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The influence of surface charge accumulation on flashover voltage of GIS/GIL basin insulator under various voltage stresses

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ABSTRACT

Under AC, DC and switching impulse voltages, the surface charges accumulated on the basin insulators of Gas Insulated Substation (GIS) or Gas Insulated Metal Enclosed Transmission Line (GIL) could distort local electric field and even reduce the surface flashover voltage. In order to quantitatively measure the influence of surface charge accumulation on flashover voltage of insulator in actual GIS/GIL apparatus, a high-precision 3D surface charge measurement platform and a reasonable model were established for flashover tests in reference to the insulation design and flashover properties of actual 220 kV GIS basin insulator. The surface charge accumulation dynamics and corresponding flashover voltages of the built models under different conditions were captured and analyzed. The results indicate that, as the density of accumulated surface charges increases under either AC, DC or switching impulse voltage application, the surface flashover voltage would decrease from 62.1 kV to 55.7 kV, namely a margin of 10.3% under AC voltage application. In the context of DC voltage, there appears a 22.8% flashover voltage drop, from 61.0 kV to 47.1 kV. While for the case of switching impulse voltage, the charge accumulation reduced the flashover voltage to 52.9 kV with a 13.6% decline from 61.2 kV. Based on the simulation and theoretical calculations, the 'enhanced electric field zone' was identified to justify the influencing mechanism of surface charges on flashover voltage. The research results could contribute to optimal insulation design and fault diagnosis of basin insulator in GIS/GIL.

1. Introduction

Gas Insulated Substations (GIS) and Gas Insulated Metal Enclosed Transmission Lines (GIL) are widely applied in high voltage direct current (HVDC) transmission system as it not only excels in optimum dielectric property and high reliability but also requires for relatively smaller flooring space and less maintenance [1–3]. With more and more GIS or GIL apparatus being put into operation in power grids, its reliability and stability are drawing greater attention, for which, the insulating properties of basin insulator could play the crucial roles.

One of the most frequently occurred faults in GIS or GIL apparatus is the surface flashover of basin insulator, the generation and influencing mechanism of which remain unclear, especially when it comes to the presence of surface charges [4–6]. Existing researches have reported that the surface charges would not only partially distort the electric field but also provide the charges needed for surface discharge, which therefore weakens the surface insulation strength and creates risks for the flashover [7–9].

A large number of studies have been conducted on various solid insulation models to understand the characteristics of surface charge accumulation and its correlation with surface flashover. M. Gubanski studied the effect of surface charges on DC flashover characteristics of a composite polymeric insulator. According to the tests carried out on an insulator, which is consisted of a glass fiber reinforced epoxy core covered with a layer of silicone rubber and terminated by metallic electrodes with rounded smooth edges, it is revealed that the negative deposited surface charges led to an enhancement of the flashover performance whereas positive ones reduced the flashover voltage level [10]. From the perspective of charge migration, H. Tanaka used porcelain insulator plate (porcelain sample) and the silicone rubber sheet (SiR sample) to figure out the influence of surface charges on flashover. The test results indicated that the DC flashover inception voltages (FOIV) decreases in spite of homo condition because the positive surface charge moved to the vicinity of the counter electrode and acted as hetero charge [11]. Farish et al. studied the influence of surface charges on surface flashover on a cylindrical insulation structure in SF_6 gas. It

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was reported that when the surface charges and applied voltage were in opposite polarity, the surface flashover voltage decreased greatly by a largest margin of 30% [12,13]. For the flaky alumina test models, Katsumi et al. reported that both positive and negative charges would reduce the surface flashover voltage when they accumulate alongside the surface discharge pathway [14]. Studying the cone-plate electrode in SF_6 under DC voltage, Jia et al. concluded that the insulator surface conductivity and charging time have significant influence on surface charge accumulation and that the existence of surface charges could reduce the surface flashover voltage [15]. Exploring the influencing mechanism of surface charge accumulation on flashover voltage, Li conducted a series of studies, to find out that the existence of hetero-polarity surface charges could decrease the DC surface flashover voltage to some extent and the charge migration played a crucial role in the voltage drop [16,17]. In summary, most of the existing studies were conducted on the simple plate, cylinder, or cone electrode models but few has been done to take into account of the fact that the insulator surface in actual GIS or GIL is actually of irregular shapes. In addition, the proposed influencing mechanism of surface charges on flashover was mainly qualitative. There is a lack of quantitative measurement which could otherwise contribute significantly to the optimal insulation design of insulator in actual GIS/GIL apparatus. Building on the results of our previous study on the distribution and accumulation characteristics of surface charges on GIS/GIL insulator under AC and DC voltages [18], the present paper attempts to furtherly explore the influence of surface charge accumulation on surface flashover.

Based on the tests conducted, the influence of surface charges on flashover voltage under AC, DC and switching impulse voltages were captured and analyzed respectively. The influencing mechanism of surface charge accumulation on insulator flashover was further proposed based on simulation and theoretical calculations. It is expected that the research findings could provide useful reference for the optimal design and fault diagnosis of GIS/GIL basin insulators.

2. Test platform

The actual 220 kV GIS basin insulator is of irregular shape and its GIS chamber is filled with SF_6 of 0.4–0.6 MPa. High precision design is therefore required for surface charge measurement on the actual basin insulator.

The test platform applied in this paper was the same one as developed in our previous research [18], the key technical composition and parameters of which are elaborated in details as follows.

Adopting the electrostatic capacitive probe method, the GIS/GIL insulator surface charge measurement system was made up of the charge measuring probes, impedance converter, and data collection device. The structure of the charge measurement system is shown in Fig. 1.

The test chamber used in the research was modified from an actual ZF16-type 220 kV GIS chamber. To simulate the same operational conditions in reality, each gas chamber was filled with SF_6 of 0.4 MPa.

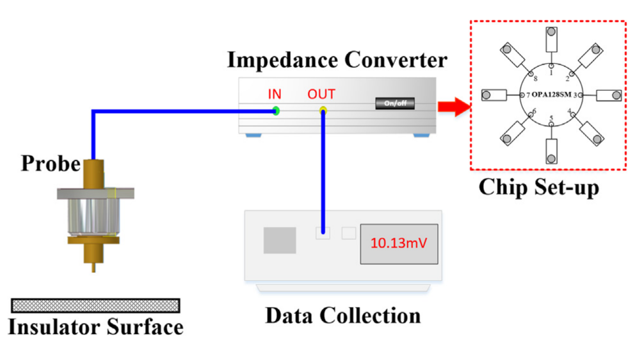

Fig. 1. Structure of surface charge measurement system.

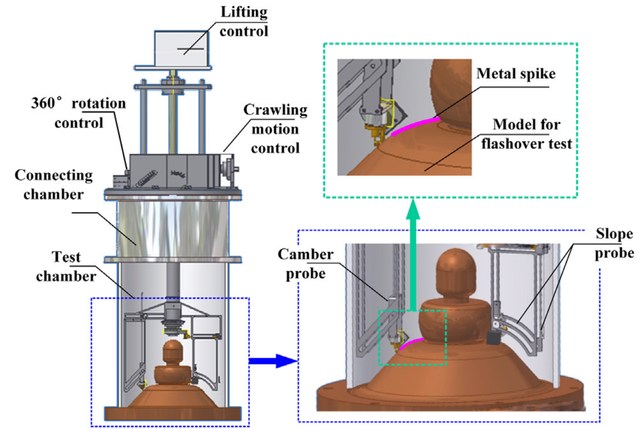

Fig. 2. Three-dimensional operational unit.

All surface charge measurements and flashover voltage tests were completed within this test chamber.

In order to undertake full-radial and all-angle measurement of the charges on the irregular-shaped surface of GIS basin insulator, a high-precision 3D surface charge measurement system made up of a camber probe and a slope probe was adopted. In addition, an operational unit in support of the 3D movement of the probes was also developed, which consisted mainly the inner/outer spindle, a lift control unit, a rotary control unit, a radial movement unit, and a position record unit. The measurement system was connected to the test chamber through a sealed connecting chamber. The accuracy for radial movement was < 1 mm and that for rotary movement was < 1°. The structure of the 3D operational unit is illustrated in Fig. 2.

Fig. 3 presents the calibration curves of the capacitive probes. Based on the curve fitting and measuring principle, the correlations between the probes' output voltage and surface charge density are shown in Eqs. (1) and (2).

Camber probe:

$$\sigma_1 = 0.0303 \times (U_0 - 1.41195)\mu\mathrm{C/m^2} \tag{1}$$

Slope probe:

$$\sigma_2 = 0.0211 \times (U_0 - 1.08491)\mu\mathrm{C/m^2} \tag{2}$$

In the above equations, σ_1 marks the charge density on the camber surface of the insulator and σ_2 denotes the charge density on the slope surface. Based on the calibration tests of the measurement system, it was obtained that the slope probe charge resolution was 0.0211 μC/(m^2·mV) and its spatial resolution was 6.3 mm^2. As the camber probe is concerned, the charge resolution and spatial resolution were 0.0303 μC/(m^2·mV) and 4.4 mm^2 respectively. Experimental verifications showed that the designed charge measurement device possessed high resolution that meets the research requirements.

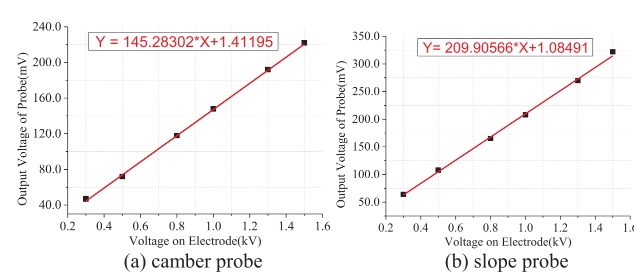

Fig. 3. Calibration curve of camber probe and slope probe.