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Surface Discharge Characteristics Study on the Laminated Solid Insulator in Quasi-Uniform Electric Field with Dry Air

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Abstract – Dry air is an excellent alternative to SF_6 gas and is used as an insulation gas in Eco-friendly Gas Insulated Switchgears (EGISs), which has gained popularity in industry. Solid insulators in EGIS play an important role in electrical insulation. On the other hand, surface discharge can occur easily when solid insulators are used. This paper explored the surface discharge characteristics on the structure of three-layered laminated solid insulators to elevate the flashover voltage. A laminated solid insulator was inserted after the quasi-uniform electric field was formed in the test chamber. Dry air was then injected to set the internal pressure to 1 ~ 6 atm, and the AC voltage was applied. When identical solid insulators were stacked, the surface discharge characteristics were similar to those of a single solid insulator. On the other hand, the flashover voltage rose when the middle part was thicker and had lower permittivity than the top and bottom parts in the laminated solid insulator. Based on experimental results, when stacking a solid insulator in three layers, the middle part of the solid insulator should be at least four times as thick as the top and bottom parts and have lower permittivity than the others. In addition, the flashover voltage increased with increasing gas pressure on the surface of the laminated solid insulator due to the gas effect. This study may allow insulation design engineers to have useful information when using dry air for the insulation gas where the surface discharge can occur.

Keywords: Dry air, Quasi-uniform electric field, Laminated solid insulator, Flashover voltage, Surface discharge, Triple junction

1. Introduction

Sulfur hexafluoride (SF_6) gas has been used as an insulation gas or arc-resistant gas in high-voltage electrical equipment because of its stable chemical and thermal properties as well as its excellent insulation [1]. On the other hand, the use of SF_6 should decrease because it was designated as a target for Green House Gas (GHG) emission trading in the Kyoto Protocol in 1997. Because of this background, several studies have been performed to reduce the use of SF_6 gas in electric power systems [2].

Eco-friendly gases, such as dry air, N_2 and N_2:O_2 gas mixture, were considered as a replacement for SF_6 gas. At pressure of 0.5 Mpa, the dielectric strength of dry air and N_2:O_2 (contained 40% of O_2) gas mixture was significantly higher than that of N_2. Also, the dielectric strength of N_2:O_2 (contained 40% of O_2) gas mixture was about 5% higher than that of dry air. However, the manufacturing cost of dry air is about one-third of that of N_2:O_2 (contained 40% of O_2) gas mixture [2]. In addition, several studies have been conducted on solid-state and vacuum insulated switchgear [2, 3]. Dry air has attracted the most attention as an insulation gas for Eco-friendly Gas Insulated Switchgears (EGIS) [4]. Solid insulators play important roles in electrical insulation in this electric power equipment [5]. On the other hand, due to the use of solid insulators, surface discharge may occur where solid insulators, electrodes and insulation gases touch the boundary (i.e., triple junction) [6]. It is known that surface dielectric strength is reduced near this triple junction [7]. Therefore, the surface discharge at the triple junction is important in the design of electric power devices. In particular, the surface discharge of the triple junction can be generated more easily when the electric field intensity is higher. Studies [8-10] have been conducted to mitigate the triple junction electric field using solid-insulator permittivity or by increasing the flashover voltage. Kato et. al. [8] and Kurimoto et. al. [9] constructed a Functionally Graded Material (FGM) using a centrifugal force to control the permittivity distribution of solid insulators. The FGM spacer was composed of two or three layers. The electric field in a triple junction in SF_6 gas can be mitigated by applying the FGM spacer. Shengtao et. al. [10] constructed three-layered insulators using Mo-Al_2O_3 cermet and Al_2O_3 to control the permittivity distribution of the solid insulator. They presented that the flashover voltage increased and that the triple junction electric field intensity was mitigated in a vacuum by applying their insulator. On the other hand, few studies which explored the surface discharge of the triple junction seem to have examined the following

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conditions in their experiments:

(1) Eco-friendly gas
(2) Laminated solid insulator stack conditions
(3) Insulation gases pressure crucial to the insulation design of electric power devices

In this perspective, this paper uses dry air which is appropriate to replace SF_6 gas in the experiment. This paper studied the surface discharge characteristics of three-layered laminated solid insulator structure which was proposed to increase the flashover voltage. These surface discharge characteristics of the laminated solid insulator were examined by changing the dry air pressure. This three-layered laminated solid insulator structure increased the dielectric strength without changing the spacer shape. The proposed method is able to solve the complexity and production cost of high voltage power devices. The relevant precedent study [11] explored the impact to surface discharge through different materials of solid insulators and dry air pressure. The changes in flashover voltage were measured as the different structures of the laminated solid insulators into which different levels of AC voltages were applied. In addition, the flashover voltage changes were measured as the insulation gases pressure changes.

2. Experimental Equipment and Method

2.1 Experimental equipment

Fig. 1 shows experimental equipment used in this study. The test chamber in Fig. 1 was made of 20 mm stainless steel in a dual structure composed of internal and external walls to observe the surface discharge characteristics. The specifications of the chamber interior were as follows: diameter 260 mm, height 460 mm, and approximate volume 25 ℓ. The chamber exterior had a diameter of 460 mm and height of 500 mm. A vacuum layer was placed between the inner and outer walls in order to block heat transfer. A quartz glass observation window of which diameter and thickness were respectively 110 mm and 20 mm was installed on the outside in order to observe the test chamber. This chamber could withstand the temperature range of -90°C~100°C and 10 atm. The dry air producing device in Fig. 1 has the three-stage filter that reduces the dew point and the amount of impurities while the air passes through them to produce pure dry air.

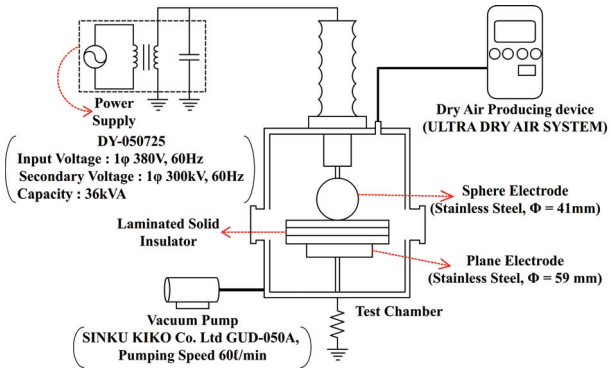


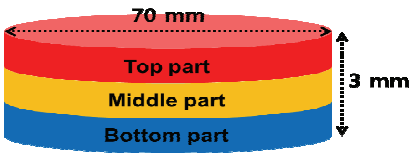
Fig.1. Experimental apparatus and circuit

The vacuum pump (i.e., GUD-050A made by SINKU KIKO Co. Ltd) of which pumping speed was 60 ℓ/min was used to create a vacuum in the inside of the test chamber before injecting dry air. A manometer made by WISE Control Inc. was used to measure the pressure in the inside the test chamber. An AC high voltage transformer (i.e., DY-050725) was used for a high voltage power supply of which capacity is 36kVA. Its input specifications are single-phase 380V 60Hz, and its secondary side has single-phase 300kV 60Hz. Electrodes were made of stainless steel; the sphere electrode had a diameter of 41 mm, and the plate electrode had a diameter of 59 mm.

2.2 Laminated solid insulator

The laminated solid insulator stack was composed of top-middle-bottom parts, as depicted in Fig. 2(a). The materials of solid-insulators used for each layer were Teflon (TE), Polycarbonate (PC), and Bakelite (BE) of which relative permittivity is respectively 2.1, 3.0, and 5.0. The materials of these solid insulators were chosen based on the relative permittivity (i.e., 2.1 ~ 4.7) of the typical spacer currently used in Gas Insulated Switchgears (GIS) [12]. Fig. 2(b) describes a sample of the laminated solid insulator of which total thickness and diameter were respectively 3 mm and 70 mm.

The experimented laminated solid insulator stacks were divided into three sample groups including groups A, B and C. Group A has an identical solid insulator to determine the impact on the flashover voltage. The order of insulation layers was TE-TE-TE, PC-PC-PC and BE-BE-BE with a 1 mm thickness of each part. Group B had a middle layer with different permittivity. The laminated



(a) Structure of the laminated solid insulator



(b) Appearance of laminated solid insulator samples: 1mm-1mm-1mm (left) and 0.5mm-2mm-0.5mm (right)

Fig. 2. Laminated solid insulator

orders of each solid insulator were TE-PC-TE, TE-BE-TE, PC-TE-PC, PC-BE-PC, BE-TE-BE, and BE-PC-BE with a 1 mm thickness of each sheet. Group C had a different thickness in the top, middle and bottom parts compared with the group B. The thickness of the top and bottom parts was 0.5 mm, and that of the middle part was 2 mm.

A laminated solid insulator used in this experiment was fabricated based on the similar principle of other researchers [8-10] that the flashover voltage was raised by controlling permittivity distribution inside insulator. However, these other studies [8-10] presented a single new material consisted of three layers with different permittivity distribution. This could produce additional cost for researching and manufacturing new materials. In addition, the permittivity of the new material used in these studies [8-10] was higher than that of spacer used in the Gas Insulated Switchgears (GIS). Therefore, this paper presented stacking well-known laminated materials whose permittivity range is within that of spacer currently used in the GIS. These findings of this study can be applied to inexpensively fabricate a spacer composed of three layers with different permittivity distribution using well-known solid insulating materials.

2.3 Experimental methodology

In this experiment, the electrodes inside the test chamber were placed vertically, as described in Fig. 1. This arrangement of electrodes formed a quasi-uniform electric field inside the test chamber. The electrode was polished to remove impurities using aluminum oxide (Al_2O_3). The laminated solid insulator was placed on the plate electrode. The sphere electrode was placed in contact with the upper part of the laminated solid insulator.

The test chamber was evacuated 5×10^{-4} Torr before injecting dry air. At that point, the dew point of dry air was -49.5 °C~51.9 °C, and the dry air was injected into the test chamber to 1~6 atm. The high voltage was applied using a DY-050725 AC power supply with the voltage rise rate of 3.15 kV/s. The flashover voltage (V_S) was measured when the surface discharge occurred along the creepage of the solid insulator. The flashover voltage was measured five times. The mean, maximum and minimum values were marked in Figs. 3, 4, and 7. The initial discharge voltage in which the leader discharge occurred was used to measure the flashover voltage. In addition, the same methodology and procedure were performed when the other laminated solid insulators were used in the experiment.

3. Results and Discussions

3.1 Surface discharge characteristics of the stack with identical solid insulators

Fig. 3 shows the flashover voltage (V_S) – pressure (P) characteristics when identical thin solid insulators were stacked. The triple junction is known as a starting point of the surface discharge owing to its very high electric field. The electric field depends on the permittivity of a solid insulator because the relative permittivity of a surrounding gas is approximately 1. The higher the permittivity of the solid insulator is, the stronger the electric field of the triple junction is, and the surface discharge occurs easily [11]. In this study, TE, PC, and BE were used as solid insulators in an identical layer of the laminated solid insulator stack. Therefore, the electric field of the triple junction was highest in BE-BE-BE because BE has the highest permittivity, and the electric field of the triple junction was lowest in TE-TE-TE because TE has the lowest permittivity. As a result, the flashover voltage (V_S) was highest in TE-TE-TE and lowest in BE-BE-BE. Thus, the surface discharge characteristics of the laminated solid insulator stack with an identical insulator were similar to that of the monolayer solid insulator if their thickness was equal [11].

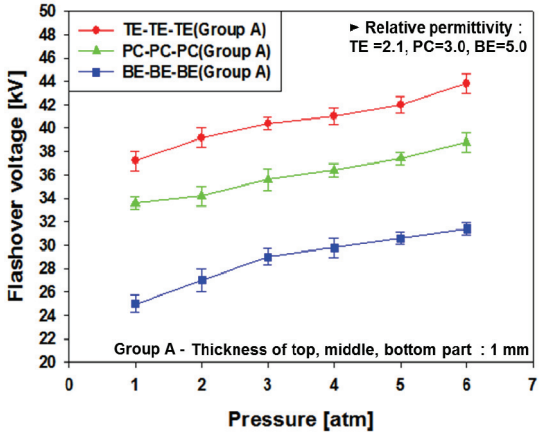
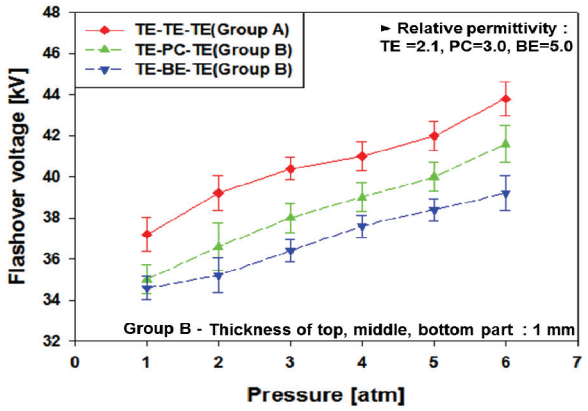


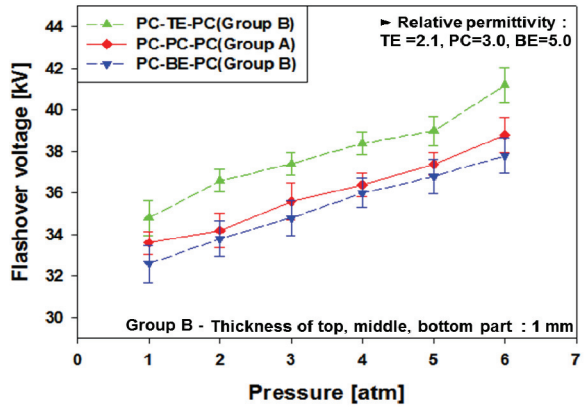
Fig. 3. Flashover voltage (V_S) – pressure (P) characteristics of the same solid laminated insulators [13]

3.2 Surface discharge characteristics with the different middle layer of the solid insulator

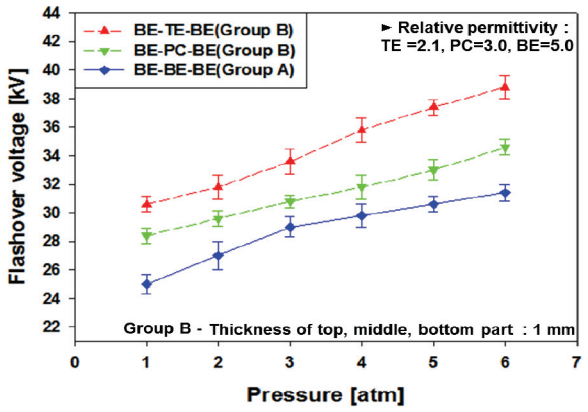
Fig. 4 describes the flashover voltage (V_S) – pressure (P) characteristics when the middle layer was changed in the laminated solid insulator stack compared with the control group A. Fig. 4(a) shows the V_S – P characteristics of TE-PC-TE and TE-BE-TE compared with those of TE-TE-TE as a reference. The middle part had higher permittivity than the top and bottom parts. If the same pressure was applied, the flashover voltage decreased with increasing permittivity of the solid insulator in the middle part. Fig. 4(b) indicates the V_S – P data of PC-BE-PC and PC-TE-PC in comparison with those of PC-PC-PC. The middle part (i.e., BE) had higher permittivity than the top and bottom parts (i.e., PC). The middle part (i.e, TE) had lower permittivity than the top and bottom parts (i.e., PC). Under the same pressure, the flashover voltage increased with



(a) TE-X-TE cases (X refers to TE, PE, and BE.)



(b) PC-X-PC cases (X refers to TE, PE, and BE.)



(c) BE-X-BE cases (X refers to TE, PE, and BE.) [13]

Fig. 4. Flashover voltage - pressure characteristics with the different middle layers of the solid insulators

decreasing permittivity of the solid insulator in the middle layer. Fig. 4(c) illustrates the V_S – P records of BE-TE-BE and BE-PC-BE compared with those of BE-BE-BE. The middle part had lower permittivity than the top and bottom parts. Under each pressure, the flashover voltage increased with decreasing permittivity of the solid insulator in the middle part. Fig. 5 shows the flashover specimen pictures of group B including BE-TE-BE and PC-TE-PC cases at 1 atm.



Fig. 5. Flashover specimen pictures of group B: (a)BE-TE-BE (left) and (b) PC-TE-PC (right)

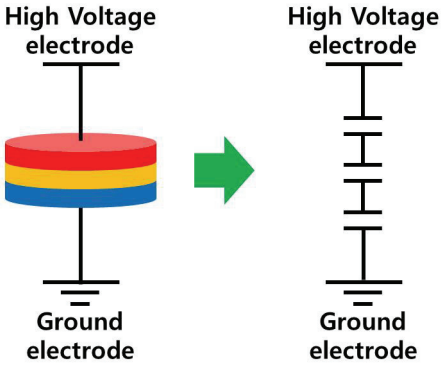


Fig. 6. Equivalent circuit of the laminated solid insulator

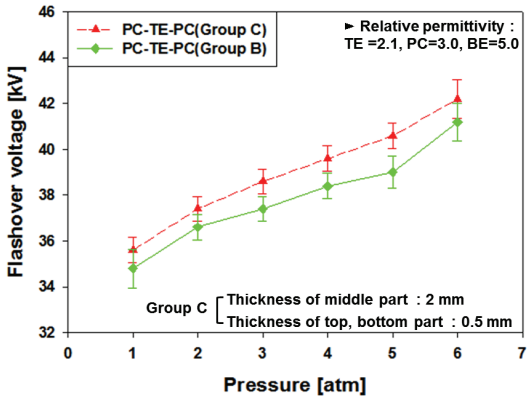
As illustrated in Fig. 6, a three-layered laminated solid insulator stack could be modeled with three series-connected lumped capacitors in the circuit analysis. As described in (1), permittivity is proportional to capacitance if the thickness and area of the capacitor are fixed. Furthermore, as shown in (2), permittivity is inversely proportional to the voltage applied to the capacitor because the stored charge is equal in the series-connected capacitors.

$$C = \varepsilon \frac{A}{d}, \tag{1}$$

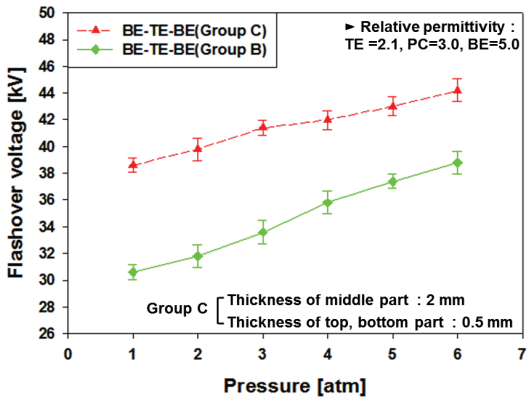
$$V = \frac{Q}{C} = \frac{Qd}{\varepsilon A}, \tag{2}$$

where C, ε, A, d, V, and Q are respectively the capacitance, permittivity, area, thickness, voltage, and stored charge of a capacitor. The relative permittivity of TE, PC, and BE is respectively 2.1, 3, and 5. In the case of TE-PC-TE, TE-BE-TE, and PC-BE-PC, the capacitances of the top and bottom parts are smaller than that of the middle part because the permittivity of the top and bottom parts is smaller than that of the middle part when their areas and thicknesses were fixed in this experiment. The voltage applied to the each capacitor increases as the each capacitance decreases because the capacitance and the voltage applied to the capacitor in the series-connected capacitors is inversely proportional to each other as described in (2). Therefore, the voltages applied to the top and bottom parts were higher than that of the middle part. In other words, voltage was applied more to the top and bottom parts than the middle part. On the other hand, in the case of PC-TE-PC, BE-TE-BE and BE-PC-BE, the capacitance of the middle part is smaller than that of the

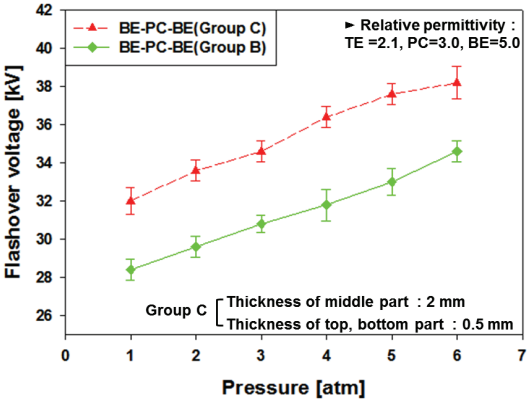
top and bottom parts according to their permittivity and (1). Therefore, the voltage applied to the top and bottom parts were smaller than that of the middle part. In other words, voltage was applied more to the middle part than the top and bottom parts. Hence, the flashover voltage increased when the permittivity of the middle part solid insulator was less than those of the top and bottom parts. In addition, the difference of permittivity between the middle part and the other parts was greater, the flashover voltage increased.



(a) PC-TE-PC cases including groups B and C



(b) BE-TE-BE cases including groups B and C



(c) BE-PC-BE cases including groups B and C

Fig. 7. Flashover voltage - pressure characteristics on the change of each part thickness

3.3 Surface discharge characteristics on the change of each part thickness

In the previous section, only the different permittivity of the solid insulator was considered in the experiments because the area and thickness of each part were assumed to be identical. On the other hand, this section presents the experimental results for the different thicknesses of solid insulator layers compared with PC-TE-PC, BE-TE-BE and BE-PC-BE of which flashover voltages increased in the group B. The thicknesses of the top and bottom parts in the group C were respectively reduced to 0.5 mm, and that of the middle part increased to 2 mm compared with the group B. These thickness changes were intended to adjust the voltage across each part by varying the capacitance of each part. Fig. 7 shows the flashover voltage (V_S) – pressure (P) characteristics as the thickness of each part was changed when the permittivity of the middle part is lower than the other parts (i.e., PC-TE-PC, BE-TE-BE and BE-PC-BE cases). Under the same pressure, the flashover voltage in the group C increased compared to that in group B as the thickness of the middle part increased while those of the other parts decreased. Fig. 8 shows the flashover specimen pictures of group C including BE-TE-BE and PC-TE-PC cases at 1 atm.

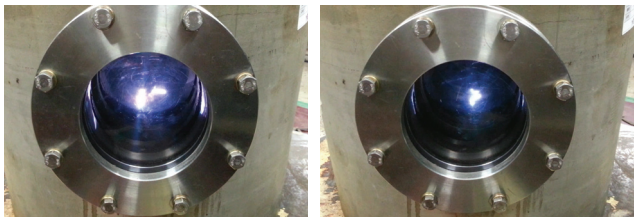


Fig. 8. Flashover specimen pictures of group C: (a) BE-TE-BE (left) and (b) PC-TE-PC (right)

The laminated solid insulator with various thicknesses can also be modeled with three series-connected lumped capacitors. As described in (1), as the thickness increased, the capacitance became smaller, and the voltage applied to the capacitors increased. Therefore, when solid insulators (PC-TE-PC, BE-TE-BE, and BE-PC-BE) were laminated with different thicknesses as the group C, the capacitance of the middle part became lower, and its applied voltage became higher than that of the group B where the thickness of each layer is 1 mm. Moreover, as the thickness decreased, the capacitance increased, and the voltage applied to the capacitors decreased according to (1). Hence, the capacitance of the top and bottom parts in the group C increased, and their applied voltages decreased.

As a result, the flashover voltage increased when the permittivity of the middle part decreased by more than those of the top and bottom parts, and the thickness of the middle part was wider than that of the top and bottom parts.

3.4 Surface discharge characteristics on the change of thickness of each part

A gas effect is known as the effect that the puncture characteristics of a solid insulator are changed by the nature of media surrounding the solid insulator and electrodes. However, the study of this gas effect is better to be conducted based on the flashover voltage because the puncture voltage of the solid insulator could not be experimentally measured with reliability [14].

The flashover voltage in all laminated solid insulators increased with increasing pressure in the test chamber, as shown in Figs. 3, 4 and 7. This is because the dielectric strength of dry air in contact with laminated solid insulator creepage increases with increasing pressure in the test chamber, and the flashover voltage increases due to the gas effect. This phenomenon appeared in the case of single solid insulator [11].

The flashover voltages of SF_6 gas and N_2:O_2 gas mixture increased respectively when the internal pressure of a test chamber raised from 1 atm to 6 atm [15]. This flashover voltage elevation resulted from the gas effect. In addition, the flashover voltage of SF_6 gas was higher than those of dry air and N_2:O_2 gas mixture. These flashover differences also resulted from the fact that the dielectric strength of dry air and N_2:O_2 gas mixture gas is about one third of that of SF_6 gas. Moreover, although the dielectric strength of dry air and N_2:O_2 gas mixture is similar, the manufacturing cost of dry air is about one third of that of N_2:O_2 gas mixture [2]. Based on these facts, dry air is a promising candidate for a SF_6 alternative gas for insulation. Thus, researchers have studied to reduce the differences of this dielectric strength.

4. Conclusions

This study examined the surface discharge characteristics of laminated solid insulators when dry air was used for an insulation gas in a quasi-uniform electric field. The findings obtained in this study are summarized as follows: (1) When an identical laminated solid insulator was stacked, the flashover voltage became higher if the laminated solid insulator had lower permittivity under the same pressure. This is similar to the surface discharge characteristics of a single solid insulator. (2) When the thickness of each part was identical, the flashover voltage became higher if the permittivity of the middle part was lower than that of the top and bottom parts. (3) When the permittivity of the middle part was lower than that of the top and bottom parts, the flashover voltage increased if the middle part became thicker than the top and bottom parts. (4) For three-layered laminated solid insulator, the middle part should be at least four times as thick as the other parts, and the permittivity of the middle part should be less than that of the other part. This structure increased the flashover voltage. (5) The flashover voltage increased due to the gas effect when the pressure on the surface of the laminated solid insulator increased. This paper is expected to provide useful data for the insulation design of electric power equipment using dry air as the insulation gas where surface discharge may occur.

Acknowledgements

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