Breakdown Characteristics of SF_6 in Different State and Bubble Movements under AC High-Voltage

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Abstract – In this paper the experiments of breakdown characteristics by temperature change of SF_6 gas (GSF_6), and SF_6 liquid (LSF_6) in model GIS (Gas Insulated Switchgear) are described. From the experiment's results, the breakdown characteristics classify the vapor stage of SF_6 according to Paschen's law, in which the gas & liquid coexisted stage of voltage value increases, resulting in much deviation and the breakdown of voltage (V_B) low stage as the interior of the chamber gets filled with a mixture of SF_6 that is not liquefacted and remaining air that cannot be ventilated. The ability of LSF_6 insulation is higher than the high-pressurized SF_6 gas. The breakdown characteristics of LSF_6 were produced by bubble formed evaporation of LSF_6 and bubbles caused by high electric emission. It is considered in this paper that the results are fundamental data for electric insulation design of superconductor and cryogenic equipments machinery that will be studied and developed in the future.

Keywords: GIS, LSF_6, Phase transition, SF_6

1. Introduction

With the improvement of the industrial society, high quality electrical energy, simplification of operation and maintenance, and assurance of reliability and safety are being required. As a result, a transforming device using high pressure SF_6 gas excellent in insulation characteristics is increasingly being established both domestically and internationally.

But with the modern society longing for the convenience of up-to-date technology, attempts at miniaturization and high reliability are being made, while requiring greater electrical energy to operate. Also, the power equipments where the SF_6 gas is applied are expanding in their supply range and are even being installed in severely cold areas.

In such a case as this, malfunctioning is being pointed out as the biggest problem because insulation characteristics would cause a huge change due to the depreciation of temperature resulting in liquefaction. Due to these reasons, it is considered that there is a necessity to research and develop the presently applied SF_6 gas in accordance with the ultra-high voltage era that is almost upon us.

Furthermore, because GIS equipment is usually applied to ultra-high voltage equipments using SF_6 as its insulation characteristics operating under high voltage status, the ripple effect is great in case of malfunction or breakdown characteristics by delicate structural defect or debris during the manufacturing process or its operation state. Accordingly, research to minimize the possibility in the outbreak of partial discharge through designing an ideal insulation layout considering the outer environment and a number of items for accidents is required.

In this research, we want to provide the base data on designing insulation for high-temperature superconductors and the cryogenic equipments by investigating the insulation characteristics of SF_6 according to change in pressure and temperature when a certain amount of gas exists in the chamber. In addition, the phase transition characteristics according to the depreciation of temperature are also a candidate for research.

2. Experimental procedure & Method

The exterior of the experimental chamber is as shown in photo 1 and this is a chamber designed and produced to research the insulation characteristics of SF_6. The highest voltage allowed is AC 300[kV]. DY-106-Korea (AC 300 [kV] / 120 [mA]) was used for the source of electricity. In order to observe the inner temperature of the experimental imitation chamber, the temperature sensor (UNICON, -90~90[℃]) was installed 8[cm] away from the vertical central axis parallel to the electrode at the center of the experimental chamber's interior. A pressure gauge (WISE, 0~15[atm]) was installed to measure the chamber's inner

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pressure. The interior of the chamber can be maintained up to 5×10^{-4}[Torr] using the vacuum pump (SINKU KIKO Co.Ltd, GUD-050A, pumping speed 60ℓ/min) and a vacuum layer was made between the interior and the exterior of the chamber for the insulation of heat. A window (Diameter 110[mm], thickness 20[mm]) was installed to allow the observation of the temperature sensor and the electrode installed inside the experimental chamber. The material for this window is transparent acrylic and was installed by making a cylinder shape.

The main specification of the experimental chamber is such that it can withstand the pressurization of 10 air pressures to be on the safe side for pressure variation (2 ~ 8[atm]), and for maintaining the secrecy within the experimental chamber. Also, the insulation is designed so that it can allow up to 300[kV] for testing internal insulation force of SF_6, which has high insulation characteristics and with which the temperature variation (-90 ~ 90[℃]) or maintenance is possible.

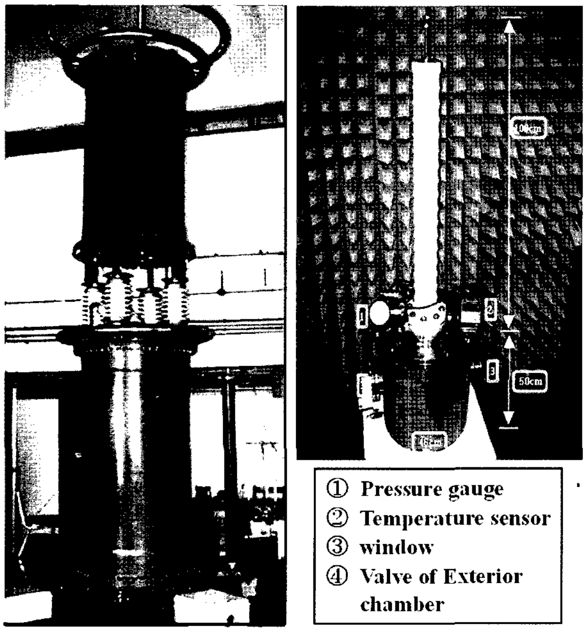


Photo 1. The experimental chamber and AC high voltage source

The electrode used is a Needle-Plane electrode (upper part: Needle, lower part: Plane, N-P, Needle: Diameter 5[mm] Angle of Needle point 20°, Plane: Diameter 59[mm]) and the distance between electrodes was set to 3[mm]. When the temperature sensor section's temperature has to be lowered up to 30 ~ -40[℃] in the case of each atmospheric pressure after ventilating the inner chamber up to 10^{-4}[torr] and inserting 4, 5 or 6[atm] before inserting SF_6, the resulting phase transition characteristics and the Breakdown Voltage (V_B) characteristics has been researched. For the voltage of breakdown characteristics, the average value after ten measurements has been used.

The voltage was set to rising speed of 1[kV/s] during the V_B measurement. It was measured after about the first 10 discharges.

3. Experimental Results & Discussion

3.1. The Temperature Dependence with Maintenance of Fixed Amount of Gas, Insulation Characteristics and Phase Transition Characteristics.

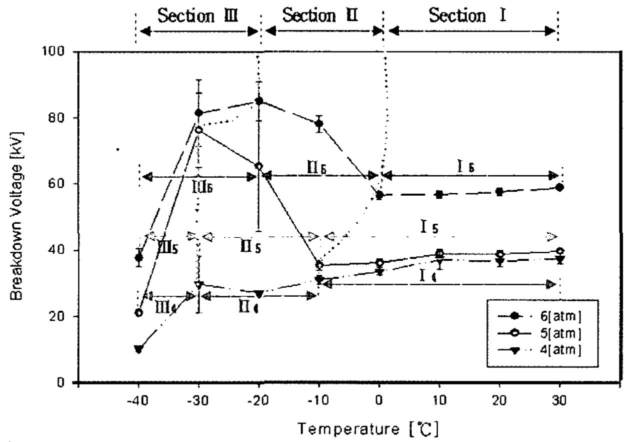


Fig. 1. The characteristic of breakdown on the temperature-pressure with a constant gas volume

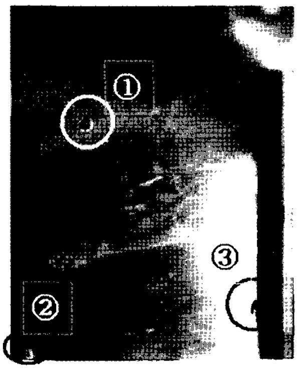
Fig. 1 shows the V_B characteristics toward temperature and pressure when N-P are installed inside the chamber and a fixed amount of SF_6 gas is maintained at 4, 5 and 6 air pressures at 30℃. This experience has the purpose of identifying the inner status of SF_6 and insulation characteristics according to changes of the power equipments' temperature using SF_6 in severely cold areas.

In Fig. 1, the Pattern I is a phase where pressure decreases according to temperature at a gaseous state toward each pressure. At this time, the pressure gradually decreases as the temperature drops and it is a section where the V_B also drops because of this. In other words, it's a field where application of Paschen's law is possible.

Pattern II is a process where the SF_6 is gradually being liquefacted from the needle electrode area and inner walls of the chamber, and it is a field where the voltage value increases as a general trend as indicated in Fig. 2. You can see that the V_B value presents much deviation and this results from showing the high value when breakdown characteristics occur while SF_6 surrounds the needle electrode (Fig. 2-(b)) and liquid SF_6 (LSF_6) is covered on the plane electrode (Fig. 2-(f)). Fig. 2-e shows the low value when measurement is made right after LSF_6, which had been surrounding the needle electrode after being dropped onto the lower part. This is the step where liquefaction is in progress and the insulation media between N-P could be seen as insulation characteristics of a field where SF_6 and LSF_6 coexist.

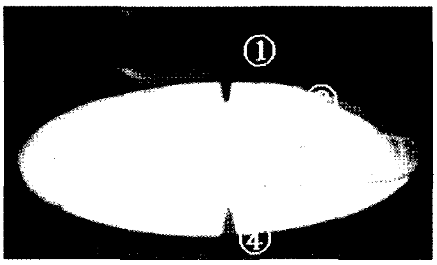
In the case of Pattern II, the liquefaction temperature is the temperature of measurement section and the actual point of liquefaction like Photo 2-(a) is a place where the upper chamber's refrigerant dry ice is attached. The liquefaction is progressed here and flows into electrodes and the inner wall of the chamber. Photo 2-(b) shows the LSF_6 covered on the plane electrode. You can also see that the liquefaction occurs at a lower temperature if the pressure is low.

Pattern III is a phase where most of SF_6 inside are liquefied. LSF_6 is collected at the lower part of imitation GIS and gets considerably lower by turning into a state of extremely low pressure where the area surrounding the electrode gets filled with a mixture of SF_6 that are not liquefacted and remaining air that couldn't be ventilated. It is a step where the V_B becomes considerably low.



1: The LSF_6 flows on needle
2: The LSF_6, which was the upper chamber area, was dropped.
3: The LSF_6 flows on inner wall of chamber

(a) A formation part of the typical LSF_6



1: Needle 2: Plane
3: Formed film LSF_6 at Plane
4: Needle reflect form

(b) LSF_6 on the plane

Photo 2. A process where the SF_6 is being liquefacted in the chamber

3.2. LSF_6 of V_B characteristic

Fig. 2 shows the d-V_B characteristics of N-P and the P-P of LSF_6 and LN_2 when connected to AC power. In the case of the LSF_6, the reason why the V_B is almost the same in the 1[mm] gap of d is because it is a single electrode, so the imbalance decreases and comparatively the balance increases. While d increases, the V_B in the N-P, and P-P electrodes increases, especially, it is higher in the P-P. However, in the V_B, along with the increased d in LN_2, the deviation is not as big as in the LSF_6. Also the N-P shows a higher value than in the P-P, which is opposite from the results found in the LSF_6.

Generally, the V_B of the P-P is lower than the N-P when there is a bubble in the LN_2 and it is under air pressure. This is called the 'BUBBLE EFFECT'[10]. However, the V_B of the P-P is higher than the N-P, which is different from the LSF_6. People call this the "POSITIVE BUBBLE EFFECT". The Positive Bubble Effect can be defined in the following way under the consideration of bubble generation and exercise characteristics.

(1) In the beginning the air pressure for the LSF_6 is 4 atmospheres, the temperature of liquefaction is about -20-30℃, but LN_2 is about -190℃, therefore, it has a big temperature gap with imitation GIS. Also the LN_2, which has a lower evaporation temperature, actively generates bubbles and is more active than LSF_6.

(2) LSF_6 has natural bubbles like the LN_2 or bubbles caused by its corona, however, the LSF_6 bubbles have better arc cancellation abilities than the LN_2 bubbles. Therefore, the corona and arc in the bubbles found in LSF_6 degrade very quickly, so the bubble phenomenon that was observed in LSF_6 is comparatively weaker than LN_2.

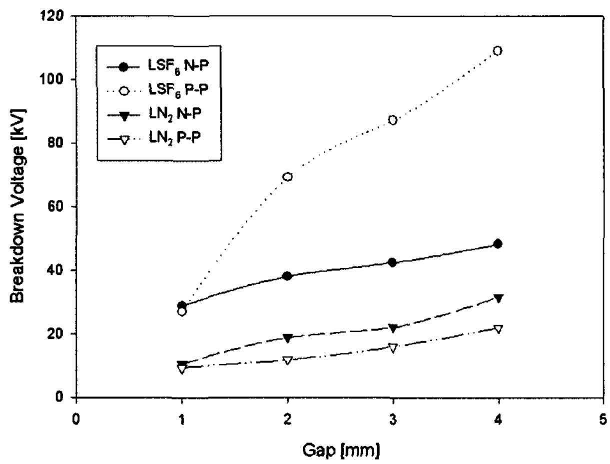


Fig. 2. The Breakdown voltage on S-P & P-P in LSF_6 & LN_2

In the results, in the case of the LSF_6, the possibility of bubbles existing inside the electrode is much lower than in the LN_2.

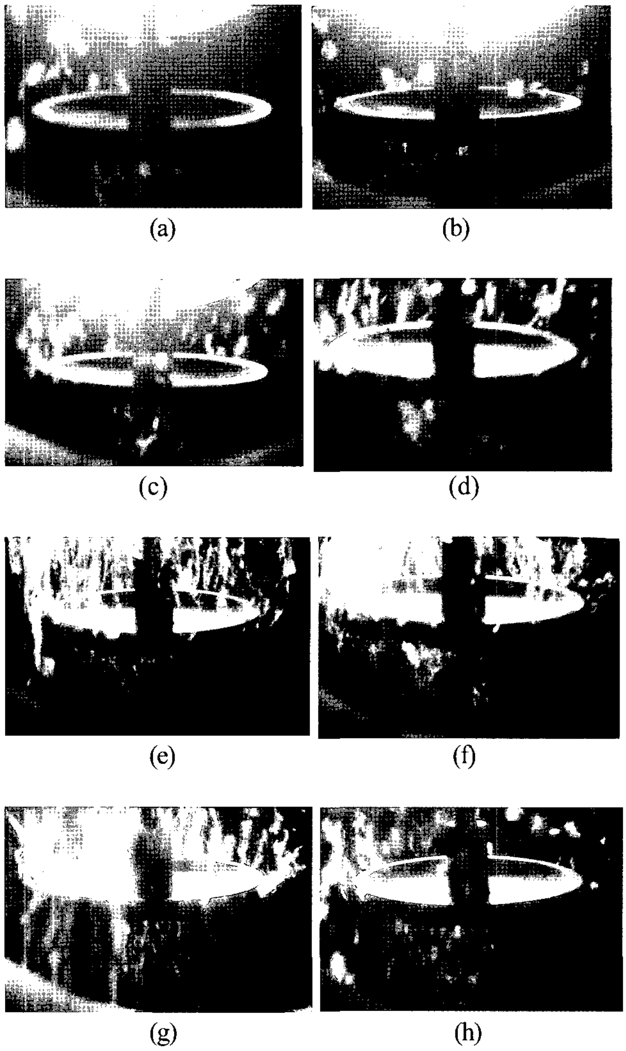
In the LSF_6, breakdown caused by the electric field is more important than the breakdown caused by these. In the result, P-P electrode, which is the sub balanced electrode shape, has higher V_B than N-P, which is an extremely unbalanced electrode.

3.3. LSF_6 of the Bubble movements

Fig. 3 shows the occurrence of the bubble and the separation in the LSF_6. The flow of a liquid is usually separated from its boundary and recirculation form is produced in its area. Such a phenomenon is called separation and is more apparent in the lower reaches of moving direction of bubbles as indicated in Fig. 3.

Fig 3-(a) is the photograph before voltage connection and the SF_6 natural bubbles elevating from the lower part moves upwards along the surface of the needle electrode. Fig. 3-(b) shows the separation phenomenon of bubbles just after voltage connection. In this case, the bubbles are formed in a fan shape as shown in the figure due to the heat of corona of the needle end. Also, as shown in Fig. 3-(c), production of bubbles was increased at the side of the needle electrode and needle end with progress of the corona and, as shown in Fig. 3-(d) and 3-(e), it could be found that, in terms of bubbles produced by the corona, the bubbles elevating over the plate electrode were gradually increased with lapse of voltage connection time. As illustrated in 3-(f), when the quantity of bubbles becomes maximum, the elevating speed of bubbles also becomes maximum. In general, the speed of flow of a viscous fluid is reduced near to the boundary due to viscous resistance compared to the speed of irrotational flow. The speed of bubbles existing at the lower part of the plate electrode becomes near zero (0) and they are shown as static bubbles. Therefore, static bubbles form the SF_6 gas layer at the back of the moving direction (lower part of plate electrode). Also, at the lower part where separation is produced, the bubbles at the outside of the separation surface move at very rapid speed and those at the inside move at relatively slow speed. As described, the high velocity gradient at separation surface produces eddy phenomenon and the eddy of bubbles may clearly be identified at the back side of the plate where bubbles are most actively produced as shown in Fig. 3-(f).

It was identified that when the voltage is disconnected, the production of corona was rapidly reduced and the elevating speed of bubbles was also significantly reduced, as indicated in Fig. 3-(g) and Fig. 3-(h).



(a) Before voltage connection
(b) Just after voltage connection
(c) 30sec after voltage connection
(d) 60sec after voltage connection
(e) 90sec after voltage connection
(f) 120sec after voltage connection
(g) Just after voltage disconnection
(h) 30sec after voltage disconnection

Photo 3.. The occurrence of the bubble & the separation (N-P, d=6[mm], V=20[kV])

4. Conclusions

This thesis is a research related to phase transition characteristics, temperature-pressure characteristics of SF_6 and V_B characteristics of LSF_6 using high voltage. Its summary is as follows.

(1) The temperature according to the fixed amount of gas- pressure V_B characteristics.

1) At the vapor stage of SF_6 according to each pressure,

the characteristics of Paschen's Law were confirmed (Section I).

2) As the liquefaction of SF_6 progresses, the V_B increases considerably and there's much deviation between the highest and lowest V_B. This phenomenon is a result of the value showing up high when the breakdown characteristics occur at the time the LSF6 surrounds the needle electrode area as the LSF6 climbs down the electrode after the SF6 gradually liquefacts from the needle electrode area and the inner walls of the chamber, and the value showing up low if measured right after the LSF_6, which was surrounding the needle electrode area when dropped to the lower section.

3) In case the liquefaction progresses more, the area surrounding the electrode becomes filled with low density SF_6 gas and remaining air and the V_B becomes considerably lower by being in an extremely low pressure state at this time.

4) The temperature where the gaseous SF_6 becomes LSF_6 differs according to pressure but liquefaction occurs when the electrode's temperature is -0 ~ -10℃ in the experiment. The actual liquefaction point is the upper chamber where the refrigerant dry ice is attached, so we can see that the liquefaction temperature is lower than this temperature.

5) If fixed pressures of 6, 5 and 4 are maintained, the liquefaction point shows up higher due to lowered temperature as pressure gets high and the actual liquefaction point is determined at a lower temperature than the one measured according to Boyle-Charles's Law.

(2) LSF_6 of V_B characteristic and the Bubble movements

1) The property of dielectric breakdown is determined by electrode form, electrode arrangement, bubble formation and movement, arc extinguishing capacity of media, difficulty in corona formation, and the distance between electrodes.

2) The bubble formation and flow separation phenomenon was identified for liquid SF_6.

(3) POSITIVE BUBBLE EFFECT

LSF_6, like LN_2, produces bubbles as natural bubbles or with the influence of corona; however, arc extinguishing capability of the bubbles of LSF_6 is significantly excellent compared to the bubbles of LN_2; therefore, the corona and arc of bubbles formed in LSF_6 are rapidly extinguished and the bubble formation in LSF_6 is relatively significantly weakened differently from the case of LN_2.

Acknowledgements

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References

[1] Landry, M. et al. "*Dielectric withstand and breaking capacity of SF_6 circuit breakers at low temperatures*", Power Delivery, IEEE Transactions on, pp. 1029~1035, July 1988.

[2] Gong Guoli et al. "*The influence of SF_6 and SF_6/N_2 dissociating products on the electrical performance of several insulating varnishes*", Electrical Insulating Materials, pp. 495-497, 1995.

[3] T. Ueda et al. "*Discrimination of Partial Discharge Electromagnetic Signal in SF_6 Gas from External Noise Using Phase Gate Control Method*", IEEE International Symposium on Electrical Insulation, pp. 117-120, 1996.

[4] Kwang-Sik Lee, "*A Study on the discharge characteristics of liquid nitrogen at atmospheric pressure*", KIEE Vol. 45, No. 7, 1996.7.

[5] C.Beyer et al. "*Influence Reactive SF_X Gases on Electrode Surfaces after Electrical Discharge under SF_6 Atmosphere*", IEEE Trans, pp. 234-240, 2000.

[6] Kwang-Sik Lee, "*A Study on the Discharge Characteristics of Liquid Nitrogen and Gases at Very Low Temperature*", KEPCO, 1993.8.

[7] Kyeung-Tae Park, "*The Characteristics of Discharge and Radiated Electromagnetic Waves with a Variation of Temperature in SF_6*", Yeungnam Univ. , 2002.12.

[8] Kwang-Sik Lee "*The Characteristics of Insulation with Temperature Variations of SF_6* " KIEE Vol. 52C, No. 8, 2003.8.

[9] Frank M. White, "*Fluid Mechanics*", McGraw-Hill, 1995.8

[10] Kwang-Sik Lee, Eun-Hyuck Choi, "*The Positive Effect and the Breakdown Characteristics in SF_6 and LN_2*", KIEE Vol. 54C, No. 8, 2005, 8.

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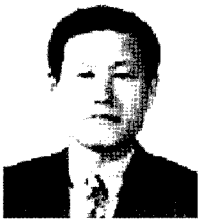

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