased to 100 kV and the duration reached 5 min, most of the particles on the surface of the trap had entered the trap groove, and there was a slight movement of the particles on the surface of the cavity. When the test voltage increased to 200 kV and the duration reached 5 min, most of the particles on the surface of the cavity had already entered the trap at this time. The particles moved axially along the cavity in this process accompanied by irregular radial motion. As the voltage continued to increase, the particles continued to move to the trap. When the test voltage increased to 664 kV and the duration reached 5 min, the particles on the surface of the cavity gathered at the edge of the trap, and the particles moved slowly thereafter. At the end of the test, all the particles on the surface of the trap entered the trap, and the particles on the surface of the cavity were distributed close to the edge of the trap.

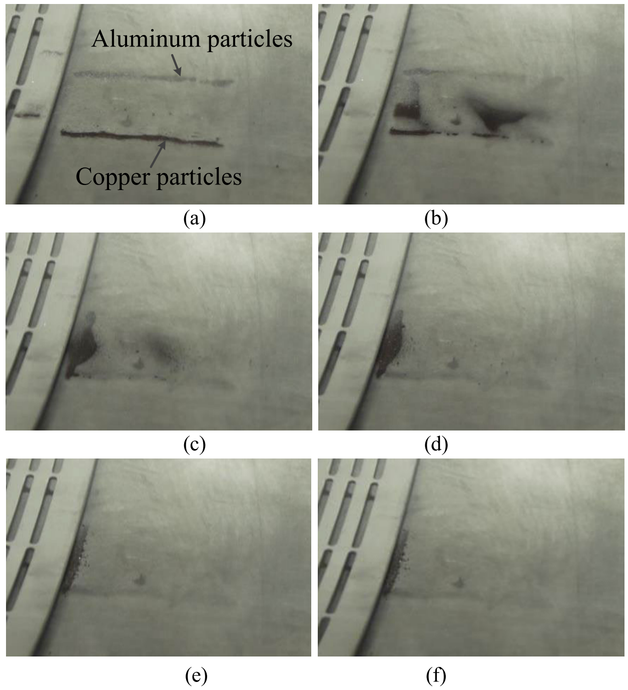

FIGURE 10. The distribution of the particles near the three-post insulator at different test voltages. (a) 5min at 100kV. (b) 5min at 200kV. (c) 5min at 300kV. (d) 5min at 400kV. (e) 5min at 664kV. (f) At the end of the test.

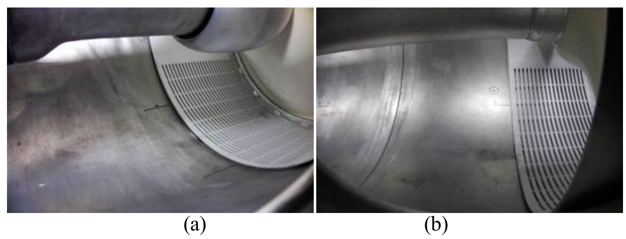

FIGURE 11. Surface condition of the insulators. (a) Surface condition of the basin insulator. (b) Surface condition of the three-post insulator.

2) MOTION CHARACTERISTICS OF PARTICLES NEAR THE THREE-POST INSULATOR

The distribution of particles near the three-post insulator at different test voltages under the graded long-time voltage application procedure is shown in Fig. 10. During the test, the particle motion characteristics near the three-post insulator were similar to those on the convex side of the basin insulator. But compared with the particles on the convex side of the basin insulator, the particles on the trap surface entered the trap completely at a lower voltage level. When the voltage increased to 664 kV, there was no longer any significant movement of the particles as the voltage continued to increase. After the test, the surface condition of the basin insulator and the three-post insulator were observed and the surface of the insulator was wiped with lint-free paper, and no particles were found on the lint-free paper. The surface condition of the insulators after the test is shown in Fig. 11.

IV. ANALYSIS OF TEST RESULTS

A. PARTICLE MOTION CHARACTERISTICS

During the test, the metal particles did not only move in the axial direction of the cavity, but also had irregular movements in the radial direction. The motion characteristics varied for particles of different materials, for different voltage application procedures and for different positions of the particles.

1) EFFECT OF PARTICLE MATERIAL ON PARTICLE MOTION CHARACTERISTICS

The motion behavior of the particles was slightly different for different materials during the test. In the above tests, the degree of movement of the aluminum particles was more intense than that of the copper particles at the same voltage. Under both voltage application procedures, when the test voltage reached 200 kV, more aluminum particles had entered the trap compared to copper particles. This phenomenon was more evident under the short-time voltage application procedure. The possible reason for this phenomenon is that the density of aluminum particles is smaller than that of copper particles, which leads to the fact that the aluminum particles can jump and move at lower voltages for the same particle size.

2) EFFECT OF VOLTAGE APPLICATION PROCEDURE ON PARTICLE MOTION CHARACTERISTICS

The particle motion behavior varied for different voltage application procedures. Under the short-time voltage application procedure, when the test voltage reached 200 kV, the motion of the particles along the axial direction of the cavity was weak. This axial motion was manifested as some of the particles moved towards the trap due to the low electric field caused by the trap. But also some of the particles moved in the direction away from the trap. However, the degree of particle motion in the axial direction of the cavity was more intense under the graded long-time voltage application procedure. Also, the particles had the most obvious movement in the test when the test voltage reached 100 kV-300 kV. Comparing the movement of particles at this test voltage section under both voltage application procedures, the motion of the particles under the graded long-time voltage application procedure was more adequate. Taking the particles near the convex side of the basin insulator as an example, only a few particles placed on the surface of the trap entered the trap when the test voltage was 100 kV under the short-time voltage application procedure. But under the graded long-time voltage application procedure, when the test voltage was 100 kV for 5 min, most of the particles located on the trap surface had already entered the trap. As can be seen from Fig. 6, under the short-time voltage application procedure, the particles placed on the inner wall of the cavity had obvious movement in the axial direction during the test voltage increase from 200 kV to 300 kV. When the test voltage increased to 400 kV-664 kV, the particles moved to the edge of the trap and were regarded as captured by the trap. However, under the graded long-time voltage application procedure, when the test voltage was 300 kV for 5 min, almost all the particles placed on the inner wall of the cavity moved to the edge of the trap, which could be regarded as being captured by the trap. From this, It can be concluded that the graded long-time voltage application procedure allows the particles to be captured by the trap at lower voltages by applying test voltage in a graded manner and extending the duration of the low voltage section to achieve full motion.

In practical engineering, there are many types of particles in the GIL, and the size and material of the particles are unknown. Setting up a stepwise voltage procedure so that different particles move at suitable voltages and capturing the particles by traps is a feasible particle suppression scheme. The sophisticated test of GIL is to reduce the risk of particles to the equipment by applying voltage to the GIL in steps or continuously, so that any active particles that may be present in the GIL move to a low electric field area. The basic principle of the sophisticated test is both to decontaminate the equipment and to minimize the damage to the equipment caused by metal particles during the decontamination process. This requires sufficient movement of the particles at a lower voltage. The graded long-time voltage application procedure in this paper meets this requirement well.

3) DIFFERENCES IN THE MOTION CHARACTERISTICS OF PARTICLES IN DIFFERENT AREAS

In addition to the particles placed in front of the trap, particles were also placed on the surface of the trap. The test results showed that the particles on the surface of the trap moved and were captured by the trap at lower test voltages. This is due to the fact that the electric field on the surface of the trap increases due to the uplift of the trap. The particles on the surface of the trap are more likely to move under the force of the electric field than those on the inner wall of the cavity.

The movement characteristics of the particles placed on the convex side of the basin insulator and near the three-post insulator also differed. Particles on the surface of the trap on the convex side of the basin insulator are more likely to enter the trap than particles on the surface of the trap near the three-post insulator. Taking the graded long-time voltage application procedure test as an example, when the

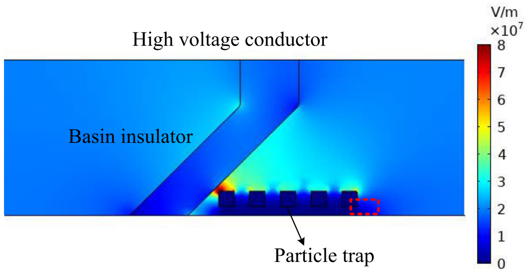

FIGURE 12. The low electric field region in front of the trap.

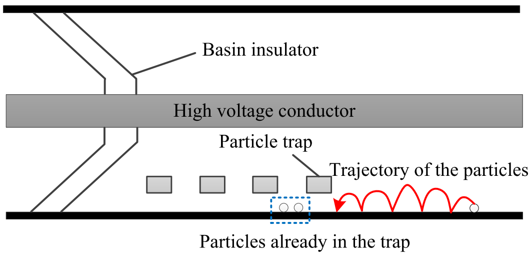

FIGURE 13. The way the particles move towards the trap during the test.

test voltage reached 100 kV and the duration was 5 min, all the particles on the trap surface of the convex side of the basin insulator had entered the trap, while only a few particles on the trap surface near the three-post insulator had entered the trap. Also, there are differences in the motion characteristics of the particles arranged in the inner wall of the cavity, and this difference is mainly in the degree of radial motion. The degree of radial motion of the particles near the three-post insulator is more intense, and this phenomenon is most obvious when the test voltage is 100 kV-300 kV.

B. DISTRIBUTION CHARACTERISTICS OF METAL PARTICLES

At the end of the test, particles placed on the surface of the trap all entered the trap. Particles placed on the inner wall of the cavity partially entered the trap from the trap slot and partially gathered at the edge of the trap. There are two main reasons for this phenomenon. The first reason is that the traps used in the tests of this paper are lifting traps with grid structure. A low electric field region exists in front of the trap, as shown in Fig. 12. When the particle moves to this low electric field region, the electric field force decreases and the particles gradually lose their activity and eventually stay in the region. The second reason is that during the test, it was observed that most of the particles moved towards the trap by small jumps or rolls, as shown in Fig.13. The low electric field region at the edge of the trap and the way the particles moved caused some of the particles to gather at the edge of the trap. Since the motion of this part of the particles was not obvious during the continuous voltage increase, it can be considered that this part of the particles had been captured by the trap. The test results also showed that at the end of the test, fewer particles gathered at the edges of the trap when the voltage was applied to the prototype using the graded long-time voltage application procedure.

At the end of the tests, no particles were found on the insulators for both voltage application procedures. This indicates that the particle traps are effective in suppressing particle movement and successfully captured particles. The statistics of particles in each trap slot after the test showed that the particles were concentrated in the trap slot away from the insulator side when the voltage was applied to the prototype by the graded long-time voltage application procedure. However, when the short-time voltage application procedure was selected to apply voltage, a small number of particles were found in the trap slot near the insulator side. Under this voltage application procedure, the particles were more likely to move to the insulator surface, leading to a greater likelihood of insulation failure. Therefore, when particle traps are used to suppress particle motion in the UHV GIL, a graded long-time voltage application procedure can be used to achieve better results by allowing the particles to move sufficiently in the low voltage section.

V. CONCLUSION

In this paper, a 1000 kV GIL test prototype was developed and particle motion tests were carried out. Some conclusions can be drawn as follows:

1) The behavior of particle motion under AC voltage is complex. During the test, in the axial direction, some particles moved toward the trap, some particles moved away from the trap. This movement away from the trap was obvious at the test voltage of 100 kV-300 kV, but the particles were eventually captured by the trap. In addition to the axial motion, there was also an irregular motion in the radial direction.

2) The particles of different materials have different degrees of motion at the same voltage. At the end of the test, the distribution characteristics of aluminum and copper particles were similar. Due to the low field strength region in front of the trap and the fact that the particles enter the trap by rolling, this causes some of the particles to gather at the edge of the trap at the end of the pressurization.

3) The particle movement characteristics differed under different voltage application procedures. When the test voltage was applied through the graded long-time voltage application procedure, the particles placed on the surface of the cavity partially entered the trap when the test voltage was 300 kV for 5 min, and the remaining particles moved to the edge of the trap and could be regarded as captured by the trap. When the test voltage was applied through the short-time voltage application procedure, the particles could not move to the edge of the trap until the test voltage increased to 400 kV-664 kV. Under the graded long-time voltage application procedure, the particles got full motion at voltages where their motion was evident and were captured by traps at lower voltages.

4) The basic principle of the sophisticated test is to decontaminate the equipment while minimizing damage to the equipment from metal particles during the decontamination process, which requires sufficient movement of the particles into the trap at a low voltage. This paper finds that the

particles move most significantly at 200 kV-300 kV, so it is advantageous to extend the time for this voltage level for the 1000 kV GIL sophisticated test. The research results of this paper can provide some guidance for the optimization of the voltage application procedure of UHV GIL sophisticated test.

REFERENCES

[1] J. Li, Y. Wang, J. Dong, H. Liang, B. Du, Y. Xu, and X. Li, "Surface charging affecting metal particle lifting behaviors around epoxy spacer of HVDC GIL/GIS," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 4, pp. 1546–1552, Aug. 2022.

[2] J. Wang, J. Wang, Q. Hu, Y. Chang, H. Liu, and R. Liang, "Mechanism analysis of particle-triggered flashover in different gas dielectrics under DC superposition lightning impulse voltage," *IEEE Access*, vol. 8, pp. 182888–182897, 2020.

[3] Z. Hou, R. Guo, C. He, J. Li, and X. Yao, "Synergistic effect of SF_6/N_2 gas mixtures on surface partial discharge under DC voltage," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 2, pp. 692–699, Apr. 2020.

[4] R. Wang, C. Cui, C. Zhang, C. Ren, G. Chen, and T. Shao, "Deposition of SiO_x film on electrode surface by DBD to improve the lift-off voltage of metal particles," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1285–1292, Aug. 2018.

[5] X. Li, C. Cao, and X. Lin, "Influence of conducting particle on DC flashover characteristics and tracking property of GIS/GIL insulator," *IEEE Access*, vol. 10, pp. 17212–17220, 2022.

[6] Z. Wu, Q. Zhang, J. Song, and X. Li, "Improved method for acoustic identification of free conductive particle defects in GIL," *IEEE Trans. Power Del.*, vol. 34, no. 4, pp. 1317–1323, Aug. 2019.

[7] B. Du, J. Dong, H. Liang, and X. Kong, "Polarity reversal and over voltage affecting discharge inception of tri-post insulator in ±800 kV GIL," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 1, pp. 223–230, Feb. 2022.

[8] Z. Wu, Z. Li, P. Liu, Z. Peng, H. Wang, B. Cui, and H. Li, "Simulation and analysis on motion behavior of metal particles in AC GIL," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 29, no. 2, pp. 567–574, Apr. 2022.

[9] F. Dai, C. Zhu, X. Tang, H. Ma, D. Duan, and L. Wang, "Wire metal particle movement and discharge characteristics under DC voltage in GIL," in *Proc. 12th IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Nanjing, China, Sep. 2020, pp. 1–4.

[10] Q. Shao, W. Sima, P. Sun, X. Hang, Y. Ze, and Z. Fu, "Study on the motion pattern of a spherical metal particle in DC GIL," in *Proc. IEEE Int. Conf. High Voltage Eng. Appl. (ICHVE)*, Athens, Greece, Sep. 2019, pp. 1–4.

[11] Z. Zhan, D. Wang, J. Xie, W. Xin, W. Wang, and Z. Zhang, "Motion characteristics of metal powder particles in AC GIL and its trap design," *IEEE Access*, vol. 9, pp. 68619–68628, 2021.

[12] F. Wang, L. Yang, D. Cao, X. Wang, and X. Cheng, "Motion and trap suppression of spherical free conducting particles in DC GIL," *High Voltage Eng.*, vol. 44, no. 10, pp. 3141–3149, Oct. 2018.

[13] L. Zhang, H. Cheng, W. Wei, B. I. Ayubi, and A. S. Bretas, "Suppression on particle movement and discharge by nanocomposite film coating on DC GIL electrode surface," *IEEE Access*, vol. 9, pp. 126095–126103, 2021.

[14] Q. Shao, W. Sima, P. Sun, M. Yang, H. Xu, and Z. Yin, "A novel nonlinear conductive ZnO micro-varistor/epoxy resin composite film for metallic particle deactivation in DC GIL," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 2, pp. 675–683, Apr. 2020.

[15] Q. Li, Y. Chang, J. Wang, Q. Hu, J. Wang, and R. Guo, "Methodological advances of metal particle traps design in gas insulated transmission lines," *High Voltage Eng.*, vol. 46, no. 12, pp. 4182–4193, Dec. 2020.

[16] J. Wang, Q. Hu, Y. Chang, J. Wang, R. Liang, Y. Tu, C. Li, and Q. Li, "Metal particle contamination in gas-insulated switchgears/gas-insulated transmission lines," *CSEE J. Power Energy Syst.*, vol. 7, no. 5, pp. 1011–1025, Sep. 2021.

[17] S. Wang, H. Liu, K. Ma, Q. Ou, H. Geng, and F. Lv, "Effect of particle trap on motion characteristics of metal particles in AC GILs and parameter optimization," *Coatings*, vol. 12, no. 7, p. 981, Jul. 2022.

[18] A. Ping, J. Wang, R. Xiao, R. Liu, Y. Chang, and Q. Li, "Trap parameters optimization based on metal particle dynamic simulation method," *Symmetry*, vol. 14, no. 6, p. 1187, Jun. 2022.

[19] J. Wang, Y. Chang, J. Wang, Q. Hu, R. Liang, and Q. Li, "Design and optimization of particle traps in DC GIL based on the capture effect analysis," in *Proc. IEEE Conf. Elect. Insul. Dielectric Phenomena (CEIDP)*, Aug. 2020, vol. 40, no. 15, pp. 5050–5060.

[20] F. Lv, K. Ma, H. Liu, S. Wang, and Z. Zhan, "Capture mechanism analysis and optimization design of DC GIL particle trap," in *Proc. CSEE*, Oct. 2021, vol. 42, no. 15, pp. 5751–5763.

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