Breakdown Characteristics of Particle-Contaminated HVDC GIL under Superimposed Voltage of DC and Impulse

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ABSTRACT

Contamination of free conducting particles is a major threat to gas insulated systems. In HVDC GIL, free conducting particles can be even more harmful due to the fact that particles can easily cross the gas gap under DC voltage and distort the electric field. In HVDC systems, impulse overvoltage can be generated and superimposed on the DC operating voltage. As a result, GIL will experience superimposed DC and impulse voltage. In this paper, the behavior of free conducting particles in HVDC GIL is observed and breakdown characteristics of particle contaminated GIL under superimposed DC and impulse voltages are studied. Two motion patterns of free conducting particles in HVDC GIL are mainly found: bouncing and firefly motions. Particles tend to firefly motion near the enclosure under positive DC voltage and near the high voltage bus bar under negative DC voltage. With increased DC voltage amplitude, the probability of firefly motion increases while the probability of bouncing motion decreases. It is found that the insulation strength of GIL is greatly reduced by free conducting particles under superimposed DC and impulse voltages. With increasing particle length, the breakdown voltage of GIL under superimposed voltage decreases sharply. Breakdown voltage decreases slightly with the increase of particle radius. Breakdown voltage of GIL is lower under superimposed voltage of negative DC and positive impulse than under negative DC and negative impulse with the same size of particle. The results indicate that superimposition of DC operating voltage and impulse overvoltage can be a critical condition for HVDC GIL if free conducting particles exist. Therefore, a superimposed DC and impulse voltage on-site test can be considered for HVDC GIL to check for insulation performance.

Index Terms —**HVDC GIL, free conducting particle, behavior, breakdown characteristics, superimposed voltage of DC and impulse**

1 INTRODUCTION

DUE to the need of high power transmission capacity and improved energy efficiency over long distances, high voltage direct current (HVDC) transmission is under development worldwide [1]. Further, the increasing integration of renewables in the electrical energy supply will enhance the use of HVDC technology [2]. In this context, HVDC gas insulated line (GIL) has attracted much attention since it has the advantage of large transmission capacity, low electrical loss, high reliability, and significant reduction in space [3-4]. Therefore, GIL is a desirable and essential component in the future HVDC installations.

Contamination of free conducting particles has long been recognized as a major threat to the insulation of gas-insulated systems [5-8]. Conducting particles can be inevitably formed in gas insulated systems due to manufacturing, transportation and assembly processes. The insulation strength of dielectric gas can be significantly weakened by the existence of these particles. Operating experience shows that 20% of insulation failures of GIS are caused by metal and foreign particles [9].

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In HVDC GIL, free conducting particles can be even more harmful due to the fact that particles can easily cross the gas gap under DC voltage and greatly distort the electric field [10-13]. Previous research shows that particles closer to the high voltage bus bar cause larger distortion of electric field and pose a greater threat to the insulation system. Moreover, corona discharge can occur from both ends of the particles and have significant influence on motion patterns of particles [14-18].

In HVDC systems, impulse overvoltage can be generated and superimposed on the DC operating voltage. As a result, GIL will experience superimposed DC and impulse voltage. Previous studies have shown that for a gas insulated system with no defect, breakdown characteristics of gas gap under the superimposed voltage are almost the same with that under impulse voltage alone [19-20]. However, if free conducting particles exist, particles will lift off under DC operating voltage and distort the electric field. Since impulse withstand voltage is sensitive to distortion of electric field [21], breakdown may occur under superimposed DC operating voltage and impulse overvoltage, which can be a critical condition for HVDC GIL.

In this paper, the behavior of free conducting particles in HVDC GIL is studied. Relationship between particle size and probability of different motion patterns is obtained. Breakdown characteristics of particle contaminated HVDC GIL under superimposed DC and impulse voltages are acquired. These eexperiments have been conducted in GIL of different geometrical sizes.

2 EXPERIMENTAL CONDITIONS

2.1 EXPERIMENTAL CIRCUIT

Figure 1 illustrates the schematic diagram of the experimental circuit. A high-voltage DC source and an impulse generator are connected in parallel to generate superimposed voltage of DC and impulse. The rated voltage of the high-voltage DC source is ±600 kV and the rated current is 10 mA. The impulse voltage generator includes 8 stages and can generate impulse voltage up to 1600 kV. According to IEC standard, in order to generate composite test voltage, each connection of voltage source should be realized by an element, which couples one voltage and blocks the other. In the experimental circuit, a blocking capacitor of 30 nF is used to isolate DC voltage from the impulse generator. A protective resistor of 320 kΩ is placed before the DC source to reduce the impact of impulse voltage on it. In case that breakdown occurs in GIL, both the DC voltage and impulse voltage will be applied to the blocking capacitor. Therefore in order to protect the blocking capacitor, a protective gap is placed in parallel with it. In addition, a resistance-capacitance divider is adopted to measure the DC voltage and impulse voltage at the same time. Figure 2 shows a photograph of the experimental circuit.

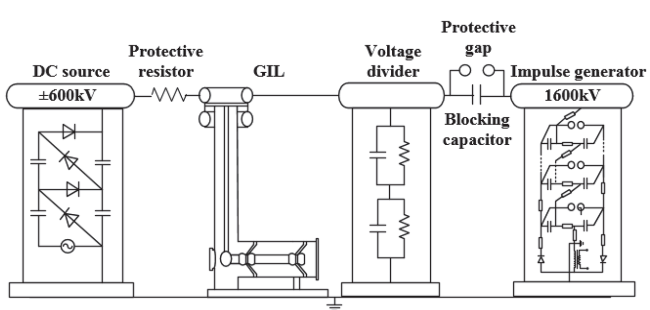


Figure 1. Diagram of the experimental circuit.

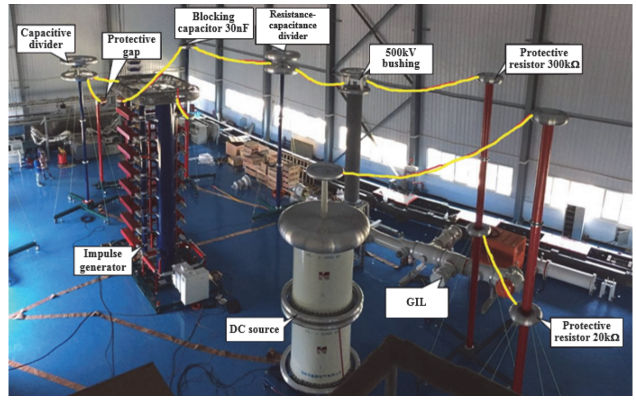


Figure 2. Picture of experimental circuit.

Four waveforms of superimposed voltage can be generated by the circuit, as shown in Figure 3. In the superimposed voltage waveforms, U_{DC} refers to the amplitude of pre-stressed DC voltage. U_{Imp} is the peak value of the impulse voltage. And U_{s} is the peak value of the superimposed voltage. The breakdown voltage described in this paper refers to U_{s}, namely peak value of the superimposed voltage relative to ground potential. Standard lightning impulse of 1.2/50 μs is generated by the impulse generator and superimposed on the pre-stressed DC voltage.

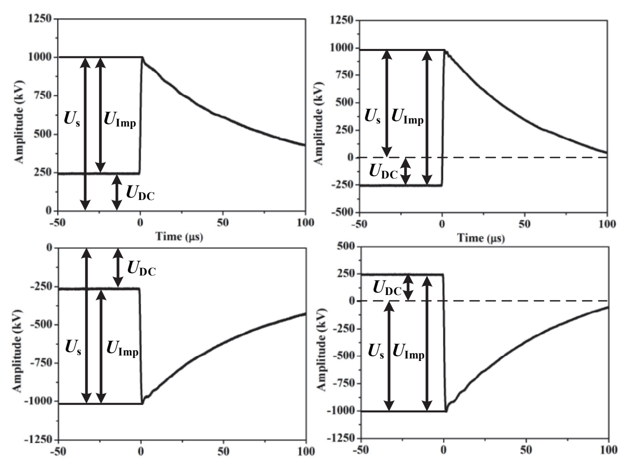


Figure 3. Waveforms of superimposed voltage.

2.2 EXPERIMENTAL SETUP

Since there is no DC GIL available, AC GIL are used as test chambers to conduct experiments. Three geometrical sizes of GIL are used to study influence of free conducting particles in GIL of different voltage grades. The radiuses of high-voltage conductor and enclosure of the three test chambers are respectively 72/230, 90/290 and 170/550 mm, corresponding to AC GIL of 110, 220 and 500 kV. The superimposed voltage is applied through a 500 kV bushing. As shown in Figure 4, an observation window is set at the side of the chamber. Several LED lights are pasted on the window to illuminate the chamber. A high speed camera is used to observe particle motions and discharge. The video signal is transported to a computer by optical fiber for real-time observation.

Aluminum wires of 1, 3, 5 and 10 mm length and 0.1, 0.25 and 0.5 mm radius are used to simulate free conducting particles existing in GIL. Particle is deposited freely on the enclosure of GIL chamber before each experiment.

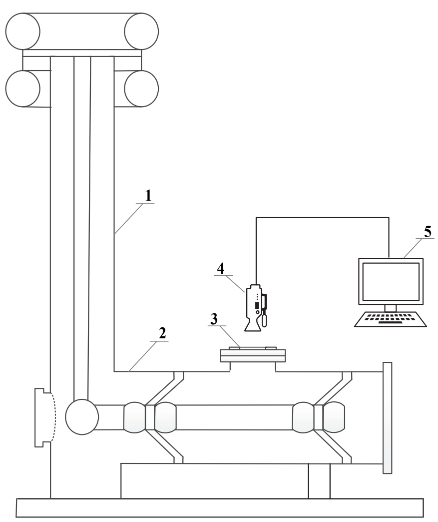


Figure 4. Diagram of the experimental vessel: 1-high-voltage bushing; 2-GIL; 3-LED lights; 4-high-speed camera; and 5-computer.

2.3 EXPERIMENTAL METHOD

In the experiment, DC voltage is firstly raised to the required voltage with a rising rate of 3 kV/s and the motion of conducting particle is observed. Then impulse voltage is generated and superimposed on the existing DC voltage. 50% breakdown voltage is obtained in a way similar to the up-and-down method. That is, if breakdown doesn't occur under the applied superimposed voltage, higher amplitude of impulse voltage is generated and applied to GIL. If breakdown occurs, lower amplitude of impulse voltage should be generated after application of the same DC voltage. Generally, the increment between successively applied impulse voltages should meet the rule of $\Delta U \leqslant 0.03 U_{50\%}$. After a number of experiments, 50% breakdown voltage could be obtained. Particles should be replaced after each breakdown to eliminate the influence of erosion during the discharge. In order to eliminate the influence of impurities in GIL, silk soaked with alcohol is used to clean the experimental chamber before each experiment. Each test with the same condition should be repeated more than 10 times to get the average breakdown voltage.

In order to make sure that the DC voltage applied will not cause damage to GIL, the amplitude of DC voltage should not exceed peak value of the operating voltage (referred to as U_p) of the AC GIL. Therefore maximum DC voltage that can be applied to 110, 220, and 500 kV GIL is respectively ±90, ±180 and ±400 kV.

3 BEHAVIOR OF FREE CONDUCTING PARTICLE UNDER DC VOLTAGE

3.1 LIFT-OFF VOLTAGE OF FREE CONDUCTING PARTICLE

When DC voltage is applied, particles will acquire charge and be subjected to Coulomb force. If Coulomb force is equal to gravity, particles begin to lift off. In the coaxial cylindrical electrode structure, the relationship between the lift-off voltage and particle size is [22]:

$$U_{\mathrm{lift}} = \left(\frac{a \rho_{\mathrm{Al}} g}{1.664 \varepsilon_0} \right)^{\frac{1}{2}} R_2 \ln \frac{R_2}{R_1} \tag{1}$$

where U_{lift} is the lift-off voltage of particle. a is the radius of wire particle. ρ_{Al} is the density of aluminum, i.e. 2700 kg/m^3. ε_0 is the vacuum dielectric constant 8.85×10^{-12} F/m. R_1 is the radius of high-voltage bus bar and R_2 is the inner radius of enclosure. It can be seen from the formula that lift-off voltage is irrelevant with particle length, but depends on particle radius.

Aluminum wires having the length and radius mentioned are placed into the test chamber, and the average lift-off voltage is obtained after repeated experiments. Figure 5 shows the relationship between lift-off voltage and radius of particle. Solid lines represent experimental results and broken lines show the theoretical results calculated from Equation (1). It can be seen that the experimental results are generally in accordance with the theoretical results but slightly larger. With the increase of particle radius, lift-off voltage becomes higher. The experimental results confirm that lift-off voltage is independent of particle length, as shown in Figure 6.

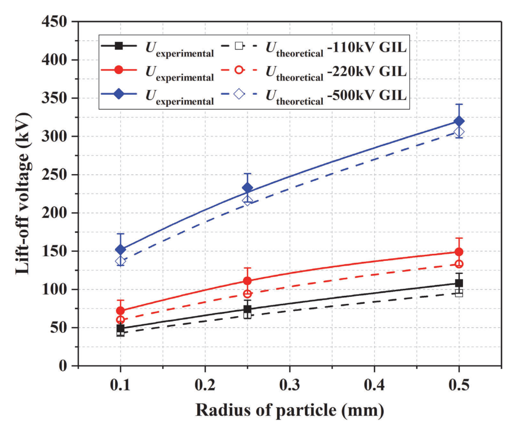


Figure 5. Relationship between lift-off voltage and radius of particle.

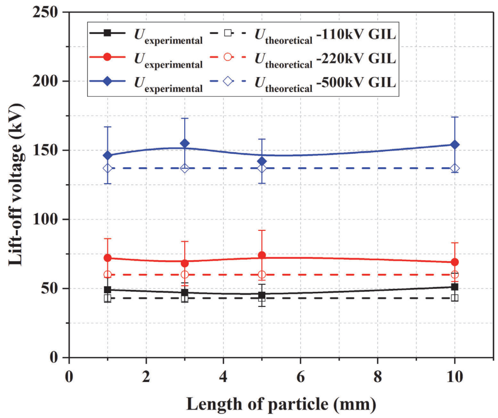
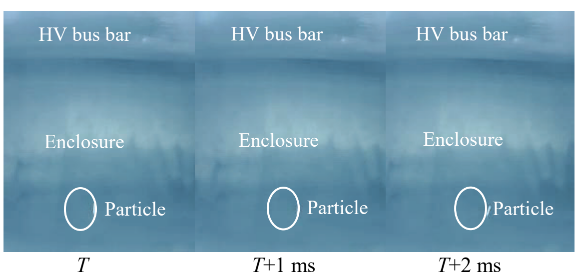


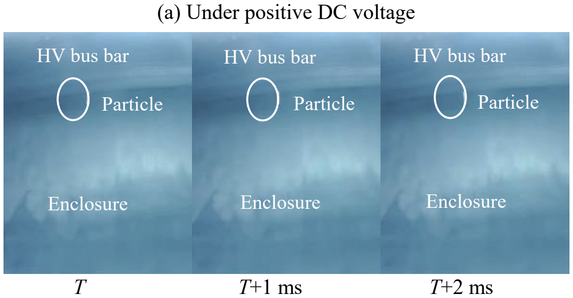
Figure 6. Relationship between lift-off voltage and length of particle (r=0.1mm).

3.2 MOTION CHARACTERISTICS OF FREE CONDUCTING PARTICLE

Motion of free conducting particles under DC voltage is observed by the high-speed camera. Two motion patterns of particles are mainly found: bouncing motion and firefly motion. Bouncing motion is the motion of reciprocating movement between the high-voltage bus bar and enclosure. Firefly motion refers to the particle's oscillation motion near one electrode accompanied by corona and light emission. Particles tend to do firefly motion near the enclosure under positive DC voltage and near the bus bar under negative DC voltage, as shown in Figure 7. Firefly motion is believed to be caused by the corona discharge at the ends of particles.



(a) Under positive DC voltage

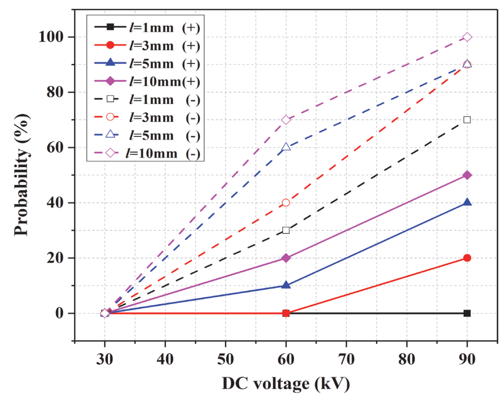


(b) Under negative DC voltage

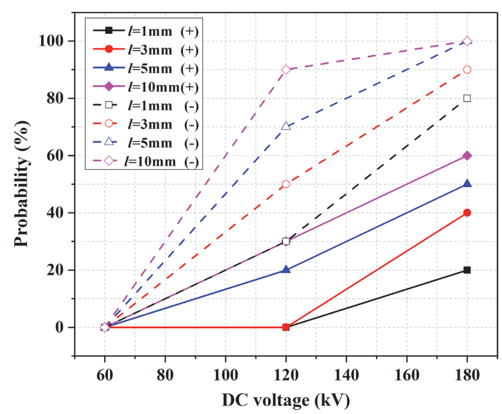
Figure 7. Firefly motion of wire particle under DC voltage.

When particles collide with the negative electrode, they are charged with negative charge. However, the corona discharge at their ends will cause accumulation of positive ions on the particle surface and the polarity of charges in particles will rapidly change to positive. Then particles are subjected to a force directed to the negative electrode and once more collide with the electrode. This process will be continually repeated and as a result, particles will do firefly motion near the negative electrode.

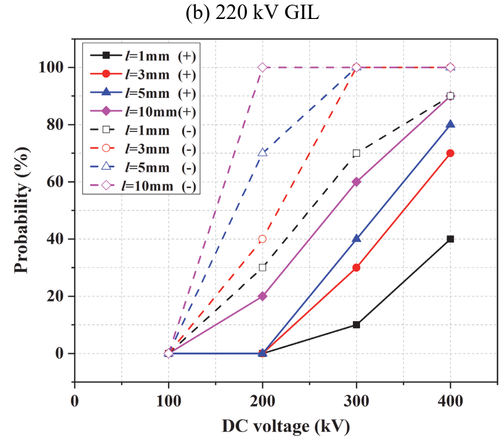
Under 0.5 MPa, various particles of the same geometric size are deposited into the test chamber at the same time to study the probability of each motion pattern. After repeated tests, the probability of firefly motion for particles in different sizes is obtained under DC voltage, as shown in Figures 8 and 9. When DC voltage is below the lift-voltage of particle, slight vibration is applied to the experimental chamber to simulate vibration of GIL under operating conditions. In this case particles



(a) 110 kV GIL



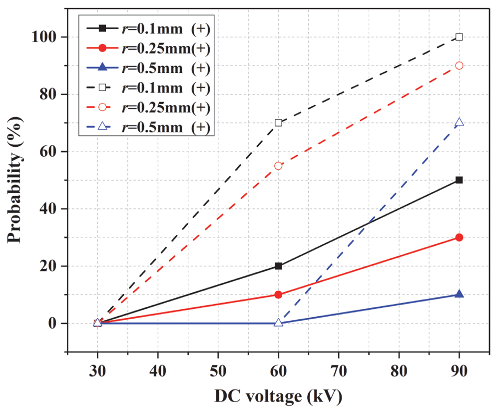
(b) 220 kV GIL



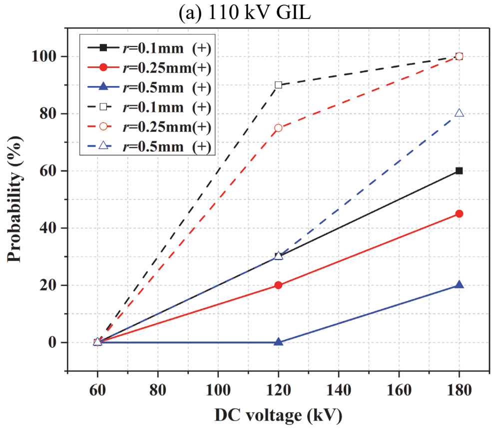
(c) 500 kV GIL

Figure 8. Influence of particle length on probability of firefly motion under DC voltage (r=0.1mm).

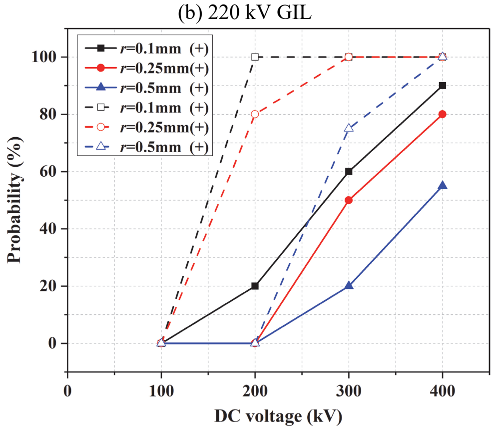
can easily lift off even far below the lift-off voltage. From Figure 8 and 9, it can be seen that with the increase of DC voltage, probability of firefly motion becomes larger, while probability of bouncing motion becomes smaller. Particles with longer length and smaller radius can more easily do firefly motion. Moreover, the probability of particles' firefly motion under negative voltage is much larger than that under positive voltage. The reason is that under negative DC voltage, particles do firefly motion near the high-voltage bus bar, while under positive voltage particles tend to do firefly motion near the enclosure. The electric field near the high-voltage bus bar is much larger than that near the enclosure, so corona discharge of particles is much stronger, leading to higher probability of firefly motion.



(a) 110 kV GIL



(b) 220 kV GIL



(c) 500 kV GIL

Figure 9. Influence of particle radius on probability of firefly motion under DC voltage (l=10mm).

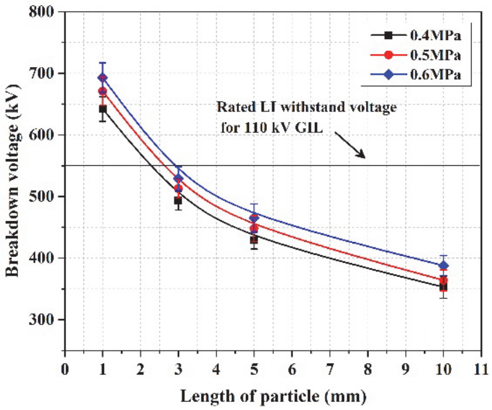
4 BREAKDOWN CHARACTERISTICS OF PARTICLE-CONTAMINATED GIL UNDER SUPERIMPOSED VOLTAGE OF DC AND IMPULSE

In this section, the breakdown characteristics of GIL with free conducting particles under superimposed voltage of DC and LI are reported. The above experimental results indicate that under negative DC voltage, particles tend to do firefly motion near the high-voltage bus bar and will seriously distort the electric field. As a result, this paper mainly studies the breakdown characteristics of GIL under superimposed voltage of negative DC and positive/negative LI, which is a condition more critical for HVDC GIL. In the experiments, DC voltage of $-U_p$ is firstly applied to GIL, then LI is generated and superimposed on the DC voltage.

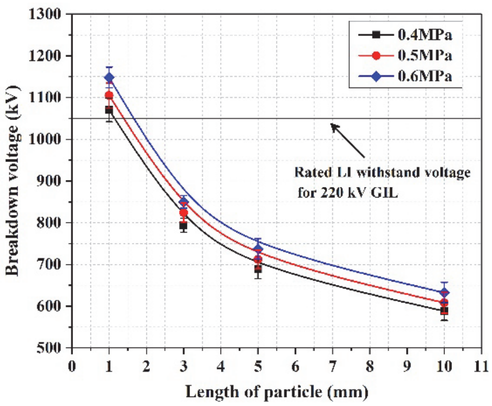
4.1 INFLUENCE OF PARTICLE LENGTH

Particles of 0.1 mm in radius and 1, 3, 5, and 10 mm in length are respectively deposited in GIL before each experiment. Figure 10 shows the relationship between breakdown voltage and particle length in 110, 220, and 500 kV GIL under superimposed voltage of negative DC and negative LI. Breakdown voltage of GIL decreases rapidly with the increase of particle length. According to Chinese national standard, the rated LI withstand voltage of GIL are respectively 550 kV for 110 kV GIL, 1050 kV for 220 kV GIL and 1550 kV for 500 kV GIL [23]. It can be seen that the insulation strength of GIL is greatly reduced by free conducting particles under superimposed voltage of DC and LI. Particles of the same size pose greater threat to GIL of higher rated voltage. In addition, the discharge channel depends on the position of particle when impulse voltage is generated. If the particle is close to the insulator, discharge initiates from the particle and propagates along the surface of the insulator. In most cases, particles are relatively far from the insulator, so discharge initiates from the particle and propagates through the SF_6 gas gap.

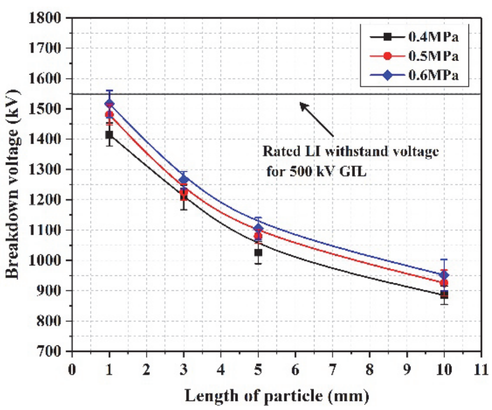
Figure 11 shows relationship between breakdown voltage and particle length in 110, 220 and 500 kV GIL under superimposed voltage of negative DC and positive LI. It can be seen that breakdown voltage of GIL is lower under superimposed voltage of negative DC and positive LI than under negative DC and negative LI with the same size of particle. The reason can be explained as follows. When particle is doing firefly motion near the high-voltage bus bar under negative DC voltage, corona discharge occurs at the end of the particle. The electrons generated in the discharge can be quickly absorbed by SF_6 molecule and form negative ions. As a result, a mass of negative ions accumulate near the end of particle. When positive LI is applied, these negative ions can enhance the electric field at the end of particle and thus breakdown voltage will decrease [24]. On the contrary, when negative LI is applied, the electric field at the end of particles will be weakened by negative ions and therefore breakdown voltage increases. As a result, free conducting particles pose greater threat to the insulation strength of GIL under negative DC and positive LI.



（a）110 kV GIL

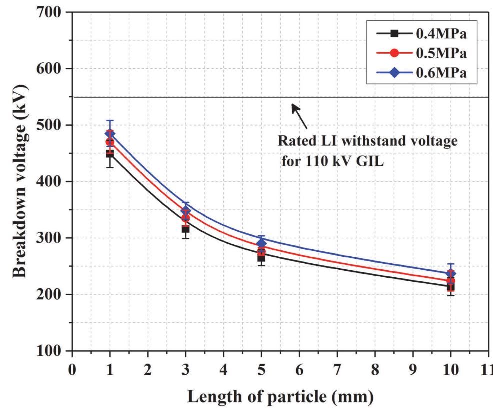


（b）220 kV GIL

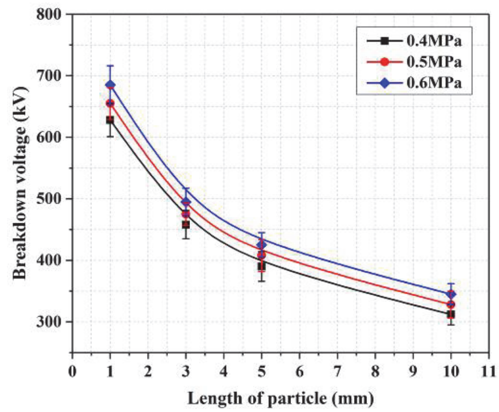


（c）500 kV GIL

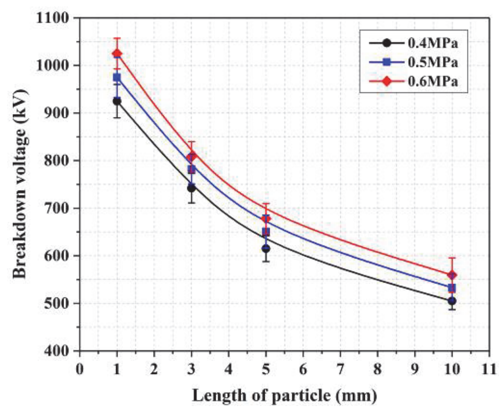
Figure 10. Breakdown voltage of GIL under superimposed voltage of negative DC and negative LI (*r*=0.1mm).



（a）110 kV GIL



（b）220 kV GIL



（c）500 kV GIL

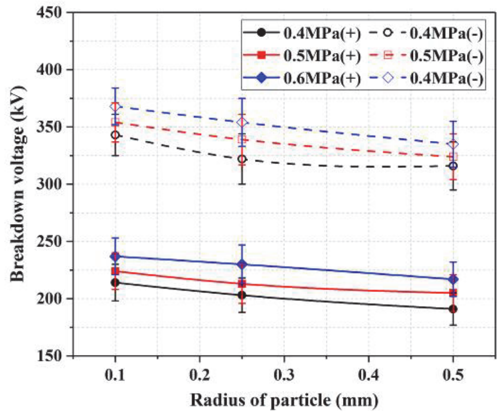
Figure 11. Breakdown voltage of GIL under superimposed voltage of negative DC and positive LI (*r*=0.1mm).

4.2 INFLUENCE OF PARTICLE RADIUS

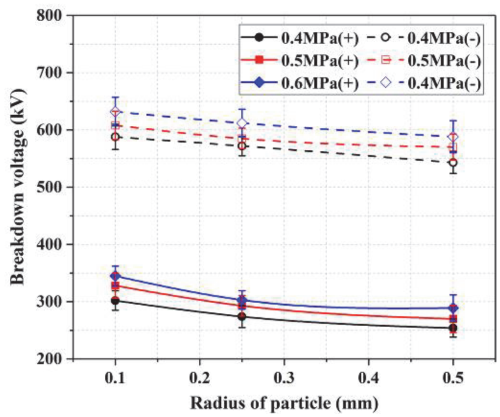
Particles of 10 mm in length and 0.1, 0.25 and 0.5 mm in radius are respectively deposited in GIL to study the influence of particle radius on breakdown voltage. The results are shown in Figure 12. The dotted lines in the figure represent breakdown voltage of GIL under superimposed voltage of negative DC and negative LI. The solid lines are the breakdown voltage under superimposed voltage of negative DC and positive LI. It can be seen that breakdown voltage of GIL decreases when particle radius becomes larger. Under negative DC voltage, a layer of plasma is formed in the area very close to the particle due to massive electron avalanche and and positive ions. It will weaken the electric field at the end of conducting particle and increase the breakdown voltage. For particles with smaller radius, more electron avalanche occurs and the area with plasma becomes larger. As a result, the electric field is further weakened and breakdown voltage becomes higher.

5 DISCUSSION

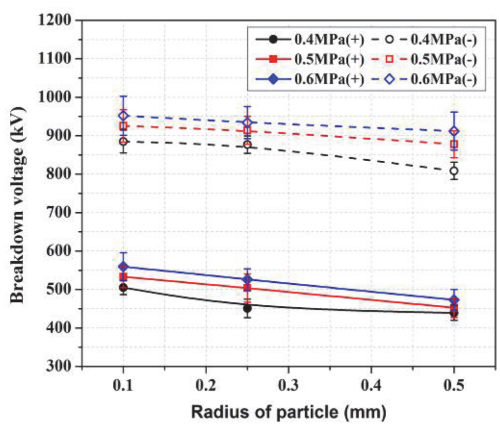
In this paper, breakdown characteristics of particle-contaminated HVDC GIL under superimposed voltage of DC and impulse are studied. Free conducting particles can easily cross the gas gap and distort the electric field under DC voltage.



（a）110 kV GIL



（b）220 kV GIL



（c）500 kV GIL

Figure 12. Relationship between breakdown voltage and radius of particle under superimposed voltage (l=10mm).

Impulse withstand voltage is sensitive to distortion of electric field. As a result, breakdown happens easily under the superimposed voltage. The results indicate that superimposition of DC operating voltage and impulse overvoltage is a critical condition for HVDC GIL if free conducting particle exists.

At present, detection of free conducting particles in gas-insulated system mainly relies on partial discharge signal caused by particles. The partial discharge detection method involves the conventional method, VHF/UHF method, acoustic method, etc. [25-27]. However, operating experience shows that there is always serious on-site noise interference and the partial discharge detection method is not effective enough in detecting free conducting particles.

Up to now, no valid standards are available for HVDC GIL. In recent years, the Cigré joint working group D1/B3. 57 is working on test procedures of HVDC gas insulated system [28-31]. In HVDC system, impulse overvoltage is not generated along but generally superimpose on the DC operating voltage, which means superimposition of resistive field with capacitive field for the insulation system. Therefore, superimposed voltage test of DC and impulse is proposed by Cigré to be part of the type tests for HVDC GIL to ensure the reliability of the design under the service condition. According to the research results in this paper, superimposition of DC operating voltage and impulse overvoltage can be a critical condition for HVDC GIL if free conducting particles are produced in the process of installation. Therefore, superimposed voltage test of DC and impulse can also be part of on-site tests for HVDC GIL to check the insulation performance and to ensure that breakdown would not happen upon superimposition of DC operating voltage and impulse overvoltage due to free conducting particles.

In the superimposed voltage test, four combination of polarity of DC and impulse voltage is proposed to be applied, namely, superimposed voltage of positive/negative DC and positive/negative impulse voltage. The amplitude of DC voltage U_{DC} should be the operating voltage. The amplitude of superimposed voltage should be the rated impulse withstand voltage of GIL. That is, when DC and impulse voltage are of the same polarity, the amplitude of impulse voltage should be $U_{Imp}=U_r-U_{DC}$, in which U_r is the rated impulse withstand voltage. When DC and impulse voltage are of the opposite polarity, the amplitude of impulse voltage should be $U_{Imp}=U_r+U_{DC}$.

6 SUMMARY

In this paper, behavior of free conducting particles in HVDC GIL is observed and breakdown characteristics of particle contaminated GIL under superimposed voltage of DC and impulse are studied. The results are summarized as follows:

1) Under DC voltage, two motion patterns of free conducting particles in GIL are mainly found: bouncing motion and firefly motion. Particles tend to do firefly motion near the enclosure under positive DC voltage and near the high-voltage bus bar under negative DC voltage. With the increase of DC voltage amplitude, probability of firefly motion becomes larger, while the probability of bouncing motion becomes smaller. Particles with longer length and smaller radius can more easily do firefly motion.
2) Insulation strength of GIL is greatly weakened by free conducting particles under superimposed voltage of DC and impulse. With the increase of particle length, breakdown voltage of GIL under the superimposed

voltage decreases sharply. Breakdown voltage decreases slightly with the increase of particle radius. Breakdown voltage of GIL is lower under superimposed voltage of negative DC and positive LI than under negative DC and negative LI. Particles of the same size pose greater threat to GIL of higher rated voltage.

3) Superimposition of DC operating voltage and impulse overvoltage can be a critical condition for HVDC GIL if free conducting particles are produced in the process of installation. Therefore, superimposed voltage test of DC and impulse can be considered to be part of on-site tests for HVDC GIL to check the insulation performance and to ensure that breakdown would not happen upon superimposition of DC operating voltage and impulse overvoltage due to free conducting particles.

ACKNOWLEDGMENT

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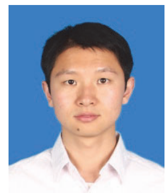

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