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Effect of Multi-Contaminating Particles on Breakdown Voltage of Mixture Gases inside GIS

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***Abstract* - SF_6 gas insulated switchgear plays an important role in electric power networks all over the world due to its merits as compared to traditional air insulated switchgear. According to a numerous studies, it appears very difficult that any pure gas can bring a solution to the issue of desirable insulation ability and low environmental impact, so the mixtures composed of a strongly electronegative gases with high dielectric strength such as SF_6 and ordinary gas (N_2, CO_2, or Air) are used to reduce the gas price and liquefaction temperature. From this point of view, various types of gas mixtures are used inside gas insulated switchgear (GIS) and gas insulated lines (GIL) to give a higher dielectric strength with lower cost and lower environmental impact. In this paper, the Finite Elements Method (FEM) is used to evaluate the potential and electric field distributions on and around multi contaminating particles. Two cases are studied in this work, the first is that there are three contaminating particles rested at ground plate, and the second case is that there are two particles, one of them is rested on the ground plate and other is hovering inside the gap between two parallel plates. The effect of spacing between the particles on the electric field values is studied. The breakdown voltage calculations under uniform field in case of clean gap and non-uniform field in case of gap with multi-particles contamination are studied. The effect of gas pressure, SF_6 gas concentration in mixture and the spacing between particles on the breakdown voltage calculations are also studied.**

Index Terms - mixtures; GIS; FEM; particles; breakdown.

I. Introduction

SF_6 has been widely used as insulation media for gas insulated switchgear (GIS) and gas insulated transmission line (GIL), due to its excellent insulation and arc quenching properties. Although the SF_6 gas has superior dielectric properties, SF_6 gas has become an issue of environmental influence due to its high global warming potential (GWP=23900). Thus the development of an alternative gas or gas mixtures having much lower GWP is strongly required. Mixtures composed of a strongly electronegative gas of high dielectric strength such as SF_6 and an ordinary gas (N_2, CO_2 or air) are used.

The presence of contaminating particles lowered the dielectric strength of the gas mixtures sharply. Many studies were carried out theoretically to determine the role of single contaminating particles in initiating breakdown in gaseous insulation [1-3]. This work considered a multi-particle contamination in the gas mixture which is very limited in the published researches. The determination of the breakdown voltage in the gas requires the knowledge of the potential and field distribution on and around the charged particle surface. So in this paper, the electric potential and field distribution are studied between two parallel plates with multi-particles contamination when it rested on the earthed plate and hovering in the gap. The finite element method (FEM) has been used throughout the calculations in this work, for its favorable accuracy, when applied to high voltage problems.

II. Electric Field Calculations for Multi-particles Contamination

The electric field is calculated using the Finite Element Method (FEM) throughout this work. The Finite Element Method Magnetics (FEMM) Package is used to simulate the problems and to calculate the electric field inside the GIS. FEMM is a finite element package for solving 2D planar and axi-symmetric problems in electrostatics and in low frequency magnetic fields [4].

The FEMM Version 4.2 is used throughout the work in this paper for computation the electric field distributions around multi-contaminating particles. The voltage on the upper plate of the configurations considered is taken as 1V, For any applied voltage the values of the electric fields can be proportioned.

A. Modeling of Two Vertical Particles Located inside the Gap

Two conducting particles of length (L) and radius (r) are located inside the gap between two parallel plates. One of them is rested on the earthed plate and other is hovering in the gap as shown in Fig.1. Assume that the hovering particle has floating potential (i.e the total charge on the particle surface is equal to zero) where the hovering particle charge is lost by partial discharge effect. Particle length and hemispherical radius are taken as 2mm and 0.2mm respectively. The gap (G) between the plates is taken as 20mm.

Where E1 is the electric field at upper tip of earthed particle and E2;E3 are the electric fields at lower and upper tip of hovering particle, respectively.

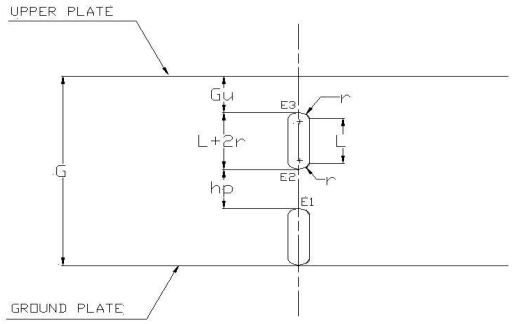

Fig. 1 Two parallel plates configuration with two wire particles located inside the gap.

1) For 1mm spacing between the two particles

Fig. 2 shows the electric field distribution along the gap between the two parallel plates, with two wire contaminating particles placed vertically in the gap. Assume that the hovering particle has floating potential (i.e the total charge on the particle surface is equal to zero) where the hovering particle charge is lost by partial discharge effect. It can be observed that the electric field is maximum value at the upper tip of the earthed wire particle.

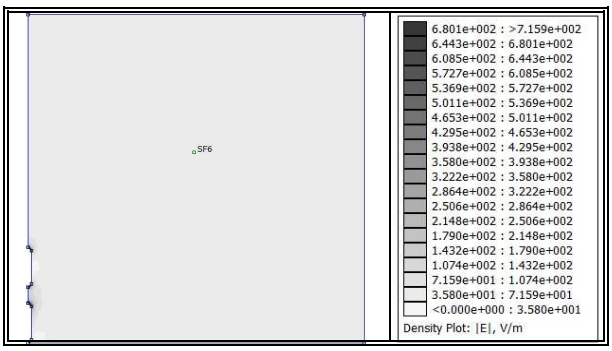

Fig. 2 Electric field distribution along the gap between two parallel plates with two wire contaminating particles.

2) Effect of spacing between two particles on the electric field

Fig. 3 shows the effect of the spacing between the two particles on the electric field values. It is observed that as the spacing between the two particles increases, from 1mm to 9mm, the electric field at the upper tip of the earthed particle decreases from about 707.7V/m to about 653.8V/m. The electric field at the lower tip of the hovering particle decreases also from about 486.7V/m to about 397.6V/m. Also, the electric field at the upper tip of the hovering particle is decreased from about 430.6V/m to about 404V/m.

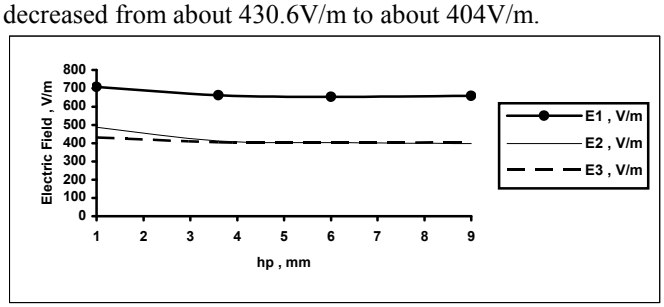

Fig. 3 Maximum Electric field versus spacing between the two particles.

B. Modeling of Three Vertical Particles Rested on The Earthed Plate

Fig. 4 shows three conducting particles are similar in length (L) and radius (r) and it rested on the earthed plate. Particle length and hemispherical radius are taken as 2mm and 0.2mm respectively. The gap (G) between the plates is taken as 20mm. Where E1 is the electric field at upper tip of the middle particle and E2 is the electric field at upper tip of the outermost particles.

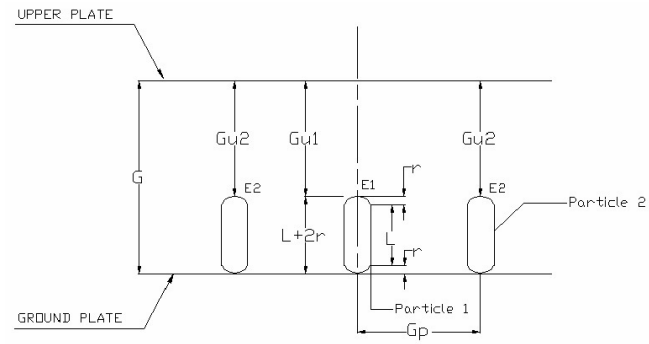

Fig. 4 Two parallel plates configuration with three wire particles rested on the earthed plate.

1) For 2mm Spacing between particles

Fig. 5 shows the electric field distribution along the gap between the two parallel plates with the three wire contaminating particles. It can be observed that the electric field is maximum value at the upper tip of the middle particle.

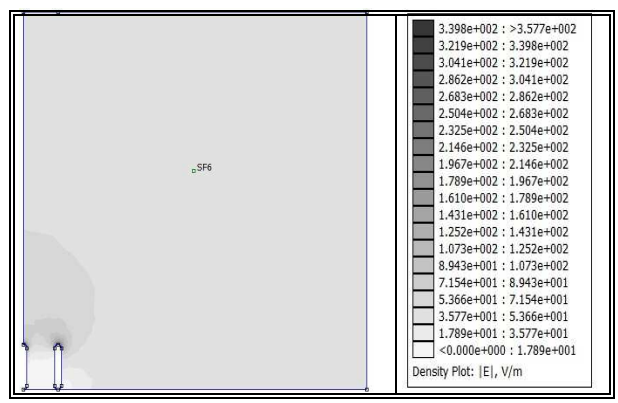

Fig. 5 Electric field distribution along the gap between the two parallel plates with the three wire contaminating particles.

2) Effect of spacing between particles on the electric field

The effect of spacing between particles on the electric field values is shown in Fig. 6. The electric field on the upper tip of the middle particle is greatly affected by the distance between the particles. The electric field on the upper tip of the middle particle is increased rapidly by increasing the distance between the particles, while the maximum value of the electric field of the outermost particles are slightly decreased by increasing the distance between the particles. The electric field on the upper tip of the middle particle is increased by about 200% as the distance between particles increases from 1mm to 10mm.

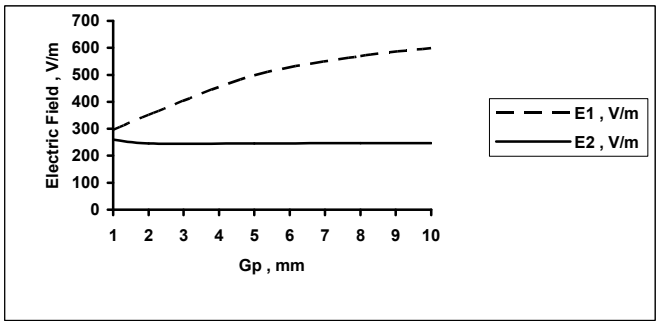

Fig. 6 The maximum electric field versus spacing between particles.

III. Ionization Coefficients for SF_6-gas mixtures

In order to compute the breakdown voltages of SF_6 - gas mixtures, a knowledge of the effective ionization coefficient $\bar{\propto} = \alpha - \eta$ as a function of the electric field intensity (E) in the neighborhood of $\bar{\propto} = 0$ is a prerequisite. The net ionization coefficients for SF_6 –gas mixtures $(\bar{\propto})_{mix}$ can be calculated from the values of $\bar{\propto}$ in pure gases. For pure Nitrogen the net ionization coefficients $\bar{\propto}$ can be approximated by [5];

$$\frac{\bar{\propto}}{P} = 66\exp\left[\frac{-2.15}{E/P}\right] \tag{1}$$

The measurements of the effective ionization coefficient $\bar{\propto}$ for CO_2 has been summarized by Rein and can be approximated by the following equations [6] :

$$\frac{\bar{\propto}}{P} = 176.5\exp\left[\frac{-2.565}{E/P}\right] \quad \textit{for } 0.2<=E/P<=0.28 \tag{2}$$

$$\frac{\bar{\propto}}{P} = 50.3\exp\left[\frac{-1.515}{E/P}\right] \quad \textit{for } 0.28<E/P<=100 \tag{3}$$

For air, the ionization coefficients can be approximated by [7],

$$\frac{\bar{\propto}}{P} = 22(E/P - 0.244)^2 \quad \textit{for } 0.244<E/P<=0.5 \tag{4}$$

$$\frac{\bar{\propto}}{P} = 15.8114(E/P - 0.244)^{1.75} \quad \textit{for } 0.5<E/P<=1.2 \tag{5}$$

For pure SF_6, $\bar{\propto}/P$ can be expressed as [8],

$$\frac{\bar{\propto}}{P} = 27(E/P - 0.8775) \tag{6}$$

In Eqs. (1) through (6) , P is the gas pressure in kPa , $\bar{\propto}/P$ is given in $(cm.kPa)^{-1}$ and E/P has the units of $kV(cm.kPa)^{-1}$.

For a given SF_6-gas mixture, the effective ionization coefficient is assumed to be given by :

$$(\bar{\propto}/P)_{mix} = F(\bar{\propto}/P)SF_6 + (1-F)(\bar{\propto}/P)_{gas} \tag{7}$$

where, $F = P(SF_6) / P(mix)$ is the partial pressure ratio of the SF_6 component in a given gas mixture.

When added two electronegative gases to SF_6-gas mixture, the effective ionization coefficient is assumed to be given by :

$$(\bar{\propto}/P)_{mix} = F_1(\bar{\propto}/P)SF_6 + F_2(\bar{\propto}/P)_{gas1} + F_3(\bar{\propto}/P)_{gas2} \tag{8}$$

where, $F_1 = P(SF_6) / P(mix)$ is the partial pressure ratio of the SF_6 component in a given gas mixture, $F_2 = P(gas_1) / P(mix)$ is the partial pressure ratio of the first electronegative gas in a given gas mixture and $F_3 = P(gas_2) / P(mix)$ is the partial pressure ratio of the second electronegative gas in a given gas mixture.

IV. Methodology for Breakdown Voltage Calculations

In order to study the breakdown voltages for a particle which is represented by a hemi-spherical tip with diameter (2r) and length (L) which is contaminating a parallel-plane gap with spacing (G) for SF_6 - gas mixture under DC voltage. The electric field around particles is satisfied in this work by using finite element method.

With an applied electric field, discharges in the gas occur as a result of ionization, which lead to streamer formation and ultimately to breakdown of the gas mixture. One way to predict breakdown voltage of the gas mixture is, therefore, by knowing its effective ionization coefficient.

In a non-uniform field gap, corona discharges will occur when the conditions for a streamer formation in the gas are fulfilled. Streamer formation is both pressure and field dependent, and therefore depends on the electrode profile, geometry of the contaminating particle, its position in the gap between electrodes if it is free, and on the instantaneous value of the ambient field. The condition for streamer formation is given by;

$$\int_0^{xc} \bar{\propto}(x)dx \geq K \tag{9}$$

Where, $\bar{\propto}(x) = \alpha(x) - \eta(x)$, $\alpha(x)$ and $\eta(x)$are the first ionization coefficient and the coefficient of attachment, respectively; both being functions of field and thus of geometry.

The distance (xc) from the particle's tip is where the net ionization is zero, normally known as the ionization boundary. There is some controversy over the value of K, the discharge constant. The value of K for pure gases in the pressure range of 100 to 400 kPa is obtained as follows using the breakdown data given in CIGRE paper [9];

K for pure N_2 is (5±0.5). Malik and Qureshi [10] assumed that K has a value in between 5 and 25 for the different SF_6 gas mixtures.

In this study for breakdown voltages we take the value of K = 18.42 for SF_6 gas and SF_6 - gas mixture but K=5 for N_2 gas and K=27 for CO_2 gas.

V. Breakdown voltage calculations for a uniform field gap

From Fig. 7 we see that, the breakdown voltage for (5%SF_6 +90%N_2+5%Air) is greater than (5%SF_6+90%CO_2+5%Air) by 21%. Also breakdown voltage for (80%SF_6+15%N_2+5%Air) is greater than (80%SF_6+15%CO_2+ 5%Air) by 2.3%.

In some cases, although breakdown voltage of (80%SF_6+ 15%N_2 +5%Air) is greater than (5%SF_6+90%N_2+5%Air) but it is preferred to decrease the percentage of SF_6 in mixture to avoid high price and environmental impact of SF_6 gas.

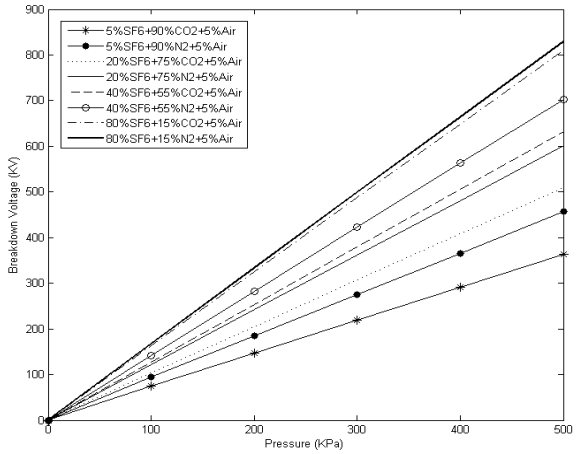

Fig. 7 Effect of gas pressure for SF_6:N_2:Air & SF_6:CO_2:Air mixtures on Breakdown Voltage for clean gap at G=20mm.

VI. Breakdown Voltage calculations for gas mixtures with particle contamination

In this section, the breakdown voltage will be calculated under the effect of two vertical particles contamination, located inside the gap between two parallel plates, one of them rested on the earthed plate and the other is hovering inside the gap. Also, the breakdown voltage will be calculated under the effect of three vertical particles contamination rested on the earthed plate.

A. Effect of two contaminating particles

The effect of fractional concentration of SF_6 gas in mixture under different gas pressure in the gap with two contaminating wire particles of length 2mm, hemispherical radius 0.2mm and height between them of 1mm is shown in Fig. 8. It can be observed that, if the fractional concentration of SF_6 gas in mixture increases, the breakdown voltage will be increased. Also, the breakdown voltage for mixture is increased as the pressure of mixture increases.

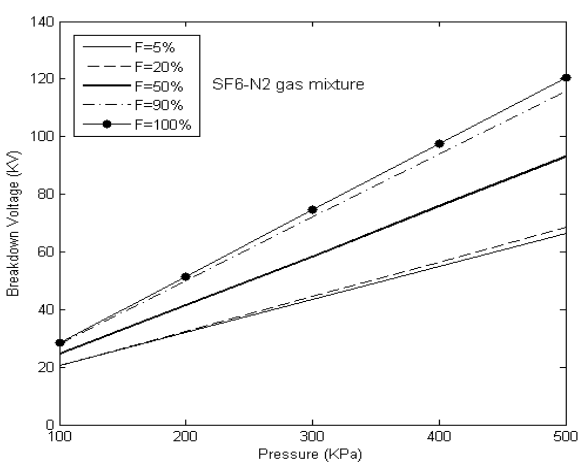

Fig. 8 Effect of gas pressure for SF_6-N_2 gas mixture on Breakdown Voltage

The effect of gas pressure on breakdown voltage values with a various gas mixtures is shown in Fig. 9. It can be observed that breakdown voltage for 5%SF_6-95%N_2 is greater than that of 5%SF_6-95%CO_2 which in turn is greater than that of 5%SF_6-95%Air.

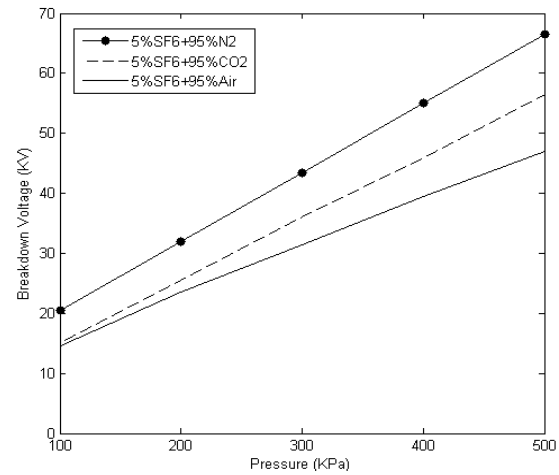

Fig. 9 Effect of gas pressure for 5%SF_6-gas mixture on Breakdown Voltage

1) Effect of height between two particles on Breakdown Voltage

Fig. 10 shows the effect of the height between the two particles on the breakdown voltage at 5% SF_6-gas concentration in mixture with a gas pressure of P=500kPa. It can be shown that the breakdown voltage is slightly increased as spacing between the two particles increases. Also it can be observed that the breakdown voltage of 5%SF_6-95%N_2 gas mixture is greater than that of 5%SF_6-95%CO_2 gas mixture.

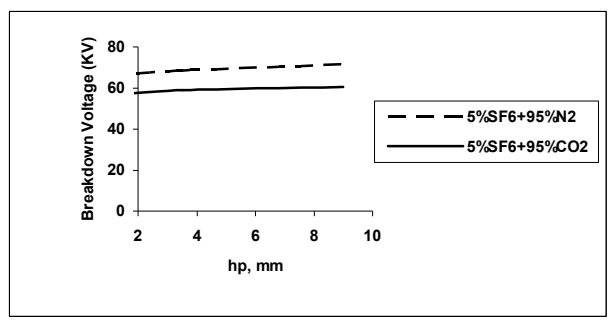

Fig. 10 The effect of the height between the two particles on the breakdown voltage.

B. Effect of three contaminating particles rested on the earthed plate

The effect of gas pressure on breakdown voltage values under different fractional concentrations of SF_6 gas in mixture with three wire contaminating particles of length 2mm, hemispherical radius 0.2mm and gap spacing between them of 2mm, rested on the earthed plate are shown in the Fig. 11. From the figure, it can be seen that, as the fractional concentration of SF_6 gas increases in mixture, the breakdown voltage will be increased. Also, the breakdown voltage for mixture is increased as the pressure of mixture increases.

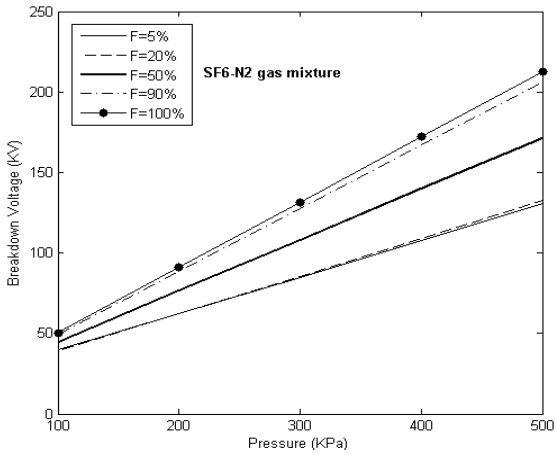

Fig. 11 The effect of gas pressure for SF_6-N_2 gas mixture on the breakdown voltage.

Fig. 12 shows the effect of the gas pressure on the breakdown voltage with a various gas mixtures. It can be observed that breakdown voltage of 5%SF_6-95%N_2 gas mixture is greater than that of 5%SF_6-95%CO_2 gas mixture, which in turn is greater than that of 5%SF_6-95%Air gas mixture.

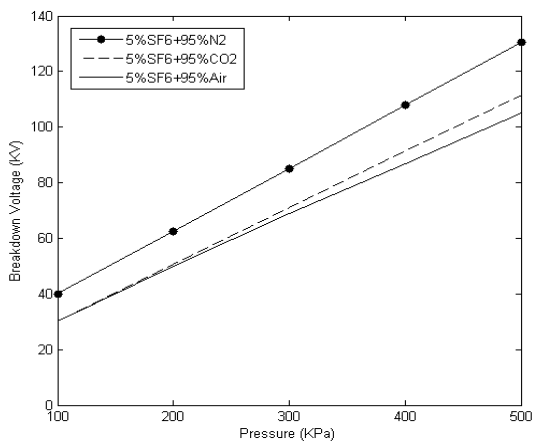

Fig. 12 The effect of gas pressure for 5%SF_6-gas mixture on the breakdown voltage.

1) Effect of Gap Spacing between particles on Breakdown Voltage

Fig. 13 shows effect of gap spacing between particles on the breakdown voltage with a various concentration of SF_6-gas in mixture at pressure of 500kPa. From this figure, it can be seen that the breakdown voltage decreases gradually as gap spacing between particles increases.

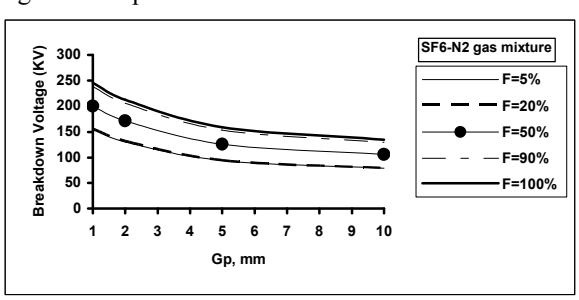

Fig. 13 The effect of spacing between particles on the breakdown voltage.

CONCLUSIONS

From this work, it can be concluded that the electric field is minimum value at lower tip of earthed wire particle and maximum value at upper tip of it in case of two wire particles in the gap, one of them rested on the earthed plate and the other is hovering inside the gap. The electric field decreases as the spacing between the two particles increases. For three contaminating wire particles rested on the earthed plate, the electric field is maximum at the upper tip of the middle particle. The electric field on the upper tip of the outermost particles is slightly decreased by increasing the distance between the particles for a certain gap spacing and after that it becomes approximately constant. The breakdown voltage increases as fractional concentration of SF_6 gas increases in mixture and it also increases as the pressure of mixture increases. The breakdown voltage for (5%SF_6-95%N_2) gas mixture is greater than that for (5%SF_6-95%CO_2) gas mixture which in turn it is greater than that for (5%SF_6-95%Air) gas mixture. The breakdown voltage increases as the spacing between the two particles increases. Finally, the breakdown voltage decreases as the gap spacing between three particles increases.

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