Study on Insulation Characteristics of GIS under Combined Voltage of DC and Lightning Impulse

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ABSTRACT

Operating experience shows that residual DC voltage remains in GIS bus bar for a long time after opening of disconnectors. This DC voltage will not only cause accumulation of charges and contaminants on the insulator surface, but will also easily lead to motion of free metallic particles in SF_6 gas gap, weakening the insulation ability of GIS. At the time of disconnectors reclosing, impulse voltage could be generated in the bus bar and superimpose on the pre-existing DC voltage. As a result, GIS will be under combined voltage of DC and impulse. This paper experimentally studies the insulation characteristics of GIS under combined voltage of DC and lightning impulse. It is found that, for non-contaminated insulators, when DC and LI voltage are of the same polarity, flashover voltage under combined voltage is nearly the same as the flashover voltage under LI alone. However, when they are of the opposite polarity, flashover voltage decreases with increasing DC voltage. In cases there are metallic particle or powder around insulator, pre-stressed DC voltage will cause adhesion of contaminants on the insulator surface and lead to decrease of flashover voltage. Specially, for the particle-contaminated insulator, it is found that the surface charge accumulation caused by DC voltage will have big influence on the flashover voltage, and the most critical condition is when DC and LI voltage are of the opposite polarity. In addition, the breakdown characteristics of SF_6 gas gap with free metallic particle are investigated. It is found that under pre-stressed DC voltage, particle will do standing motion or bouncing motion. And breakdown voltage becomes lowest when particle is doing standing motion. The results of the experiments show that residual DC voltage in GIS could deteriorate its insulation ability and the combined voltage of DC and impulse is found to be a critical condition for GIS insulation. Moreover, the combined voltage is shown to be more sensitive to detect some insulation defects in GIS than applying impulse voltage alone, especially for free metallic particles, which are commonly found in GIS but up to now no effective detection method is proposed. Therefore combined voltage of DC and impulse could be considered to serve as a supplement of field test for GIS.

Index Terms — **Gas insulated switchgear (GIS), residual voltage, combined voltage of DC and lightning impulse, insulator, SF_6 gas gap, contaminants.**

1 INTRODUCTION

GAS insulated switchgear (GIS) is widely used due to their compactness and high reliability. Much research has been conducted focusing on the insulation design of GIS under AC voltage. However, Operating experience shows that residual DC voltage of 0.6-1.0 p.u. remains in GIS bus bar for a long time after opening of disconnectors. This DC voltage will not only cause accumulation of charges and contaminants on the insulator surface, but will also easily lead to motion of free metallic particles in SF_6 gas gap, weakening the insulation ability of GIS. At the time of disconnectors reclosing, impulse voltage could be generated in the bus bar and superimpose on the pre-existing DC voltage. As a result, GIS will be under

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combined voltage of DC and impulse. Various accidents of GIS are reported to have happened upon reclosing of disconnectors, so study on insulation characteristics of GIS under the combined voltage will help to find out causes of these accidents and propose prevention measures. Besides, for DC power transmission system, impulse voltage is not generated along but generally superimpose on the DC operating voltage, therefore this study will also be beneficial for the insulation design of DC system.

Previous studies show that under DC voltage, there will be charge accumulation on the surface of GIS insulators. The surface charge density increases with higher amplitude and longer application time of DC voltage [1-7]. If there are metallic contaminants on the surface of insulators, the electric field will be distorted and charge accumulation becomes severer. The distortion of electric field is greatest when metallic particle is in contact with the high voltage electrode. And most of the surface charges are of the same polarity as the applied voltage [8-13]. As for SF_6 gas gap, metallic particle can easily lift off under DC voltage and repeat reciprocating movement between electrodes at a high frequency [14-17]. The particle, which is of floating potential, will cause severe distortion of electric field, depending on its position and geometrical shape [18-19]. What's more, when it collides with the electrodes, it will change the electrode surface topography. It is shown that the surface topography has big influence on the performance of insulation equipment. The microscopic electric field could cause inhomogeneity of free electron concentration in the inter-electrode region and increases the probability of free electrons being initiatory [20-21]. In conclusion, some potential defects in GIS can develop and become active under DC voltage, thus weakening its insulation ability.

In this paper, the insulation characteristics of GIS under combined voltage of DC and lightning impulse is experimentally studied. For non-contaminated insulators, the effect of magnitude, polarity and duration of pre-stressed DC voltage on the flashover characteristics is obtained. In addition, metallic particle and powder are deposited around the insulator to simulate contaminants existing in GIS. Movement of the contaminants under pre-stressed DC voltage is observed and flashover characteristics of the contaminated insulators under combined voltage are acquired. As for SF_6 gas gap, behaviors of free metallic particles under pre-stressed DC voltage are observed and breakdown voltage of the gap under combined voltage is measured.

2 EXPERIMENTAL CONDITIONS

2.1 EXPERIMENTAL SETUP

In order to observe the motion of contaminants in SF_6 gas, an organic glass chamber is specially designed for the test, as shown in Figure 1. Six nylon rods are used to fix the top and bottom flange. Rogowski electrodes of 156 mm in diameter are used and distance between the electrodes is fixed to 15 mm. During the experiments, the chamber is filled with SF_6 gas of 0.4 MPa.

Cylindrical insulators of epoxy resin filled with alumina (Al_2O_3), 25 mm in diameter and 15 mm in height, are used as test samples. In order to simulate contaminants commonly found in GIS, aluminum wire particles and powder are respectively deposited into the test chamber. The aluminum wire particles are 0.5 mm in diameter and 3 mm in length while the maximum size of the aluminum powder is 200 μm.

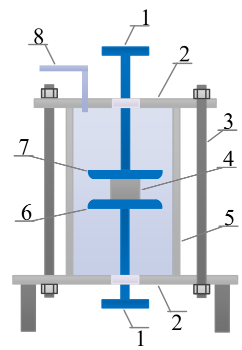

Figure 1. Diagram of the experimental chamber.
1-distance adjustment device; 2-top and bottom flange; 3-nylon screw; 4-insulator; 5- organic glass cylinder; 6-ground electrode; 7-high-voltage electrode; 8-gas tube.

2.2 EXPERIMENTAL CIRCUIT

Figure 2 illustrates the schematic diagram of the experimental circuit. High voltage DC source and impulse generator are connected to generate combined voltage. A protective resistor of 1 MΩ is used to reduce the impact of impulse voltage on the DC source. And a blocking capacitor of 50 nF is placed before the impulse generator to isolate DC voltage from it. In order to measure the DC voltage and impulse voltage at the same time, a resistance-capacitance divider is adopted.

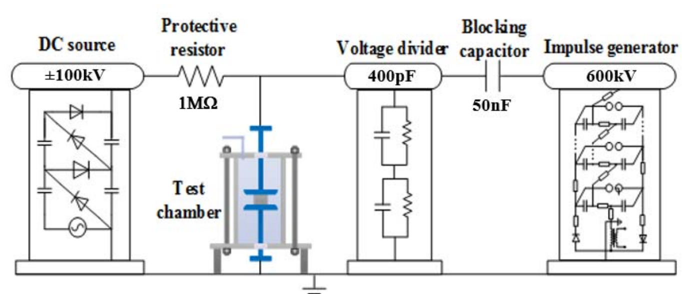

Figure 2. Diagram of the experimental circuit.

Standard lightning impulse of 1.2/45 μs is generated and superimposed on the DC voltage. To study the effect of polarity, four combinations of voltages are used, as shown in Figure 3. In the combined voltage waveforms, U_{DC} is the amplitude of pre-stressed DC voltage. U_{Imp} is the peak value of the lightning impulse. And U_S is peak value of the combined voltage. The discharge voltage described in this paper refers to U_S, namely peak value of the combined voltage relative to ground potential.

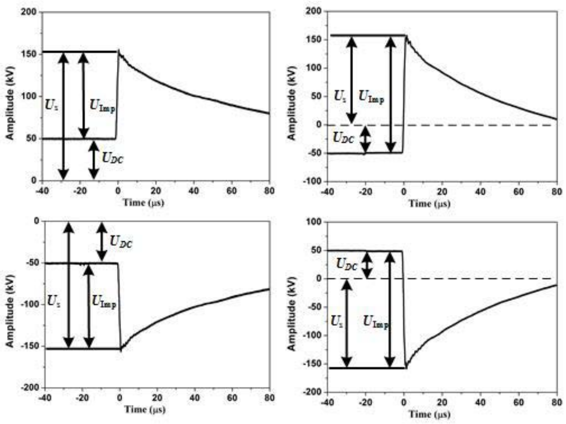

Figure 3. Waveforms of combined voltage.

2.3 EXPERIMENTAL METHOD

In the experiments, DC voltage is firstly applied to the test chamber with a rising rate of 2 kV/s and kept for a given time. Then impulse voltage is generated and superimposed on the existing DC voltage. 50% discharge voltage is obtained in a way similar to the up-and-down method. That is, if discharge doesn't occur under the applied combined voltage, DC voltage should be once more maintained for the same time, then higher amplitude of impulse voltage is generated and applied to the test chamber. If discharge occurs, lower amplitude of impulse voltage should be generated after application of the same DC voltage. Generally, successively applied impulse voltages should meet the rule of $\Delta U \leq 0.03U_{50\%}$. After a number of experiments, 50% discharge voltage could be obtained. For experiments with insulators, after each flashover, insulators are polished with abrasive papers and each test is repeated 20 times with the same condition. While for SF_6 gas gap, the amount of effective data in each condition is over 30.

3 RESULTS AND DISCUSSION

3.1 FLASHOVER CHARACTERISTICS OF NON-CONTAMINATED INSULATOR

To study the effect of pre-stressed time of DC voltage, DC voltage is applied on insulators for respectively 10, 30, 60 and 90 min. Then lightning impulse is generated and flashover voltages of insulators under combined voltage are obtained, as shown in Figure 4. In the figure the horizontal axis represents pre-stressed time of DC voltage and the vertical axis is flashover voltage of insulators under combined voltage. Points of different colors represent flashover voltages with different amplitudes of pre-stressed DC voltage. Flashover voltages of the insulator under LI voltage alone are also shown in the figure by points where pre-stressed time equals zero. It can be seen that flashover voltage under combined voltage differs observably from the flashover voltage under LI voltage alone. And the change in flashover voltage becomes larger with longer pre-stressed time of DC voltage. The reason is that surface charges continue to accumulate with longer application time of DC voltage, thus having greater influence on the flashover voltage. It is also found that when pre-stressed time of DC voltage is larger than 60 min, flashover voltages decrease slightly with longer application time. Consequently, in the following research, pre-stressed time of DC voltage is fixed to 60 min.

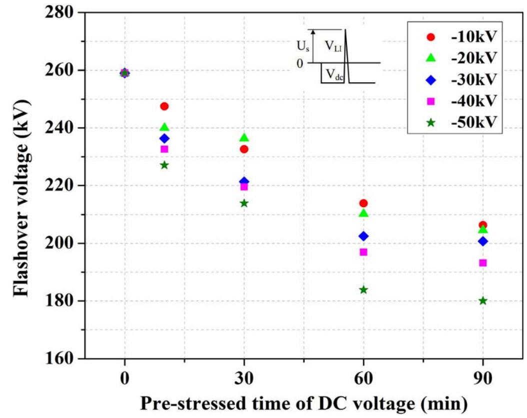

Figure 4. Relationship between pre-stressed time of DC voltage and flashover voltage.

Flashover characteristics of non-contaminated insulators under combined voltage are summarized in Figure 5. The horizontal axis represents amplitude of the pre-stressed DC voltage and the vertical axis represents flashover voltage under combined voltage of DC and LI. Four quadrants show respectively flashover voltages under four waveforms of combined voltage. Flashover voltages of insulators under LI voltage alone are also shown in the figure by points where DC voltage equals zero. As can be seen from the figure, when DC and LI voltage are of the same polarity (first and third quadrants), flashover voltage under combined voltage is nearly the same as the flashover voltage under LI alone. However, when they are of the opposite polarity (second and fourth quadrants), flashover voltage decreases with increasing DC voltage. With pre-stressed DC voltage of 50 kV, flashover voltage decreases by 24%. And with pre-stressed DC voltage of -50 kV, flashover voltage decreases by as much as 29%. This will cause a big threat to the insulation ability of GIS.

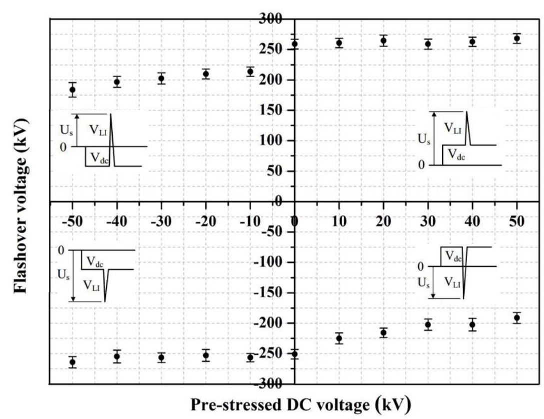

Figure 5. Flashover characteristics of non-contaminated insulator under combined voltage.

The change in flashover voltage under combined voltage is due to charge accumulation on the insulator surface. Previous studies using similar test samples show that the insulator surface in the vicinity of high voltage electrode will be electrified with charges of the same polarity as the applied DC voltage. The distribution of the surface charges is non-uniform: in some areas the charge density is very large while in some other areas there is little charge accumulation [22-25]. Based on these results, the mechanism of flashover for non-contaminated insulator under combined voltage can be explained by Figure 6. As shown in Figure 6a, after application of positive DC voltage, positive charges accumulate non-uniformly on the surface of the insulator (To make it clear, only the charges near the high-voltage electrode are drawn in the figure). When LI voltage of positive polarity is applied to the high voltage electrode, the electric filed formed by the positive charges is in the opposite direction to the electric field of LI voltage and thus the electric field is weakened. As a result, flashover will begin from areas with very little charge accumulation, where the electric field is stronger, and flashover voltage will consequently be almost the same as the flashover voltage under LI alone. Conversely, when negative LI voltage is applied, positive charges on the insulator surface will intensify the electric field. Therefore, flashover will begin in areas with mass charge accumulation and flashover voltage will decrease. When the pre-stressed DC voltage is negative, the change in flashover voltage can also be explained by the same mechanism.

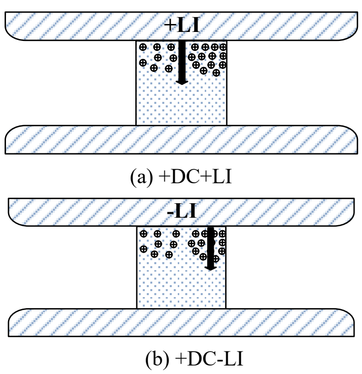

Figure 6. Mechanism of flashover under combined voltage for non-contaminated insulator.

3.2 FLASHOVER CHARACTERISTICS OF INSULATOR WITH METALLIC PARTICLE NEARBY

3.2.1 PARTICLE MOTION AROUND INSULATOR UNDER PRE-STRESSED DC VOLTAGE

Metallic particles are always inevitably formed in GIS during the process of manufacture, transportation and assembly. Field investigation shows that metallic particles commonly found in GIS are in the shapes of wire, disc and spire. Among these particles wire particle is found to cause stronger distortion of electric field and thus pose a greater threat. Therefore wire particle is chosen to simulate metallic particle existing in GIS. An aluminum wire particle of 3 mm in length and 0.5 mm in diameter is deposited on the ground electrode in every experiment. Distance between the particle's center and insulator is denoted by d. It is found that under DC voltage, particle tends to move towards the insulator and adheres to it. There are mainly three motion patterns of particles in approaching the insulator, as is shown in Figure 7. If the initial position of particle d_0<1 cm, the particle always directly adheres to the insulator once it lifts off. If d_0>1 cm, the particle will either do reciprocating movement between the electrodes or spin on one electrode, while moving towards the insulator laterally. It is found that the polarity of DC voltage has influence on the spinning motion: under positive DC voltage particles are likely to spin on the ground electrode while under negative DC voltage the particles tend to spin on the high-voltage electrode.

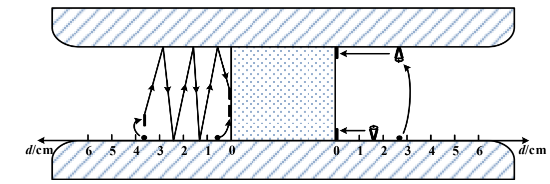

Figure 7. Motion of aluminum wire particle around insulator under pre-stressed DC voltage.

When particles are initially very close to the insulator and directly fly to it, it will easily adhere to the insulator. However, when particles approach the insulator in reciprocating motion or spinning motion, they can adhere to the insulator but may also collide with the insulator and move in the opposite direction. To get the probability of particles' adhesion to the insulator at different initial positions, experiments are repeated 50 times for each position and the results are shown in Figure 8. It can be seen that particles closer to the insulator are more likely to attach to it. In the experiments it is found that once particle adheres to the insulator, whether the DC voltage is largely raised or removed, the particle remains adhered to the insulator and can hardly fall off. The firm adhesion of particle is due to the "image force" applied on the particle in the direction perpendicular to the insulator surface. When particle is close to insulator, the image force will be much larger than other forces applied on the particle, so the particle will remain adhered to the insulator surface [26].

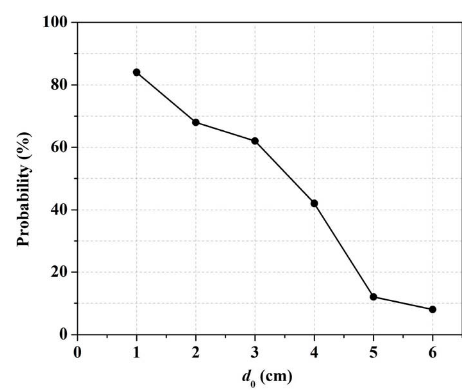

Figure 8. Probability of particles' adhesion to insulator at different initial position.

3.2.2 FLASHOVER CHARACTERISTICS OF PARTICLE-CONTAMINATED INSULATOR

It is found that particles adhere to different positions of insulator surface under pre-stressed DC voltage in every experiment. Therefore, to study the flashover characteristics of particle-contaminated insulator under combined voltage, the particle is artificially adhered to the top of the insulator and in contact with the high-voltage electrode, where the particle will cause severest distortion of electric field and pose the biggest threat to the insulator. The effect of pre-stressed time of DC voltage is firstly studied and it is noticed that for particle-contaminated insulator, pre-stressed time has little influence on the flashover characteristics. In the following experiments, the pre-stressed time of DC voltage is fixed to 10 min.

Flashover characteristics of particle-contaminated insulator under combined voltage are summarized in Figure 9. When DC and LI voltage are of the opposite polarity, flashover voltage decreases with increasing DC voltage. With pre-stressed DC voltage of 50kV, flashover voltage decreases by 30%. With -50kV, flashover voltage decreases by as much as 47%. Compared with Figure 5, it can be seen that flashover voltages of particle-contaminated insulator are more largely affected by pre-stressed DC voltage. The reason is that for particle-contaminated insulator, the electric field is seriously distorted, and there will be much more charge accumulation on the insulator surface, which will greatly enhance the local electric field.

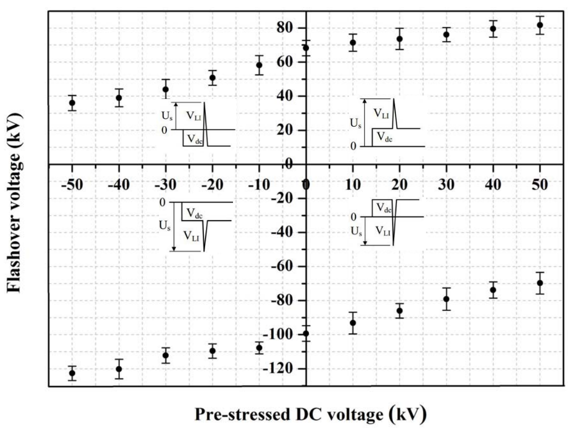

Figure 9. Flashover characteristics of particle-contaminated insulator under combined voltage.

When DC and LI voltage are of the same polarity, unlike non-contaminated insulator, flashover voltage under combined voltage increases with higher amplitude of DC voltage. With pre-stressed DC voltage of 50 kV, flashover voltage increases by 20%. And with -50 kV, flashover voltage increases by 24%. The difference between flashover characteristics of non-contaminated insulator and particle-contaminated insulator, in case when DC and LI are in the same polarity, comes from the charge distribution on the insulator surface. As shown in Figure 10, for particle-contaminated insulator, surface charges intensively accumulate around the tip of the metallic particle. So the electric field at the tip of the particle, where flashover starts, will inevitably be affected by the charge accumulation. Since surface charges in the same polarity with LI voltage weakens the electric field, flashover voltage will increase. While in the case of non-contaminated insulator, as explained above, discharge tends to develop from areas with very little charge accumulation and therefore flashover voltage remains almost unchanged.

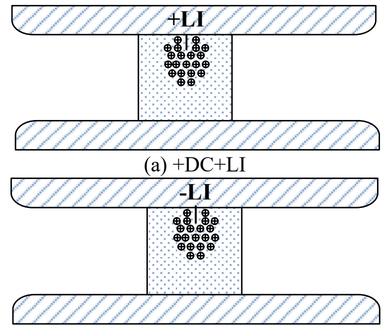

Figure 10. Mechanism of flashover under combined voltage for particle-contaminated insulator.

Typical flashover traces are recorded in Figure 11. As can be seen, when DC and LI voltage are of the same polarity, the discharge trace bends to one side at the tip of metallic particle. The reason is that at the tip of the particle a large number of homocharges accumulate and the local electric field is weakened. Discharge will bypass the areas with mass charge accumulation, so the discharge channel curves, just like discharge with corona stabilization. The effect of surface charges is also demonstrated by the measurement of discharge time lag, which shows that pre-stressed DC voltage of the same polarity increases the time lag while pre-stressed DC voltage of the opposite voltage causes a decrease in the discharge time lag.

(a) +DC+LI (b) –DC+LI

Figure 11. Flashover traces of particle-contaminated insulator under combined voltage.

3.3 FLASHOVER CHARACTERISTICS OF INSULATOR WITH METALLIC POWDER NEARBY

Metallic powder is commonly found in GIS. The powder can easily lift off and adhere to the insulator surface. It will cause distortion of electric field along the insulator surface and thus threaten the insulation ability of GIS. In the experiment, aluminum powder of 0.1 g is arbitrarily deposited near the insulator. Pre-stressed DC voltage is applied for 10 min, and then LI voltage is superimposed to study the flashover characteristics of powder-contaminated insulator under combined voltage.

It is found that once DC voltage is increased to several hundred volts, some tiny powder begins to lift off. With the increase of DC voltage, more powder moves. Most of the powder adheres to the insulator surface once it lifts off. Some other powder does reciprocating motion between the electrodes and finally attaches to the insulator. Only a small part of the powder moves in the opposite direction and finally leaves the electrode. Figure 12 shows a powder-contaminated insulator after application of pre-stressed voltage. The powder remains adhered to the insulator surface even after DC voltage is removed. And it can be seen that there is more powder accumulated on the bottom part of the insulator surface.

Figure 12. Insulator with aluminum powder adhered after application of pre-stressed DC voltage.

Flashover characteristics of powder-contaminated insulator under combined voltage are shown in Figure 13. Once pre-stressed voltage is applied and metallic powder adheres to the insulator surface, flashover voltage decreases greatly (compared with non-contaminated insulator). It can be noted that flashover voltages are in large dispersion, for the distribution of metallic powder on the insulator surface varies greatly in every experiment. With the increase of pre-stressed DC voltage, flashover voltage decreases because more powder is attached to the insulator surface. And the most critical condition is found when DC and LI voltage are of the opposite polarity.

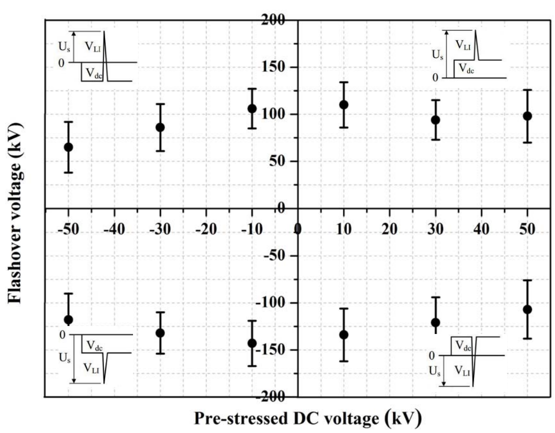

Figure 13. Flashover characteristics of powder-contaminated insulator under combined voltage.

3.4 BREAKDOWN CHARACTERISTICS OF SF_6 GAS GAP WITH FREE METALLIC PARTICLE

In this section the insulator is removed and breakdown characteristics of SF_6 gas gap under combined voltage is studied. Previous studies show that pre-stressed DC voltage doesn't influence breakdown voltage of non-contaminated gas gap [27-28], so here the aim is to study breakdown characteristics of SF_6 gas gap with contaminants in it. An aluminum wire particle is deposited on the ground electrode to simulate contaminants in GIS. Pre-stressed voltage of ±50 kV is respectively applied to the gas gap and motion of the metallic particle is observed. Two motion patterns of the particle are mainly found: standing motion and bouncing motion. Standing motion refers to the particle's motion of standing on one electrode while spinning. When positive DC voltage is applied, standing motion is found on the ground electrode and when negative DC voltage is applied, the particle will lift off and do standing motion on the high-voltage electrode. Bouncing motion is the motion of reciprocating movement between the two electrodes. Experiments are repeated for 100 times under each polarity and the probability of the particle's motion pattern under ±50 kV is summarized in Figure 14. It can be seen that under ±50 kV standing motion is more commonly found than bouncing motion.

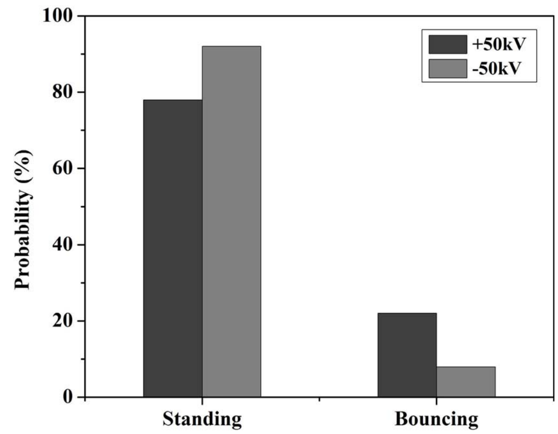

Figure 14. Probability of particles' motion pattern under pre-stressed DC voltage of ±50 kV.

LI voltage is superimposed on pre-stressed DC voltage while the particle is in different motion pattern and the results are shown in Figure 15. In this figure the horizontal axis represents motion pattern of the particle at the moment when LI voltage is applied, and the vertical axis stands for breakdown voltage of the SF_6 gas gap under combined voltage. When the particle is doing bouncing motion, the dispersion in breakdown voltage is very large because it depends on the instantaneous position of the particle when LI voltage is applied. In the experiments it is observed that the closer the particle is to the electrodes, the lower the breakdown voltage becomes. When the particle is doing standing motion on the ground electrode under positive DC voltage, breakdown voltage of the gap becomes lowest when negative LI voltage is applied, because in this case discharge begins from the positive electrode. Conversely, under negative DC voltage particle will do standing motion on the high-voltage electrode, and breakdown voltage becomes lowest when positive LI voltage is applied. The results show that combined voltage of DC and impulse could be an effective method for detection of free metallic particles in GIS, because particle lifts off easily under pre-stressed DC voltage and impulse voltage is sensitive to detect local distortion of electric field. Considering the coaxial configuration of GIS, particle will cause severest distortion of electric field when standing on the high-voltage electrode. Therefore the most critical condition should be when pre-stressed DC voltage is in negative polarity.

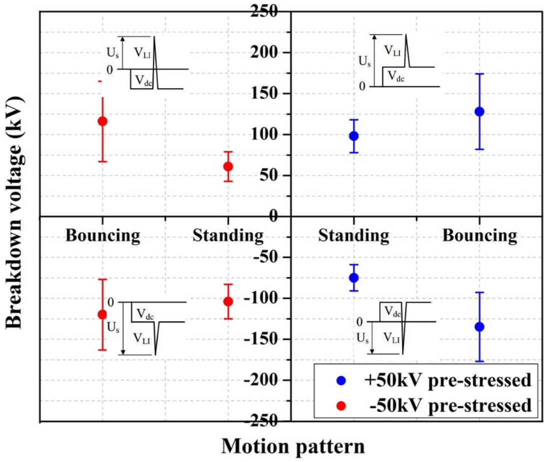

Figure 15. Breakdown characteristics of SF_6 gas gap with metallic particle in different motion pattern.

4 SUMMURY

In this paper, the insulation characteristics of GIS under combined voltage of DC and LI are experimentally studied. The development of potential defects under residual DC voltage is observed. The effect of magnitude, polarity and duration of DC voltage on the discharge characteristics of insulator and SF_6 gas gap is obtained. The results are summarized as follows.

For non-contaminated insulators, when DC and LI voltage are of the same polarity, flashover voltage under combined voltage is nearly the same as the flashover voltage under LI alone. However, when they are of the opposite polarity, flashover voltage decreases with increasing DC voltage. And the application time of DC voltage has significant influence on the flashover voltage. In cases there are metallic particle and powder around insulator, DC voltage will cause adhesion of the contaminants on the insulator surface and lead to decrease of the flashover voltage. Specially, for the particle-contaminated insulator, it is found that the surface charge accumulation caused by DC voltage will have big influence on the flashover voltage and the most critical condition is when DC and LI voltage are of the opposite polarity. In addition, the breakdown characteristics of SF_6 gas gap with free metallic particle is investigated. It is found that under pre-stressed DC voltage, particle will do standing motion or bouncing motion. And breakdown voltage becomes lowest when particle is doing standing motion.

According to the results, it can be seen that residual DC voltage could deteriorate the insulation of GIS (charge accumulation, adhesion of contaminants and motion of free metallic particle) and combined voltage of DC and impulse is found to be a critical condition for GIS insulation. However, at present the insulation performance of GIS is only verified by impulse voltage test and power-frequency test. No test is performed to examine its insulation ability under the influence of residual DC voltage. Moreover, the combined voltage is shown to be more sensitive to detect some insulation defects in GIS than applying impulse voltage alone, especially for free metallic particles, which are commonly found in GIS but up to now no effective detection method is proposed. Therefore combined voltage of DC and impulse could be considered to serve as a supplement of field test for GIS.

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