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Lightning Impulse Breakdown Characteristic of Dry-Air/Silicone Rubber Hybrid Insulation in Rod-Plane Electrode

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Abstract – Sulfur hexafluoride (SF_6) gas is used widely in electric power equipment such as Gas Insulated Switchgear (GIS), Gas Insulation transmission Line (GIL), and Gas Circuit Breaker (GCB). But applications of SF_6 should be restricted because SF_6 gas is one of the greenhouse effect gases. To reduce use of SF_6 gas, a study on eco-friendly alternative insulation medium is needed. In this paper, we investigated lightning impulse (LI) breakdown of dry-air which is attracting attention as an eco-friendly alternative gas and the LI breakdown of hybrid insulation combined with dry-air and solid insulation (Room-Temperature Vulcanizing Silicone Rubber-RTV SIR) and dry-air in inhomogeneous fields according to gap distance and pressure. The experiment results showed that the LI breakdown strength of hybrid insulation system was higher than that of dry-air insulation system. It was verified that the development of technology related to eco-friendly power apparatus compact such GIS, GCB and GIL can be used as basic research data.

Keywords: SF_6, Dry-Air, Rod-Plane electrode, Hybrid insulation, Lightning impulse

1. Introduction

SF_6 gas chemically is extremely stable and not only has excellent insulation performance compared with other gases but also outstanding current block and arc extinguishing capability [1]. So gas insulated high voltage equipment such as Gas Insulated Switchgear (GIS), Gas Insulation transmission Line (GIL), and Gas Circuit Breaker (GCB) in electric power applications have been mainly used in pressured SF_6 gas. SF_6 significantly contributed to reduce economic costs and size of the high-voltage equipment for a GIS, GCB and GIL. The emission of SF_6 gas into the atmosphere needs to be reduced drastically because SF_6 gas is one of the greenhouse gases [2-8].

Accordingly, to reduce amount of SF_6 gas the researchers on an alternative insulated medium in a various ways are active situation over the world. Studies on mixed with N_2, CO_2 and other gases have been proceeding to reduce amount of SF_6 gas [9]. SF_6/N_2 mixture gas is known as a valid current breaking medium [10]. SF_6/CO_2 mixture gas has been reported to have more excellent insulation characteristics than SF_6/N_2 mixture gas [11-13]. Also in non-uniform electric field, SF_6/air and SF_6/CO_2 mixture gas showed a higher breakdown strength than breakdown strength of SF_6 gas and by addition of 1% CO_2 in 50% SF_6/N_2 gas mixture, breakdown strength has been reported to be more increased than breakdown strength of SF_6/N_2 and SF_6 respectively 1.31 and 1.15 times [14-15]. But in case of these mixture gases, there are problems that do not completely ban the use of SF_6. Therefore, for the development of eco-friendly gas insulated component that does not use SF_6 gas at all, research on Solid Insulated Switchgear (SIS), Dry-Air Insulated Switchgear (DAIS), and Nitrogen Insulated Switchgear (NIS) is being actively conducted and distribution class power apparatus has already been commercialization. However, because such the insulating strength of an alternative insulating gas is considerably lower than dielectric strength of SF_6 gas, in order to obtain required dielectric strength it is necessary to maintain very high pressures of the gas. So comercialization is difficult over distribution class yet.

Studies on the dry-air, which is attracting attention as an eco-friendly alternative gas, have been mainly studied in the uniform and non-uniform electric field [16-18]. Although there are many non-uniform electric fields in actual high voltage equipment, these researches are not many. Also the field utilization factor is an important design criterion that is dependent on the shape of the components and inner structures [19-20]. Therefore, the insulation design has to the lowest field utilization. So in this paper field utilization factor is less than 0.5 and discharge characteristic process studied at extreme non-uniform field according to gap distance and pressure. Since the dielectric strength of the dry air is one third of the level of SF_6 gas and breakdown is mainly starts from weak point where the electric field is concentrated and it lead to whole breakdown of equipment. When such an electrical weak point is coated with a solid dielectric, it is possible to obtain the electric field relaxation effect [21-24].

To obtain an eco-friendly alternative insulated methods of SF_6, This paper examines lightning impulse breakdown

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characteristic of hybrid insulation combined with dry-air and solid insulation in inhomogeneous field having a field utilization factor of range 0.1 to 0.4.

2. Experiments

2.1 Experimental setup

All experiments were carried out in a laboratory gas chamber made of stainless steel having 200 mm diameter and 200 mm height. The gas chamber which connected to the high pressure dry-air cylinder was evacuated to residual pressure of 1×10^{-6} Torr and then filled with dry-air. Gas pressure confirmed pressure gauge of gas chamber. The standard LI voltages (1.2/50 μs) with both polarities were applied using an IVG-600A rated up to 600 kV and has an efficiency of 80 %. Fig. 1 shows a schematic diagram of the test facility.

The standard lightning impulse voltages with positive / negative polarities were determined by an up-and-down method until twenty sets of raw data were obtained. With a 63.2% Cumulative Failure Probability (CFP) of a breakdown voltage, the raw data was obtained from the Weibull-distribution. Fig. 2 shows an example of Weibull distribution plot which indicate positive polarity LI breakdown of dry-air at 6 atm.

The electrode configuration in the chamber consisted of a hemispherical rod, a dielectric covered (room-temperature vulcanizing silicone rubber-RTV SIR) hemispherical rod, and an earthed plane electrode. Table 1 and Fig. 3 show the experimental conditions and electrode systems, respectively.

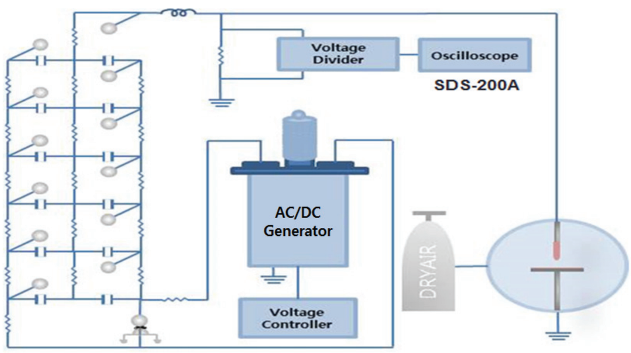


Fig. 1. Impulse breakdown experimental set-up.

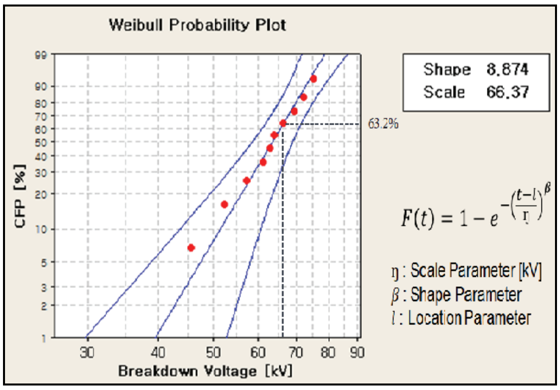


Fig. 2. Weibull distribution plot

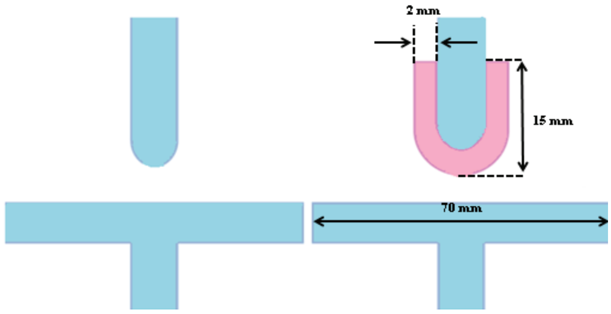


Fig. 3. Bare and coated rod-plane electrode system.

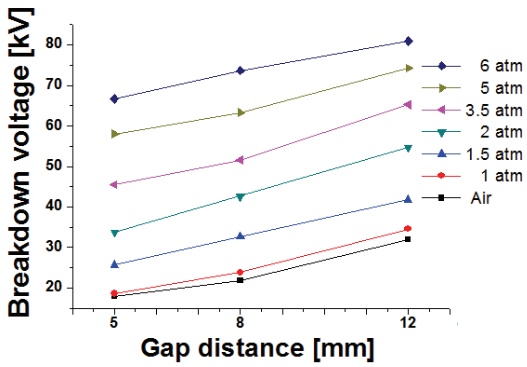
Table 1. The electrode system.

Dry-Air	Ingredient	O2: 21%, N_2:balance H2O: 1.9ppm
	Pressure[atm]	1, 3.5, 6
Electrode	Material	Stainless steel
	Rod diameter[mm]	4.5
	Plane diameter[mm]	50
Dielectric Coated	Material	RTV SIR
	T: thickness[mm]	2
	Rod-coating length[mm]	15
	Plane-coating length[mm]	70
D: gap distance[mm]		5, 8, 12

3. Results and Discussions

3.1 Lightning impulse breakdown characteristics of dry-air

The lightning-impulse-breakdown voltage of dry-air increased with increasing pressure and gap distance by right region of Paschen's law, when the pressure and the gap distance increases, the air density is increased and then collision ionization of electrons is decrease so breakdown voltage of dry-air increased as shown in Fig. 4. Under all test conditions, the negative breakdown voltage was higher than the positive breakdown voltage. This polarity effect can be understood as follows: In rod-plane electrodes, such as a non-uniform electric field, the gas breakdown mechanism proceeds in the following order: corona generation, corona progress, and spark discharge. In the case of a rod electrode with an applied negative LI, the initial electron emission is easy and the space charge effect time is short because of field emission or Schottky emission from the rod electrode metal to the gas. In addition, the negative corona generation voltage was reported to be lower than the positive corona voltage. On the other hand, growth of corona is slower than the positive



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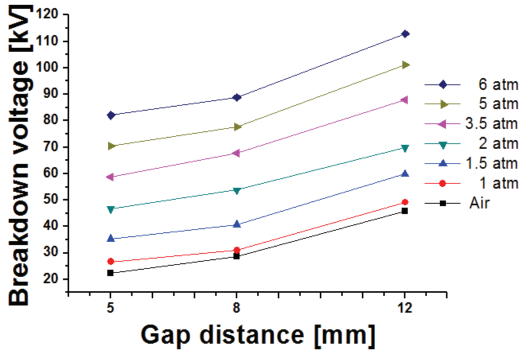


(b)

Fig. 4. LI breakdown of dry-air in the rod to plane according to gap distance with various pressure at (a) Positive polarity and (b) Negative polarity.

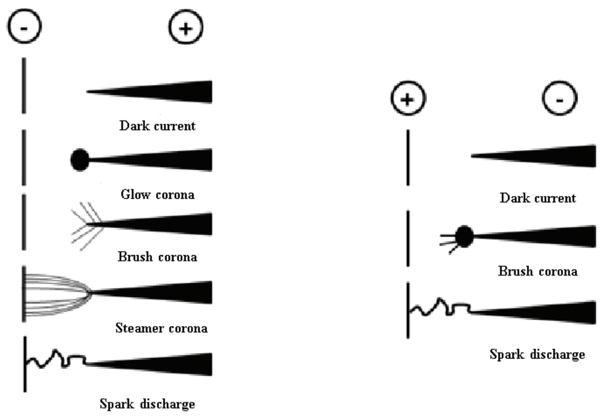


Fig. 5. Extension process of the corona: (a) Positive polarity; (b) Negative polarity.

electron avalanche because growth direction of the electron avalanche begins from a high field toward a lower field region. As the case stands, the positive breakdown voltage is lower than the negative breakdown voltage. Fig. 5 shows the extension process of corona positive and negative polarity at a non-uniform field. As indicated in Fig. 5 in the case of a positive corona, the spark discharge can be progressed easily [18, 25-26].

The field utilization factor is an important design criterion that is dependent on the shape of the components and inner structures. Therefore, the insulation design is subject to the lowest field utilization. The field utilization factor (η) is defined as the ratio of the average electric field (E_{mean}) and maximum electric field (E_{max}) [19-20]:

$$\eta = \frac{E_{mean}}{E_{\max}} = \frac{V_d / d}{E_{\max}} \tag{3.1}$$

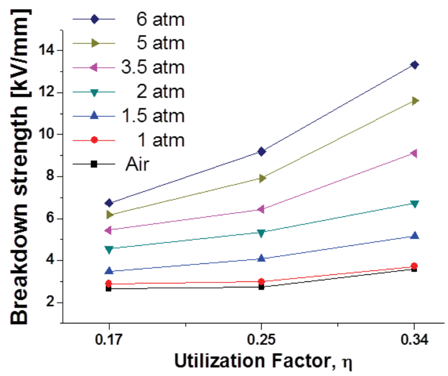
$$E_{mean} = \frac{V_d}{d}, \tag{3.2}$$

where V_d is the measured breakdown value and d is the gap distance between the rod to plane electrode. The maximum field of the rod to plane electrode is expressed in equation (3.3)

$$E_{\max} = 0.9\frac{v}{d}\cdot\frac{r+d}{r}, \tag{3.3}$$

where r is the radius of the rod electrode. Substituting equation (3.3) to equation (3.1), the field utilization between the rod and plane electrode is expressed as equation (3.3). The field utilization is expressed as a function of the electrode distance, as shown Table 2.

As indicated in Fig. 6, the breakdown strength decreases with decreasing the field utilization factor because the electric field was more concentrated at the tip of the rod



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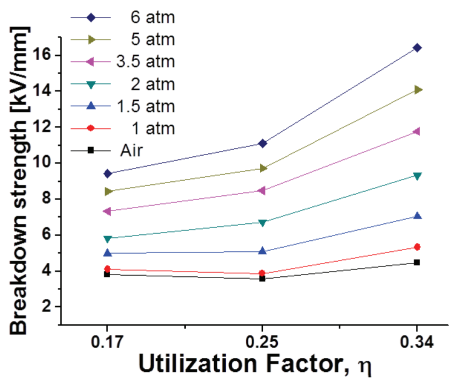

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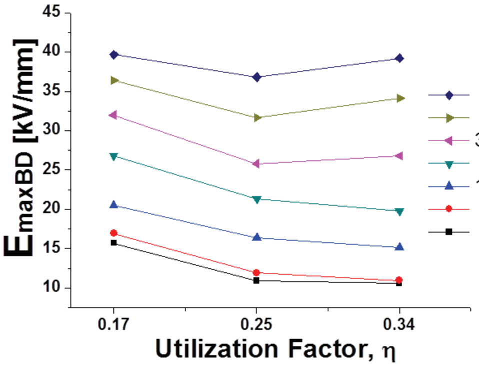
Fig. 6. Breakdown electric filed strength as a function of the electric field utilization factor in the case of (a) positive polarity and (b) negative polarity

Table 2. Electric field utilization factor of the electrode system as a function of the gap distance.

Gap distance, *d* [mm]	Electric field utilization factor, η
5	0.34
8	0.25
12	0.17



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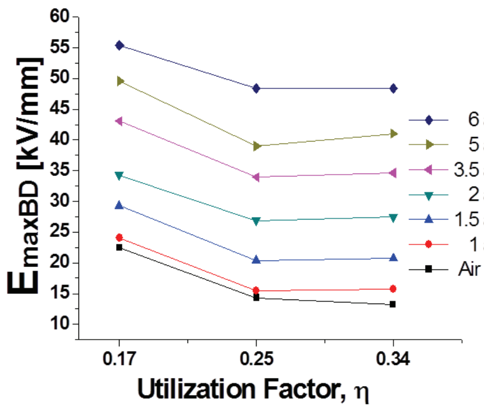


(b)

Fig. 7. Maximum electric field at breakdown, Emax.BD according to the field utilization factor in case of (a) positive polarity and (b) negative polarity

electrode. Fig. 7 shows that the maximum electric field is increased with decreasing the field utilization factor.

3.2 Lightning impulse breakdown characteristic of Dry-Air/Silicone Rubber Hybrid Insulation

The LI breakdown properties of dry-air in the case of adopting electrodes with dielectric coating were examined. The experiments were carried out for rod to plane electrode systems with a 4.5 mm diameter. The coated length of the rod electrode and plane electrode was 12 and 70 mm, respectively. The hybrid insulation system was equivalent to that corresponding to the same conditions in the bare electrode system.

The principal idea of the hybrid insulation system is the intentional use of the surface charge density to re-distribute the electric field within the insulation system. The potential difference between the metal electrodes results in a charge density ($\pm\rho_e$) at the metal surfaces and polarization of the dielectric coating, which is represented by the equivalent polarization charge density ($\pm\rho_p$). Owing to the electric field, the free charge in the dry-air gap, which is available from ionization discharge or other natural origins, is attracted to the surface of the coating. Together with the charge arising from the bulk condition through the dielectric coating, a surface charge density ($\pm\rho_s$) is formed. As a result, an electric field component is directed in opposite to the original electric field, resulting in decreased electrical stress in the dry-air gap [22-25]. Fig. 8 shows the simple principle, and Fig. 9 is a photograph taken at the breakdown of the hybrid insulation system.

As shown Fig. 10, the LI breakdown voltage of hybrid insulation shows an increase according to the pressure and gap distance and depends on the polarity. Table 3 shows an increasing rate between the measured breakdown voltage of the coated electrode and uncoated electrode. From these results, substantial increase in breakdown voltage can be seen, with the exception of some cases which were attributed to experimental error. After the breakdown, voids were observed inside the specimen. Because the electric field is concentrated in the void after partial discharge occurs, it appears to have lower dielectric

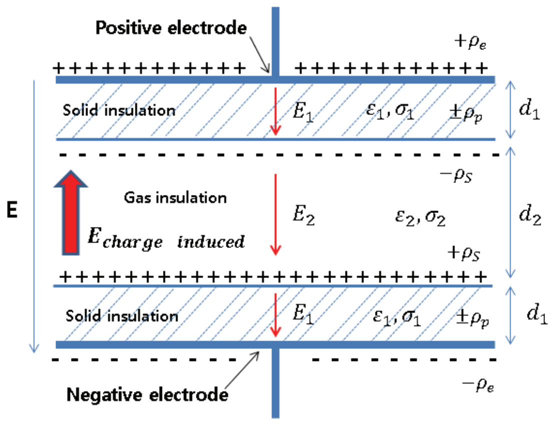


Fig. 8. Basic concept hybrid insulation

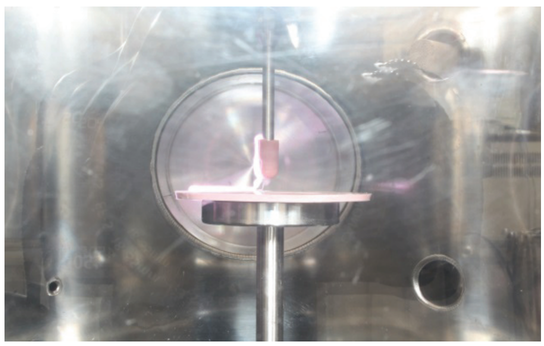
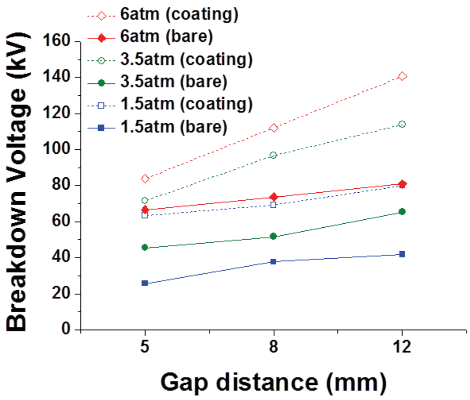


Fig. 9. Photograph taken at the breakdown of the hybrid insulation system.

Table 3. Increasing rate between the measured breakdown voltage of the coated electrode and uncoated electrode.

Increasing rate(%) – Positive polarity			
Gap distance[mm] / Pressures[atm]	5	8	12
1.5	246.00	211.58	125.65
3.5	157.13	187.23	174.37
6	125.65	165.86	173.70

Increasing rate(%) – Positive polarity			
Gap distance[mm] / Pressures[atm]	5	8	12
1.5	159.90	149.02	117.52
3.5	106.31	123.02	113.46
6	89.57	127.01	111.71



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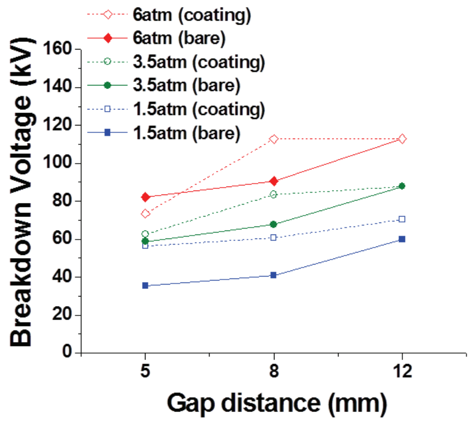
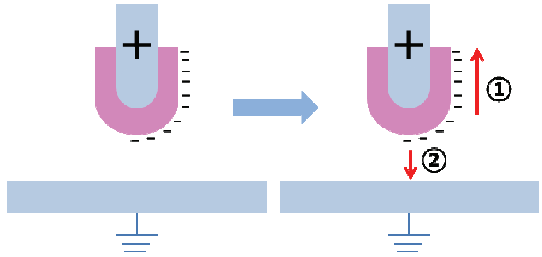


(b)

Fig. 10. Breakdown voltage of the hybrid insulation system: (a) Positive breakdown voltage; (b) Negative breakdown voltage.

strength [27-29].

Under all test conditions, the positive breakdown voltage was higher than the negative breakdown voltage. This result is different from the bare electrode system. Previous studies reported that the discharge propagation of a covered rod to plane arrangement differs according to the polarity of the rod. At a positive polarity, flashover along the cover



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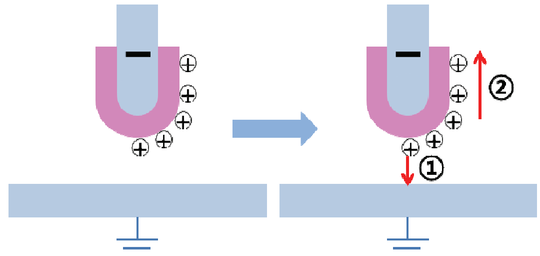

(b)

Fig. 11. Breakdown propagation: (a) positive polarity; (b) negative polarity

surface is followed by breakdown of the air gap. At negative polarity, breakdown of the air gap was followed by flashover along the cover surface, as shown Fig. 11. This can be explained as follows. In the case of positive polarity, the accumulation of surface charge, i.e. electrons, is easy because the mobility of electrons is faster than that of a positive ion. Therefore, the field relaxation effect of air gap was larger than that of the negative polarity because the surface charge density was different between the positive and negative polarity [29-33].

5. Conclusion

The study examined the breakdown characteristics of hybrid insulation in inhomogeneous fields under a lightning impulse voltage. The results can be summarized as follows:

1) LI breakdown voltage of dry-air increased with increasing pressure and gap distance. The negative breakdown voltage was higher than the positive breakdown voltage. The field utilization factor confirmed the important design criteria.
2) The LI breakdown voltage of hybrid insulation increased with increasing pressure and gap distance. The positive breakdown voltage was higher than the negative breakdown voltage. In most cases, the breakdown voltage of the hybrid insulation system increased substantially compared to that of the dry-air insulation system.

Therefore, the development of technology related to eco-friendly power apparatus compact such GIS, GCB and GIL can be used as basic research data.

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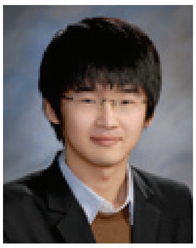

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