Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp328-332)

# Spark Discharge Characteristics of Various SF6-Based Binary Gases in Non-Uniform Fields

D. H. RHIE, H. J. SEO
The University of Suwon

***Abstract***

AC spark discharge voltage of $CO_2$, $N_2$, dry air, and mixtures of $SF_6/CO_2$and $SF_6/N_2$ containing various mixed rate in volume percent (1, 5 and 10%) of $SF_6$ in non-uniform fields are investigated. The electrode gap spacing was 5 and 10 mm, gas pressure was varied within the range of 0.1~0.7 MPa. The surface cleanness condition affects largely on the insulation properties of the gas mixtures particularly on the peak value of the breakdown voltages at lower gas pressures of 0.1~0.3 MPa range. The contaminated plane electrode shows much lower peak values of breakdown voltages than for the case of cleanly polished plane electrode. Moreover, the materials of the needle electrode affect the insulation properties of the gas mixtures drastically.

Keywords: SF6/buffer gas mixture, non-uniform field, insulation property, corona stabilization

## 1. INTRODUCTION

$SF_6$ is the most commonly used gas as insulation media for gas-insulated switchgears (GIS) due to its superior insulation properties such as high dielectric strength and arc quenching ability [1]. However, from the viewpoint of environmental aspects, since $SF_6$ is a potent greenhouse gas and its global warming potential (GWP) is estimated as an extent of 23,900 [2], its use and emission is requested to be strongly regulated. For decreasing the use of $SF_6$ gas, it is necessary to improve the design techniques to retrieve SF6 gas and reduce its emission into the atmosphere and develop alternative gases having much lower GWP values. Among these three kinds of measures, insulation characteristics of various kind of gas or gas mixture have been widely investigated for seeking an alternative to $SF_6$ [3].

It is well known that the insulation performance of $SF_6$ is limited, not by its uniform field dielectric strength, but by the effects of local field enhancement and in most typical industrial applications non-uniform field breakdown predominates. It is clear then that the requirement is not necessarily for a gas with superior uniform field dielectric strength, but rather for a gas or gas mixture which offers a significant improvement over $SF_6$ under the non-uniform field conditions associated with the presence of metallic particles or other stress raisers.

Obviously one of the desirable properties of a gaseous dielectric is high dielectric strength. The gas properties that are principally responsible for high dielectric strength are those that reduce the number of electrons which are present in an electrically-stressed dielectric gas. To effect such a reduction in the electron number densities, a gas should be (1) electronegative (remove electrons by attachment over as wide an energy range as possible) and (2) have a good electron slowing-down properties (slow electrons down so that they can be captured efficiently at lower energies and be prevented from generating more electrons by electron impact ionization) and (3) have low ionization cross section and high ionization onset (prevent ionization by electron impact).

Based upon research conducted world-wide over the last three decades or so [see, for example, Ref.1], it is known that mixtures of gases may be attractive for the following reasons; the best dielectrics are those that control electrons well at energies below the gas electronic excitation threshold energy, and the actual ionization process is apparently less important than the attachment process in preventing breakdown. In this respect, gas mixtures can be advantageous since no one gas attaches electrons well for all the energies of the electrons present. For all attaching gases, attachment becomes more difficult at high electron energy, so that gas components are included which can remove energy from electrons escaping the low energy attachment range, returning them to the energy region where attachment is more effective and away from the ionization threshold. It is generally accepted that binary mixtures should be coupled with one gas that primarily de-energizes free electrons and other gas that removes free electrons from the dielectric by electron attachment. Currently, $N_2$, $O_2$, CO and $CO_2$ are known as typical electron retarding gases in which fast electrons can be slowed and the electron energy can be reduced. The role of these electron retarding gases is to de-energize electrons reaching higher energies and return them to the lower energy range where attachment is by the electronegative gas is most effective.

From a practical point of view, only $SF_6$ mixtures with those buffer gases show promise for industrial application. The most desirable SF6 alternative would be a gas that could be put in all existing $SF_6$-equipment, requiring little or no change in hardware, procedures or ratings. Such a gas is referred to as a universal-application gas and it is defined as a gaseous medium which can be used instead of pure $SF_6$ in existing equipment without significant changes in practice, operation, or ratings of the existing gas-insulated apparatus.

Up-to-now, $SF_6/N_2$ mixtures seem to be the most thoroughly characterized gaseous dielectric media besides pure $SF_6$ [4, 5]. So there is broad acceptance of the view that these mixtures may be good replacements of pure $SF_6$. The main reasons are: (1) they perform rather well for both electrical insulation applications and in arc interruption equipment, (2) they have lower dew points and certain advantages especially under non-uniform fields over pure $SF_6$, (3) they are much cheaper than $SF_6$ especially after the recent large increases in the price of $SF_6$, and (4) industry has some experience with their use.

Apart from the above mentioned $SF_6/N_2$ mixtures, $SF_6/CO_2$ mixtures also expected to be quite promising substitute to pure $SF_6$, especially in highly non-uniform fields and in a gas-impregnated film insulation system encountered in the case of GIT [6]. Furthermore, it is known that the $SF_6$/air mixture has a higher impulse ratio than pure $SF_6$ in highly non-uniform fields [7], and therefore it is expected as an ideal substitute for $SF_6$ in C-GIS.

## 2. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows a schematic diagram of the experimental test chamber for measuring the insulation properties of gaseous dielectric media [8]. Non-uniform fields are formed with a needle to a plane electrode with gap lengths of 5 and 10 mm. In this experiment, the needles are prepared with three different kinds of steel materials, such as mild steel, SUS and high carbon steel and the tip radius of the needle are about 0.4~0.5 mm. Figure 2 shows the shapes of the needles.

The tested gaseous dielectric media are unitary gases of $CO_2$, $N_2$, Air and $SF_6$, and binary gases of $SF_6/N_2$, $SF_6/CO_2$ in a mixture ratio of 1~10% of SF6. The mixture rates for each gas are determined by the gas pressure ratio at room temperature and the maximum gas pressure is 0.7 MPa. The mixture gas is used for experiments left for 24 hours after mixing.

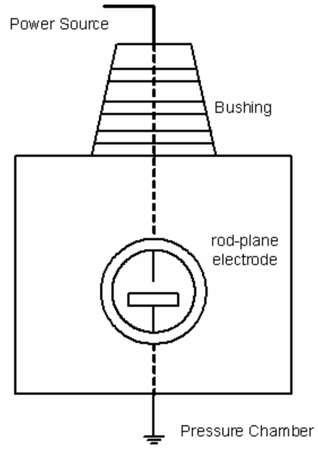

**Fig. 1 The experimental test chamber.**

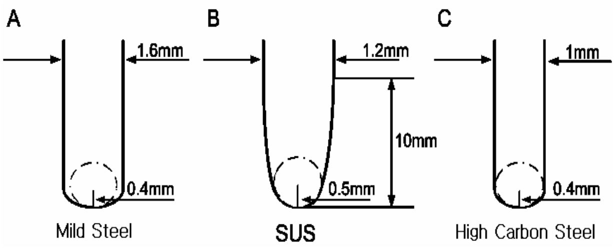

**Fig. 2 The shapes of the tested needle electrodes.**

Figure 2 shows the shapes of each tested needle electrode and its material, such as type A is mild steel, type B is SUS and type C is high carbon steel.

Partial discharge inception voltage $V_{PD}$ and spark (breakdown) voltage $V_{BD}$ are measured by applying an ac voltage at 60 Hz to the needle electrode. To measure the breakdown voltage, we connect the plane electrode directly with the earth to protect the electronic components.

## 3. RESULTS AND DISCUSSION

### 3.1 Insulation properties of unitary gas

Figure 3 shows gas pressure dependence of spark voltage for each tested buffer gas for gap length of 0.5 cm with type A needle electrode. It can be seen that the spark voltage of each buffer gas has similar ac breakdown characteristics up to 0.7 MPa, though there is slight higher values for $CO_2$ at relatively lower pressure region (0.2~0.3 MPa) than Air and $N_2$ and a little lower breakdown voltage for $N_2$ at relatively higher pressure region (0.5~0.7 MPa) than Air and $CO_2$.

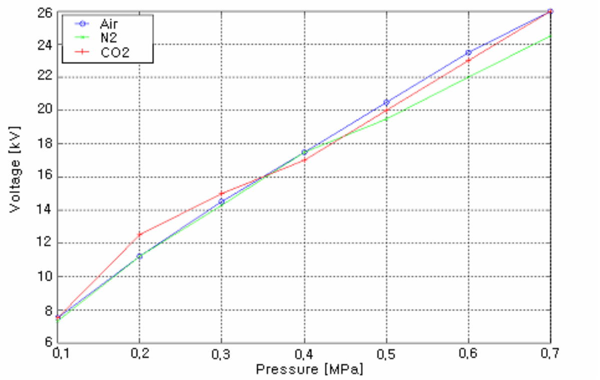

**Fig. 3 Gas pressure dependence of spark voltage for each tested buffer gas.**

### 3.2 Insulation properties of gas mixtures

Figure 4 shows spark voltage characteristics of $CO_2$ and $SF_6$ gas mixtures as a function of gas pressure using a type A needle electrode having gap length of 10 mm. From the figure, it is seen that the N-characteristics

typical of a needle-to-plane geometry have been appeared with relatively small amount of SF6 addition of 1~10% in volume ratio in $SF_6/CO_2$ gas mixtures.
This N-characteristic is explained by the redistribution of the field in the gap caused by space-charge accumulation, and has been referred to as ‘corona stabilization’. At the lower gas pressures, where corona discharge occurs at voltages lower than the breakdown value, the pre-breakdown current flowing in the gap produces space charges which tend to make the field more uniform, and the voltage required to cause breakdown of the gap is therefore increased. At higher gas pressures, above that corresponding to the voltage peak, it would appear that as soon as a streamer is formed at the point the voltage is sufficient to enable the propagation of the streamer across the gap. Breakdown consequently occurs before space charges can accumulate in the gap and affect the field distribution; under such conditions no steady corona discharge is observed to precede breakdown. This corona stabilization is largely absent or minimal for non-electronegative gaseous dielectrics such as $N_2$. Whereas it was pointed out recently [9] that under some conditions corona discharges produce electronically excited molecules in sufficient numbers to contribute to an enhancement in the breakdown voltage. This can happen because electrons are known [10] to attach to molecules in electronically excited states with higher probability, i.e., with larger cross sections, than to molecules in the ground electronic state.

In figure 4, it is noticeable that the peak of breakdown voltage for the case of $10\%SF_6/90\%CO_2$ reveals lower values that that of $1\%SF_6/99\%CO_2$ and $5\%SF_6/95\%CO_2$ gas mixtures. As stated below, seems due to the surface conditions of the plane electrode which may be contaminated by the flash-over across the gap.

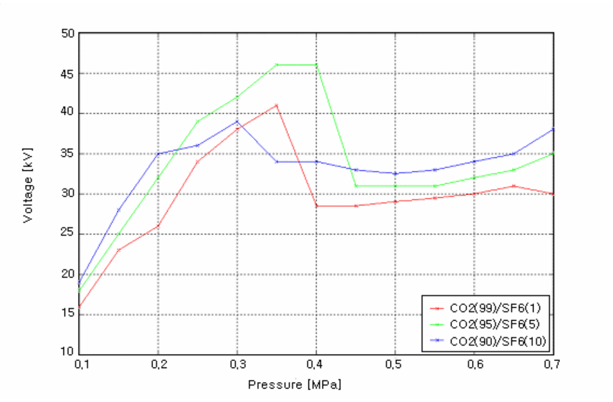

**Fig. 4 Gas pressure dependence of spark voltage for $SF_6/CO_2$ mixtures.**

Figure 5 shows the gas pressure dependence of spark voltages for the $SF_6$ and $N_2$ gas mixtures using a type A needle electrode. The result reveals the same N-characteristic as that of figure 4, but unlike the results of figure 4, in which the peak breakdown voltages appear at the pressure range of 0.3~0.4 MPa, the results indicate that the peaks of breakdown voltages of the $SF_6/N_2$ mixtures appear around the pressure range of 0.3 MPa. And also the peak breakdown voltage for the case of $90\%N_2/10\%SF_6$ has the highest value with regard to others, such as $95\%N_2/5\%SF_6$ or $99\%N_2/1\%SF_6$ gas mixtures. But the peak value of the breakdown voltage for the $5\%SF_6/95\%N_2$ gas mixture reveals somewhat lower than that of $1\%SF_6/99\%SF_6$ gas mixture.

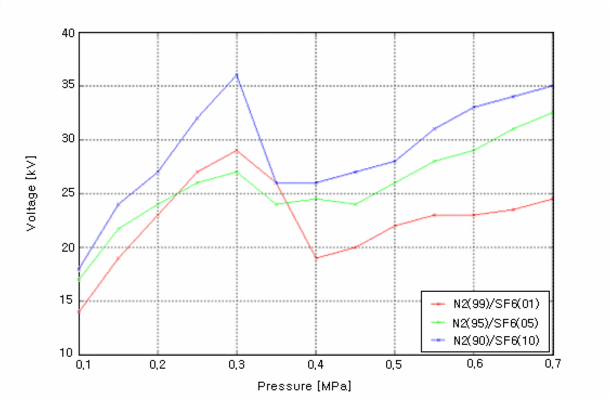

**Fig. 5 Gas pressure dependence of spark voltage for $SF_6/N_2$ mixtures.**

In figure 6, we depict the effect of electrode surface conditions affecting the breakdown characteristics of $SF_6$ and $N_2$ gas mixtures. These data are obtained from the case of plane electrode contaminated with several times of flash-over across the gap. Comparing to the results of figure 5, it seems that the peak values of the breakdown voltages for all gas mixtures are lower than that of cleanly polished plane electrode. Especially, for the case of $1\%SF_6/99\%N_2$ gas mixture, it reveals only barely perceivable N-characteristics. This shows that the corona stabilization may be weakened by the contaminated plane electrode surface.

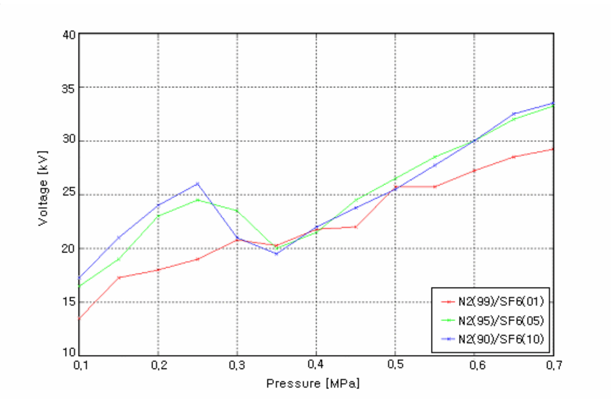

**Fig. 6 Gaspressure dependence of spark voltage for $SF_6/N_2$ gas mixtures with contaminated plane electrode surface.**

From the results of figure 6, we assume that the peak values of the breakdown voltages are greatly influenced by the surface conditions of the plane electrode. So the relatively lower peak values of the breakdown voltages for the case of 10%$SF_6$/90%$CO_2$ than 1%$SF_6$/99%$CO_2$ or 5%$SF_6$/95%$CO_2$ in figure 4 and the case of 5%$SF_6$/95%$N_2$ than 1%$SF_6$/99%$N_2$ in figure 5 are due to the surface contamination of the plane electrode.

Figure 7 shows the breakdown voltage (BDV) and partial discharge inception voltage (PDIV) characteristics of the $SF_6$ and $N_2$ mixtures for the case of type C (high carbon steel) needle electrode with mixing rate of 1% and 5% of $SF_6$, respectively. In this result, the peak breakdown voltage appears around pressure level of 0.35 MPa and the breakdown voltages at higher gas pressures reveals relatively lower values than that of type A (mild steel) needle electrode with comparing to the results of figure 5.

And at higher pressures, the breakdown voltages and partial discharge inception voltages for each gas mixtures of 99%$N_2$/1%$SF_6$ and 95%$N_2$/5%$SF_6$ are approximately well coincide with each other, though there seems somewhat a little deviation may be looked.

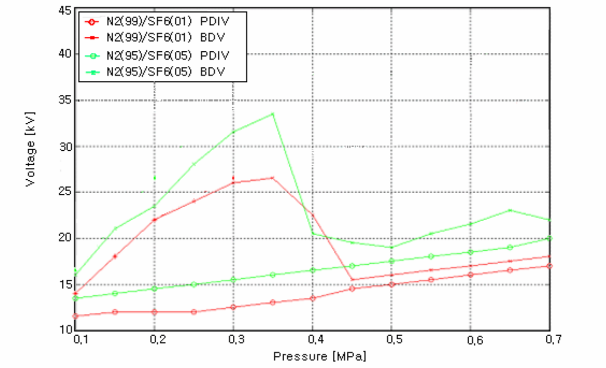

**Fig. 7 Breakdown voltage and partial discharge inception voltage characteristics for the $N_2$/$SF_6$ gas mixtures with type C electrode.**

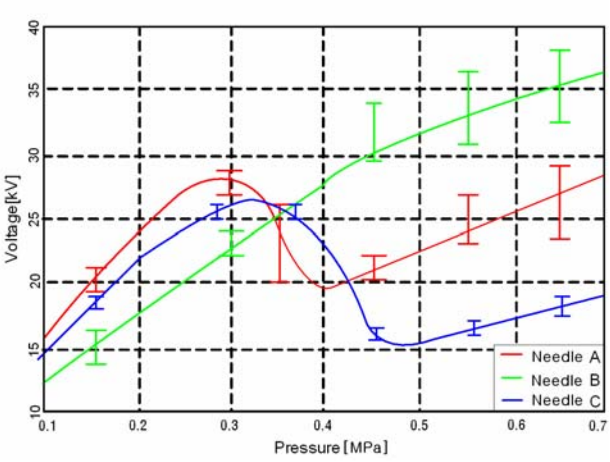

**Fig. 8 Effects of needle materials on the breakdown characteristics of 1%$SF_6$/99%$N_2$ gas mixtures.**

Figure 8 shows the effect of needle electrode on the spark voltage of $N_2$/$SF_6$ gas mixture containing 1% of $SF_6$ in volume ratio with gap length of 10 mm. From this figure, it can be seen that the mild steel needle and high carbon steel needle have similar characteristics, though the spark voltages at higher pressure region (0.4~0.7 MPa range) are somewhat different, but the SUS electrode reveals no N-characteristics typical for the electronegative gases such as SF6. It is noticeable that the appearance of the breakdown voltage characteristics for the type A and C needle electrodes looks similar the values of the breakdown voltage at higher pressures are different pretty well. Even though these results were obtained from the repeated experimental data, it should be thought twice to conclude that the materials of needle electrodes have a striking effect to breakdown characteristics of the dielectric properties of gases.

## 4. CONCLUSIONS

We experimentally investigated the effects of adding $CO_2$ and $N_2$ to $SF_6$ gas on insulating properties under a non-uniform field, changing the mixture ratio of $N_2$ and $CO_2$ and the gas pressure up to 0.7 MPa. And also we investigated the effect of surface cleanness of the plane electrode affecting insulation properties for the $SF_6$/$N_2$ gas mixtures. Moreover, we investigated the effect of needle materials such as mild steel, SUS and high carbon steel affecting insulation properties of $SF_6$/$N_2$ gas mixtures. As a result, it is seen that the breakdown voltages for the buffer gases, such as air, $CO_2$ and $N_2$ are approximately the same with each other up to pressures of 0.7 MPa at gap length of 5 mm. And the conditions of surface cleanness of the plane electrode affect largely on the breakdown voltage of the gas mixtures, especially on the peak values of the N-characteristics of the insulation properties. Finally, the materials of the needle electrodes also affect the insulation properties of the gas mixtures. In contrast to the results for the mild steel and high carbon steel needles, there are no N-characteristics for the SUS needle electrode typical for gaseous dielectrics having electronegative components. But, it should be noted that the effect of needle materials on the insulation properties of the SF6/buffer gas mixtures should be investigated further hereafter.

## 5. ACKNOWLEDGMENTS

This work has been supported by EESRI(R-2005-B-142), which is funded by MOCIE(Ministry of commerce, industry and energy) of Korea.

## 6. REFERENCES

[1] Christophorou LG, Van Brunt RJ, $SF_6$/$N_2$ Mixtures, Basic and HV Insulation Properties. IEEE Trans. on DEI, 1995; 2(5): 952-1003.

[2] Boeck W, Situation and Treatment of Environmental $SF_6$ Problems in Germany. In: Insulating Gases Meeting, CIGRE D1 WG03, Nagoya,

[3] Chalmers ID, Qiu XQ, Coventry P, The Study of $SF_6$ Mixtures with buffer gases. In Gaseous Dielectrics , New York, 1998: 189-195.

[4] Yamada T, Takahashi T, Toda T, Okubo H, Partial Discharge and Breakdown Characteristics in Different Gas Mixtures. T.IEE Japan, 1998;118-B(7/8): 831-836

[5] Christophorou LG, Olthoff JK, Green DS, Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure $SF_6$. NIST Technical Note, November, 1997

[6] Qiu Y, and Xiao DM, Investigation of SF6-N2, $SF_6$-$CO_2$ and $SF_6$-Air as Substitutes for SF6 Insulation. In: Conference Record of the 1996 IEEE International Symposium on Electrical Insulation, Montreal, Quebec, Canada, June, 1996.

[7] Qiu Y, and Xiao DM, Breakdown of $SF_6$-Air Mixture in Non-Uniform Field Gaps under Lightning Impulse Voltages. In: Proceedings of 10th International Conference on Gas Discharge and Their Applications, 1992: 1, 398-401

[8] Ohtsuka S, Nagara S, Miura K, Nakamura M, and Hikita M, Effect of Mixture of a Small Amount of $CO_2$ in $SF_6/N_2$ Mixed Gas on the Insulation Performance under Nonuniform Field. In: Proceedings of the 2000 IEEE ISEI, 2000: 288-291

[9] Pinnaduwage LA, Christophorou LG, A Possible New Mechanism Involved in Non-Uniform Field Breakdown in Gaseous Dielectrics. In: Gaseous Dielectics , Plenum Press, NY, pp.123-130, 1994

[10] Christophorou LG, Van Brunt RJ, and Olthoff J, Electron Attachment to Excited Molecules. In: Proceedings of 11th International Conference on Gas Discharges and Their Applications, Tokyo, Japan, September 10-15, 1995