Influence of metallic contamination on surface charge distribution of a 200kV cone-type insulator

DU Qiandong[1], LIU Haoyu[1], WU Zhicheng[1], ZHU Zhihao[1], ZHAO Junping[1], CUI Boyuan[2], HE Jie[2], CHEN Yun[2]
(1. State Key Laboratory of Electric Insulation and Power Equipment, Xi’an Jiaotong University, 710049 Xi’an, China;
2. China Electric Power Research Institute, 100085, Beijing, China)

***Abstract* – In the operation of HVDC GIL (Gas-insulated Transmission Line), cone-type insulator can separate SF_6 chambers, support the HV conductor and play the role of electric insulation. However, with long-term applied HVDC voltage, charges are prone to accumulate on the insulator surface, which can lead to the decrease of flashover voltage and threaten the stability of power system. Besides, the existence of metallic particles inside the GIL chamber, especially those attached along the insulator surface, can result in a more serious charge accumulation. Therefore, it is necessary to measure the surface charge distribution of clean and metal particle contaminated cone-type insulator in order to analyze its insulation properties under HVDC voltage. In this paper, a 3D 4-axis manipulating system is built to control the position of a capacitive probe to measure the surface potential of a ±200kV cone-type insulator. The probe keeps perpendicular to the concave surface at an identical distance and takes measurement along a pre-set trajectory after the applied voltage has been interpreted. Surface charge distributions of clean and metallic contaminated cone-type insulators are obtained successively. Influences of voltage polarity and application time are equally studied. The results show that metallic contamination has an enormous influence on surface charge polarities and distribution. For a clean surface, negative charge accumulates along the insulation surface under positive HVDC voltage; while under negative HVDC voltage, charges of both polarities are detected in different areas. For an insulator surface with metallic contamination, charge of the same polarity as the applied voltage is found to be significant near the contamination area. Analyses are made from the perspective of electric field distortion and partial discharge caused by the metallic contamination.**
KEYWORDS: surface charge distribution, HVDC voltage, cone-type insulator, metallic contamination, flashover

I. INTRODUCTION

With the development of HVDC transmission project, GIL has been increasingly used due to its high transmission capacity, low loss rate and reliable performance [1-2]. As a crucial part of GIL, cone-type insulator plays the role of mechanic support and electric insulation. Meanwhile, the flashover voltage along the surface of cone-type insulator is usually lower than that of SF_6 gas gap with the same length. Causes for flashover accidents may be various [3]. Investigation of numerous cases indicates that surface charges accumulated on insulators could be an important factor of flashover. What is more, in the presence of inevitable metallic particles produced in GIL assembling, particularly those attached along the surface of insulators, charge density could become enormous that local field is gravely distorted and flashover accidents may occur [4]. Therefore, it is of great significance to study the influence of metallic contamination on the charge distribution of insulator surface and analyze its consequence on flashover.

Researchers from Delft University of Technology studied the charge accumulation process of a cone-type insulator stressed with DC voltage at atmospheric conditions [5-7]. The results show that charges of opposite polarity to the applied voltage accumulate on the concave surface with each distribution having a peak near the central conductor. The study from Tsinghua University shows similar distribution characteristics and that the amplitude of average measured charge densities increases rapidly with increasing applied voltage [8-9]. However, present research on this issue mainly focuses on the charge accumulation characteristics of clean insulators. Few investigate the surface charge distribution with metallic contamination despite its significance in engineering.

The present paper deals with surface charge distribution of clean and metallic-contaminated cone-type insulator respectively. Results obtained from the charge measuring system are discussed at the end of the paper.

II. EXPERIMENT SETUP AND METHOD

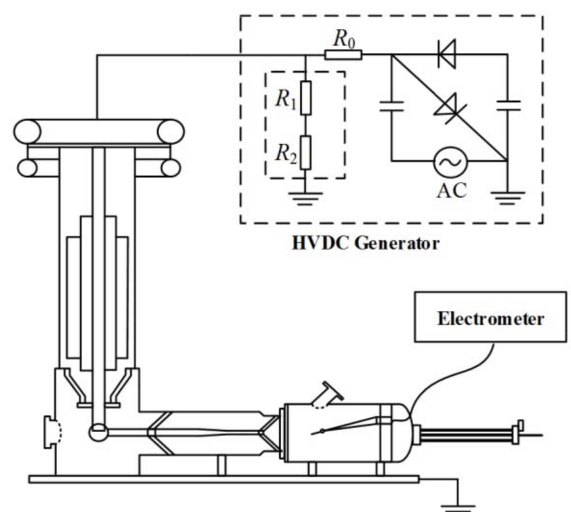

Fig. 1 Experiment setup for surface charge measurement

The experiment setup is shown in Fig. 1. HVDC voltage is applied on a 200kV cone-type insulator through a HV bushing and GIS transfer unit. A 3D 4-axis manipulating apparatus is connected to the GIS unit in order to control the movement of

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a capacitive prove to take measurement along the insulator surface. The output data of the probe are obtained from the electrometer for further processing.

The 3D 4-axis manipulating apparatus consists of two separate parts – HV shielding conductor installation system and probe control system. Before HVDC voltage application, the HV shielding installation system is used to install the shielding conductor of the cone-type insulator in order to simulate GIL field distribution. The shielding conductor is removed after voltage application and saved in a container inside the apparatus so that sufficient space is left for probe movements. The probe used for test is ESD102 vibrating capacitive probe that is hold perpendicularly to the concave surface of the insulator. PLC programs written based on the shape of insulator surface are executed by CNC machine for probe control. The probe movement is achieved in 4 axis namely radical, axial, rotational and gesture adjusting, with control precision of no more than 0.2mm/45'. Inside the 3D 4-axis manipulating apparatus inflates SF_6 gas with pressure up to 0.4MPa.

Fig. 2 and 3 are both taken from the observation window of the apparatus. Fig. 2 shows the manipulation rod removing HV shielding conductor from the insulator; Fig. 3 shows the probe scanning insulator surface at a distance of 5mm.

Fig. 2 Manipulation rod removing HV shielding conductor

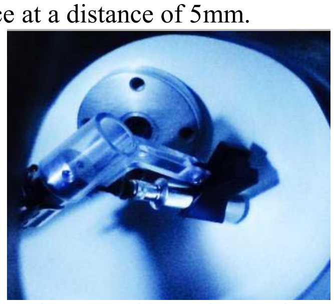


Fig. 3 Capacitive probe scanning insulator surface

The cone-type insulator is deliberately cleaned before each test with anti-electrostatic dust paper dipped in anhydrous ethanol. Its surface is scanned before voltage application to ensure the non-existence of charge. In this paper the influence of metallic particle is studied with the model shown in Fig. 4. A steel needle with diameter of 0.56mm and length of 15mm is fixed near to the HV bus to simulate metallic contamination.

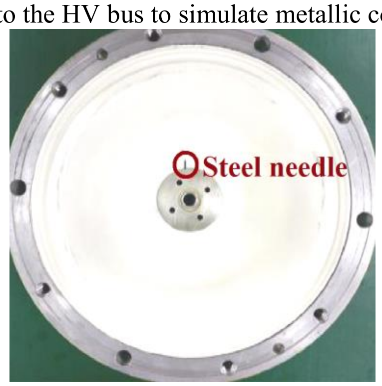


Fig. 4 200kV cone-type insulator with metallic contamination

Experiments are carried out according to the following procedure: insulator cleaning –docking of apparatus – detection of remaining charge – installation of HV shielding conductor – vacuuming – inflation of SF_6 (0.1MPa) – HVDC application – removal of HV shielding conductor – surface charge measurement – recycling of SF_6.

III. EXPERIMENT RESULTS AND ANALYSIS

i. RESULTS FOR CLEAN SURFACE

Fig. 5 shows the charge distribution of clean surface stressed with HVDC of different polarities and amplitudes. The application time of HVDC voltage is 40min. It can be concluded that under negative voltage, charges of both polarities are detected in different areas. With the increase of voltage amplitude, the covering area and density of positive charge increase remarkably. The maximum charge density occurs near the central conductor and is mostly positive under high amplitude. Under positive HVDC voltage, only negative charge is detected, which accumulates remarkably near the central conductor.

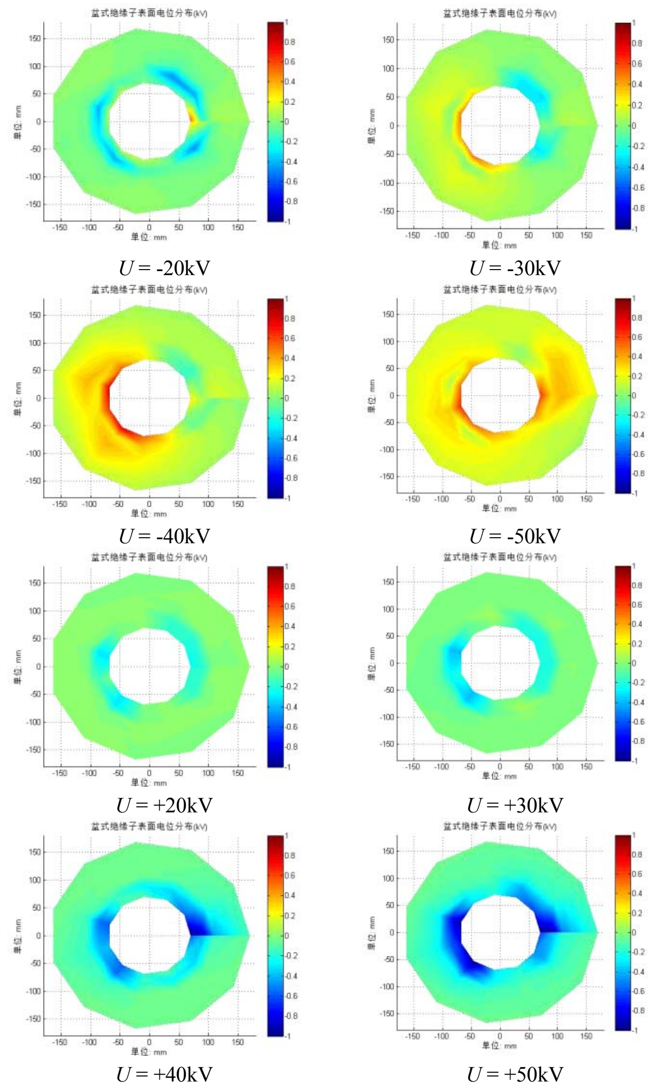


Fig. 5 Surface charge distribution of clean insulator stressed with HVDC voltage of different polarities and amplitudes (t = 40min)

Fig. 6 shows average and maximum surface potential with various HVDC voltage applications. The average potential increases evenly with HVDC voltage amplitude while the maximum potential shows randomness to a certain extent.

Negative charge is more prone to accumulate on the insulator surface with its maximum density more significant than that of positive charge.

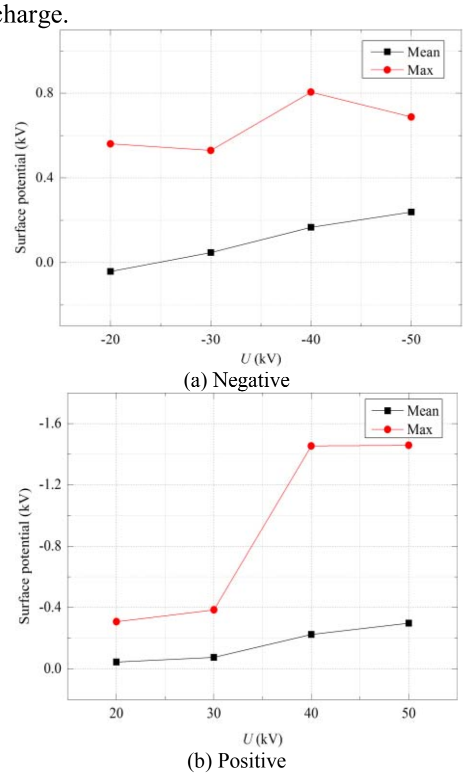
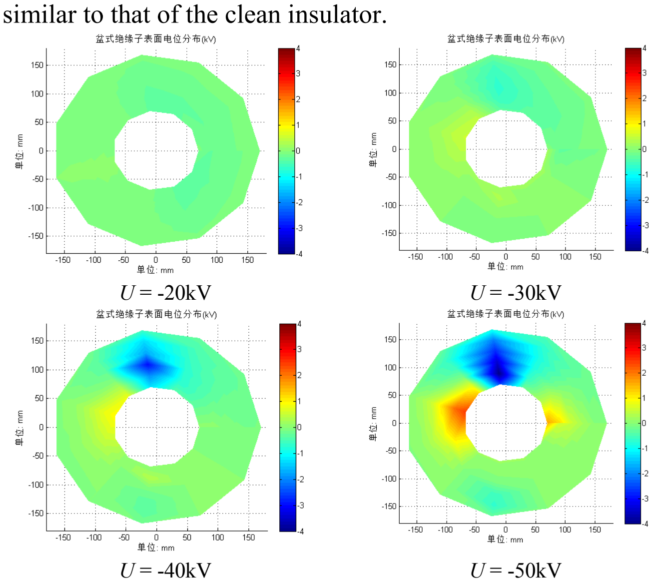


Fig. 6 Average and maximum surface potential with different voltage application

ii. RESULTS FOR METALLIC CONTAMINTED SURFACE

Fig. 7 shows surface charge distribution of the metallic contaminated insulator. HVDC voltage applications remain identical as those for the clean one. The results show that charge of the same polarity as applied voltage accumulates remarkably in the area where the steel needle is stuck. This area can expand even to the edge of insulator, with higher charge density as the voltage amplitude increases. For areas far from metallic contamination, most of the distribution is similar to that of the clean insulator.



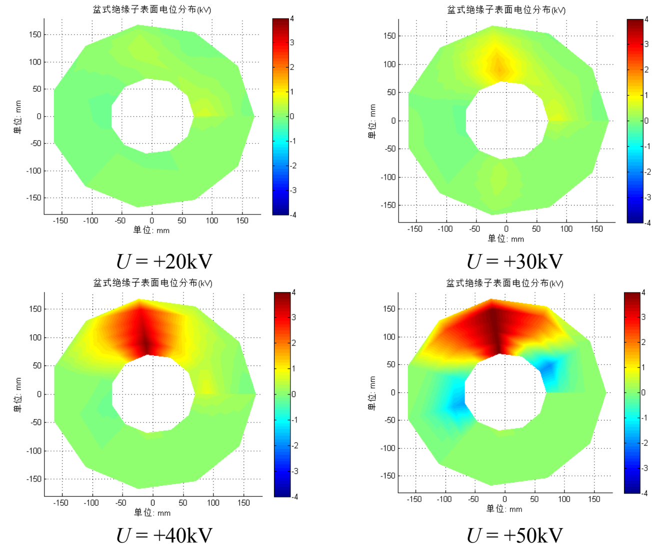


Fig. 7 Surface charge distribution of metallic contaminated insulator stressed with HVDC voltage of different polarities and amplitudes (t = 40min)

It is shown that with the presence of metallic particles, surface charges of the same polarity as the applied voltage can gravely accumulate at the contamination area. At U = ±50kV, the absolute value of maximum potential measured for metallic contaminated insulator is approximately 5 times of the clean insulator.

iii. ANALYSIS FOR THE PHENOMENON

Without the presence of metallic contamination, the polarity of accumulated surface charge is opposite from the HVDC voltage applied. The charge density decreases from near the central conductor to the edge of insulator. This distribution can be explained by the theory of charge relaxation process on an interface between two dielectrics [10-11]. In the case of GIL insulator, this refers to a gas-solid interface. Formula (1) is derived from Maxwell Equations which describes the charge relaxation process under DC voltage:

$$\sigma(t)=\frac{\varepsilon_s\gamma_g-\varepsilon_g\gamma_s}{b\gamma_s+a\gamma_g}U(1-e^{-t/\tau_e}) \tag{1}$$

In Formula (1) the direction of electric field is defined positive when field lines cross from gas to solid. ε_g, γ_g are the relative permittivity and electric conductivity of gas dielectric while ε_s, γ_s are for solid. Constants a and b are related to the electrodes structure with the dimension of length. U is the DC voltage applied.

Take the case of cone-type insulator under positive HVDC voltage as example. The field distribution is shown in Fig. 8 where most of field lines enter from gas, through the concave surface and into the solid epoxy-resin side. With the amplitude of HVDC voltage insufficiently high to cause partial discharge, the steady state of charge relaxation can be predicted according to Formula (1). Since the conductivity of gas can be neglected compared to that of solid, Formula (2) can therefore be derived. Thus, charge of opposite polarity is supposed to accumulate on the concave surface of insulator:

$$\sigma_{\text{steady}}\approx-\frac{\varepsilon_g\gamma_s}{b\gamma_s+a\gamma_g}U \tag{2}$$

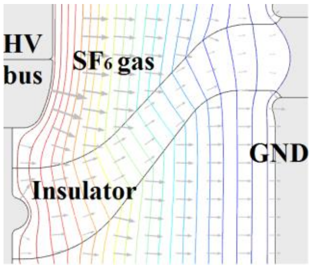


Fig. 8 Field distribution of cone-type insulator

Broadly, the steady-state of charge relaxation can be expressed through Formula (3), which reveals the inevitability of charge accumulation [6, 12]. Space charge density is related to the local electric field, as well as the electrical parameters of the dielectric. At an interface where ε/γ is discontinuous, an evident accumulation occurs. Since the field near the central conductor is higher than that near the grounding shell, a distribution with decreasing charge density from inner to outer is obtained.

$$\rho = \gamma E(\nabla \frac{\varepsilon}{\gamma}) \tag{3}$$

With the presence of metallic contamination on the insulator surface, the charge distribution can also be explained by Formula (1). As voltage amplitude increases, partial discharge is more likely to occur, producing a large number of charged particles of the same polarity. What is more, partial discharge leads to the increase of gas conductivity γ_g. When $\varepsilon_s\gamma_g - \varepsilon_g\gamma_s > 0$, charge of the same polarity as the applied voltage will accumulate in the contamination area.

Charge accumulation may cause damage to the electric insulation of GIL system. Considering the influence of metallic contamination on surface charge density, it is recommended to create traps for metallic particles or to coat electrode surface [3]. Besides, some special treatments to the surface of insulator, such as fluorination or coating [13-14], could be equally applied to improve the surface conductivity and subsequently the charge decaying rate.

IV. CONCLUSION

This paper studies the charge distribution characteristics of clean and metallic contaminated surface of a 200kV cone-type insulator under HVDC voltage. The following conclusions are drawn based on experimental phenomenon and analysis:

1. For a clean insulator, charge of opposite polarity from the applied voltage accumulates. Charge density is higher near the GIL central conductor. The distribution can be explained by the theory of charge relaxation process.
2. For a metallic contaminated insulator, charge of identical polarity to the applied voltage accumulates at the contamination area, with density much higher than that of the clean surface. This distribution can be explained from the perspective of partial discharge and increased gas conductivity.
3. Surface charge accumulation threatens the operation safety of GIL. It can be reduced by suppressing metallic particles or other measures for the improvement of surface conductivity of insulator.

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REFERENCES

[1] LIU Zhenya. Ultra-high voltage AC & DC grid [M]. Beijing, China: LIU Zhenya. Ultra-high voltage AC & DC grid [M]. Beijing, China: China Electric Power Press, 2013: 331-337.

[2] F. Messerer, W. Boeck. Gas Insulated Substation (GIS) for HVDC [C]. 2000 Conference on Electrical Insulation and Dielectric Phenomena, 698-702.

[3] LI Peng. Flashover characteristics along the insulator in SF_6 gas under DC voltage and its application in UHV DC GIL [D]. Xi'an, China: Xi'an Jiaotong University, 2015: 38-43.

[4] LI Qingmin, WANG Jian, LI Botao, et al. Review on metal particle contamination in GIS/GIL [J]. High Voltage Engineering, 2015, 42(3): 849-860.

[5] J. Tan, P. H. F. Moshuis, FH Kreuger. Surface charge accumulation and decay on a spacer stressed with DC voltages at atmospheric conditions [J]. Electrical Engineering, 1991, 74(4): 315-319.

[6] J. Tan. Surface charge accumulation in SF_6 [D]. Delft, Netherlands: Delft University of Technology, 1993: 115-142

[7] J. Tan, P. H. F. Morshuis, F. H. Kreuger. Mechanisms of surface charge accumulation in SF_6 [J]. Archchiv für Electrotechnik. 77(1994): 151-155.

[8] ZHANG Guixin, ZHANG Boya, WANG Qiang, et al. Experiment study of surface charge accumulation and decay on a cone-type insulator in HVDC GIL [J]. High Voltage Engineering, 2015, 41(5): 1430-1436.

[9] ZHANG Guixin, WANG Bei, WANG Qiang, et al. The simulation analysis of accumulated surface charge effect on DC cone-type spacers [J]. High Voltage Engineering, 2010, 36(2): 335-339.

[10] FENG Cizhang, MA Xikui. Introduction to engineering electromagnetic fields [M]. Beijing, China: Higher Education Press, 2000: 193-197.

[11] WANG Feng. Research on surface charge accumulation and its effect on flashover characteristics of the insulator [D]. Xi'an, China: Xi'an Jiaotong University, 2003: 28-37.

[12] LIU Zhimin, QIU Yuchang, FENG Yunping. The discussion about accumulation mechanism of surface charge on insulating spacer [J]. Transactions of China Electrotechnical Society, 1994(4): 65-68.

[13] ZHANG Boya, ZHANG Guixin, WANG Qiang, et al. Suppression of surface charge accumulation on Al2O3-filled epoxy resin insulator under DC voltage by direct fluorination [J]. AIP ADVANCES 5, 127207(2015), 1-12.

[14] R. Gremaud, M. Bjelogrlic, M. Schneider, et al. Surface charge decay on HVDC insulators: Temperature and field effects [C]. 2013 IEEE International Conference on Solid Dielectrics, Bologna, Italy, 2013.