Multi-Particle Initiated Breakdown of Gas Mixtures inside Compressed Gas Devices

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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 gases (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 such as(5%SF_6+5%CO_2+90%Air), (5%SF_6+40%CO_2+55%Air),(5%SF_6+80%CO_2+15%Air),(5%SF_6 +5%N_2+90%Air),(5%SF_6+40%N_2+55%Air) and (5%SF_6+80% N_2+15%Air) are used inside compressed gas devices 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 electric field distribution on and around multi-contaminating filamentary wire particles. The effect of two contaminating particles which one of them is rested at ground plate and other is hovering inside the gap on the electric field values are studied. The effect of three contaminating particles which are rested at ground plate on the electric field values are also studied. The effect of gas pressure, SF_6 gas concentration in mixture, gap spacing and height between particles on the breakdown voltage calculations are also studied.

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. There is a small variation between 2-D and 3-D analyses, which confirms that 2-D analysis is sufficient to understand the behavior of metallic particles present in GIS [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.

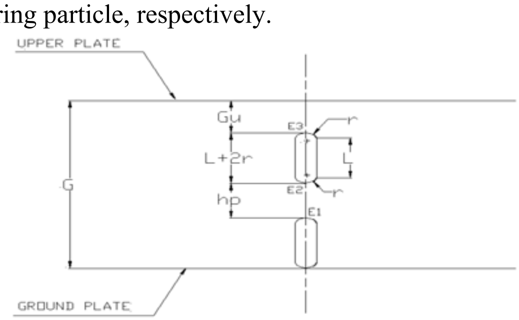

Fig. 1. Two parallel plates configuration with two wire particles located inside the gap

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. The spacing between the two particles is taken as 1mm. 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.

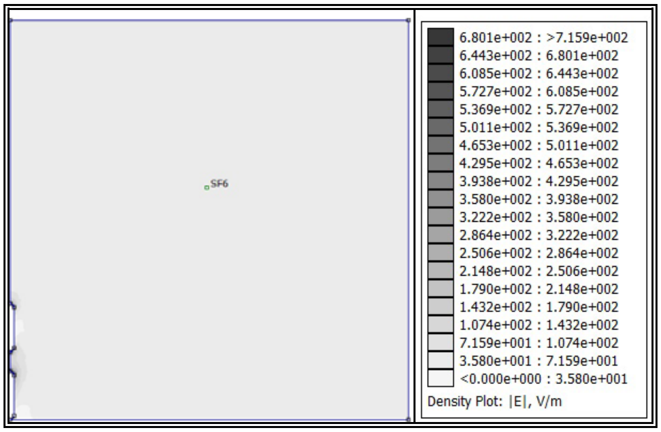

Fig. 2. Electric field distribution along the gap between two parallel plates with two wire contaminating particles

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.

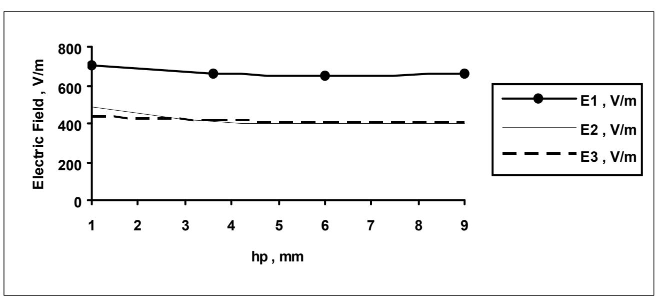

Fig. 3. Maximum Electric field versus spacing between the two particles

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

Fig. 4 shows three conducting particles of length (L) and radius (r) are 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.

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.

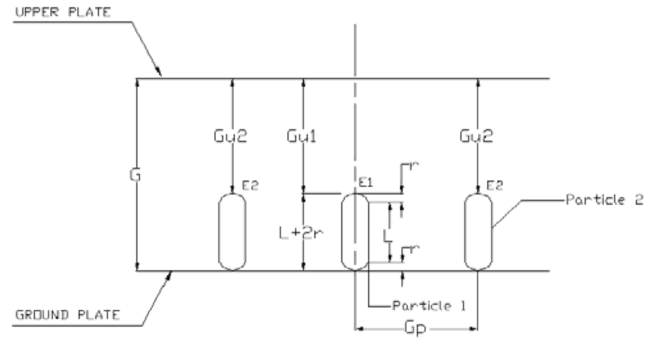

Fig. 4. Two parallel plates configuration with three wire particles rested on the earthed plate

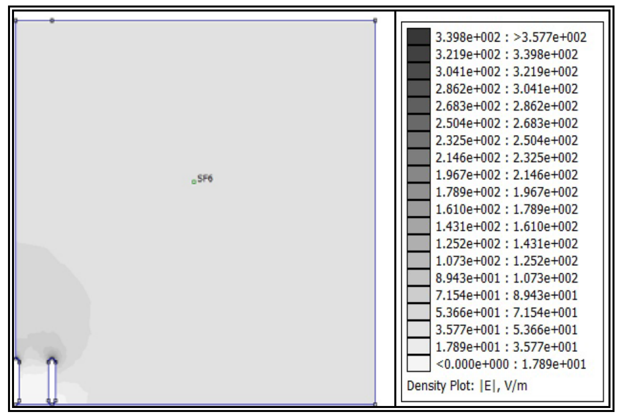

Fig. 5. Electric field distribution along the gap between the two parallel plates with the three wire contaminating particles

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

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

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

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

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

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

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

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

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

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

In Eqs. (1) through (6) , P is the gas pressure in kPa , $\overline{\propto}/P$ 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 :

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

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 :

$$(\overline{\propto}/P)_{mix}=F_1(\overline{\propto}/P)SF_6 + F_2(\overline{\propto}/P)gas_1 + F_3(\overline{\propto}/P)gas_2 \qquad (8)$$

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 SF6-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;

$$\int_0^{xc} \overline{\propto}(x)dx \geq K \qquad (9)$$

Where, $\overline{\propto}(x)=\alpha(x)-\eta(x)$, $\alpha(x)$ 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 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

Fig. 6 shows the effect of fractional concentrations for (SF_6,CO_2&Air) and (SF_6,N_2&Air) mixtures 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. It can be observed that the breakdown voltage for mixture is increased as the pressure of mixture increases. The breakdown voltage for (SF_6,CO_2&Air) mixture increases, if the fractional concentrations for CO_2 gas increases and for Air decreases with fixed fractional concentration of SF_6 gas. The breakdown voltage for (SF_6,N_2&Air) mixture increases, if the fractional concentrations for N_2 gas increases and for Air decreases with fixed fractional concentration of SF_6 gas.

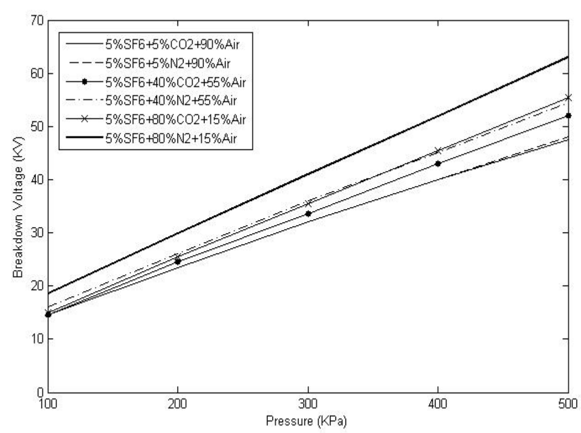

Fig. 6. Effect of gas pressure for various SF_6-gas mixtures on the Breakdown Voltage

Fig. 7 shows effect of the height between the two particles on the breakdown voltage with 5% SF_6-gas concentration in mixture at pressure of 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+80%N_2+15% Air) gas mixture is greater than that of (5%SF_6+80%CO_2 +15%Air) gas mixture.

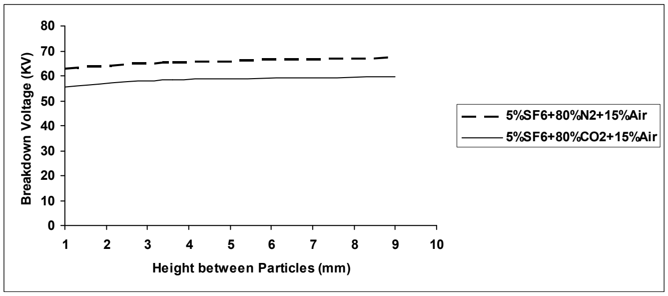

Fig. 7. Effect of the height between the two particles on the breakdown voltage

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

Fig. 8 shows the effect of fractional concentrations for (SF_6,CO_2&Air) and (SF_6,N_2&Air) mixtures under different gas pressure in the gap with three wire contaminating particles of length 2mm, hemispherical radius 0.2mm and gap spacing between them of 2mm, rested on the earthed plate. It can be observed that the breakdown voltage for mixture is increased as the pressure of mixture increases. The breakdown voltage for (SF_6,CO_2&Air) mixture increases, if the fractional concentrations for CO_2 gas increases and for Air decreases with fixed fractional concentration of SF_6 gas. The breakdown voltage for (SF_6,N_2&Air) mixture increases, if the fractional concentrations for N_2 gas increases and for Air decreases with fixed fractional concentration of SF_6 gas. It can be concluded that (5%SF_6+80%N_2+15%Air) mixture is considered the optimum gas mixture in this study for its higher breakdown voltage with lower cost.

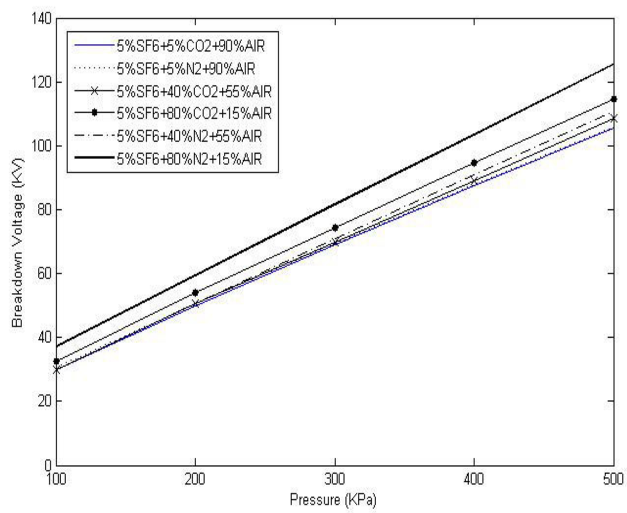

Fig. 8. Effect of gas pressure for various SF_6-gas mixture on the breakdown voltage

Fig. 9 shows effect of gap spacing between particles on the breakdown voltage with 5% SF_6-gas concentration 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 for a certain distance. Also it can be observed that the breakdown voltage of (5%SF_6+80%N_2+15% Air) gas mixture is greater than that of (5%SF_6+80%CO_2 +15%Air) gas mixture.

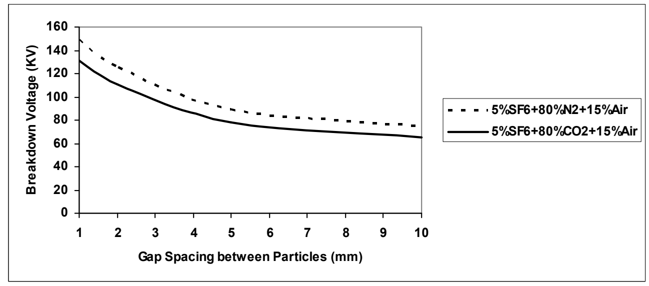

Fig. 9. The effect of spacing between particles on the breakdown voltage

CONCLUSIONS

From this work, it can be concluded that the breakdown voltage for mixture is increased as the pressure of mixture increases. The breakdown voltage for (SF_6,CO_2&Air) mixture increases, if the fractional concentrations for CO_2 gas increases and for Air decreases with fixed fractional concentration of SF_6 gas. The breakdown voltage for (SF_6,N_2&Air) mixture increases, if the fractional concentrations for N_2 gas increases and for Air decreases with fixed fractional concentration of SF_6 gas. The breakdown voltage increases as the spacing between the earthed particle and the hovering particle increases. The breakdown voltage decreases as the gap spacing between three earthed particles increases for a certain distance. (5%SF_6+80%N_2+15%Air) mixture is considered the optimum gas mixture in this study for its higher breakdown voltage with lower cost.

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