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# Effect of Coating of Earthed Enclosure and Multi-Contaminating Particles on Breakdown Voltage inside Gas Insulated Bus Duct

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**ABSTRACT**

Metallic particle contamination is one of the areas of insulation design that are considered critical. This paper demonstrates the control of metallic particles in gas insulated bus duct (GIBD) by using dielectric coating on the inside surface of the outer enclosure of a coaxial electrode system. Several models of GIBD with single and multi-contaminating particles will be studied. In this paper, the Finite Elements Method (FEM) is used to evaluate the electric field distribution on and around single and multi-contaminating wire particles which in contact with dielectric coating of earthed enclosure inside GIBD. The effect of changing the length and the radius of middle particle for multi-contaminating particles on the electric field values are studied. Breakdown Voltage calculations for gas mixtures with single and multi-contaminating wire particles are studied. The effects of gas pressure on the breakdown voltage for various fractional concentrations of $SF_6$-gas mixtures with and without particle contamination and also with and without coating of earthed enclosure are studied. The optimum gas mixture which gives higher dielectric strength with lower cost is also determined. The effect of coating thickness of earthed enclosure on the breakdown voltage for various fractional concentrations of $SF_6$-gas mixtures is also studied. Finally, the effect of length and hemi-spherical radius of multi-contaminating particles on the breakdown voltage with various $SF_6$-gas mixtures and varying gas pressure one time and another time with fixed pressure are studied.



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## 1. INTRODUCTION

Several numerical techniques have been increasingly employed to solve such practical problems since the availability of high performance computers [1, 2]. The advantage of the application of numerical methods has many advantages compared to analytical methods such as computable accuracy, simplicity and low cost.

The finite element method (FEM) is used in this paper for its favorable accuracy, when applied to high voltage problems.

## 2. ELECTRIC FIELD CALCULATIONS

FEM one of the efficient technique for solving field problems is used to determine the electric field distribution on the spacer's surface. FEM concerns itself with minimization of the energy within the whole field region of interest, whether the field is electric or magnetic, of Laplacian or Poisson type, by dividing the region into triangular elements for two dimensional problems or tetrahedrons for three dimensional problems. Under steady state the electrostatic field within anisotropic dielectric material, assuming a Cartesian coordinate system, and Laplacian field, the electrical energy W stored within the whole volume U of the region considered is [3,4]:

$$W = \frac{1}{2}\int_U \varepsilon \left| grad\ (V)\right|^2 dU \tag{1}$$

$$W = \frac{1}{2}\iiint_U \left[ \varepsilon_x \left(\frac{\partial V_x}{\partial x}\right)^2 + \varepsilon_y \left(\frac{\partial V_y}{\partial y}\right)^2 + \varepsilon_z \left(\frac{\partial V_z}{\partial z}\right)^2 \right] dxdydz \tag{2}$$

Furthermore, for GIS arrangement, when we consider the field behaviour at minute level the problem can be treated as two dimensional (2D). The total stored energy within this area-limited system is now given according to [3,4]:

$$\frac{W}{\varphi} = \frac{1}{2} * \varepsilon \iint \left[ \left(\frac{\partial V_x}{\partial x}\right)^2 + \left(\frac{\partial V_y}{\partial y}\right)^2 \right] dxdy \tag{3}$$

Where (W/φ) is thus an energy density perelementary area dA. Before applying any minimization criteria based upon the above equation, appropriate assumptions about the potential distribution V(x, y, z) must be made. It should be emphasized that this function is continuous and a finite number of derivatives may exist. As it will be impossible to find a continuous function for the whole area A, an adequate discretization must be made. So all the area under consideration is subdivided into triangular elements hence [3,4]:

$$\frac{W}{\varphi} = \frac{1}{2} * \varepsilon * \sum_{i=1}^{n} \left[ \left(\frac{\partial V_x}{\partial x}\right)^2 + \left(\frac{\partial V_y}{\partial y}\right)^2 \right] * A_i \tag{4}$$

Where n is the total number of elements and Ai is the area of the ith triangle element. So the formulation regarding the minimization of the energy within the complete system may be written as [3,4]:

$$\frac{\partial X}{\partial \{V(x,y)\}} = 0; \quad Where \quad X = \frac{w}{\varphi} \tag{5}$$

The result is an approximation for the electrostatic potential for the nodes at which the unknown potentials are to be computed. Within each element the electric field strength is considered to be constant and the electric field strength is calculated as [3,4]:

$$\vec{E} = -\vec{I}\,\frac{\partial V(x,y)}{\partial x} - \vec{J}\,\frac{\partial V(x,y)}{\partial y} \tag{6}$$

The electric field is calculated with 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 gas insulated switchgear and gas insulated bus ducts as disscussed in this paper. FEMM is a finite element package for solving 2D planar and axi-symmetric problems in electrostatics and in low frequency magnetic [5].

The analysis in the paper is done by using two concentric cylinder of infinite length. The voltage on the inner conductor of GIBD considered is taken as 1V, For any applied voltage the values of the electric fields can be proportioned.

## 3. ELECTROSTATIC MODELING OF GIBD WITH PARTICLE CONTAMINATION AND DIELECTRIC COATING OF ENCLOSURE

The purpose of coating the inside surface of gas insulated bus duct (GIBD) enclosure with a dielectric material reduces the deleterious effect of electrode surface roughness, increases the field required to lift particles, and reduces the charge acquired by particles.

Figure 1 shows Gas insulated bus duct with filamentary wire contaminating particle in contact with dielectric coating of earthed enclosure. In this figure, (t) is defined as dielectric coating thickness and it varies from 200micro-meter to 2000micro-meter. The dielectric material of coating can be epoxy, varnish or polymeric films.

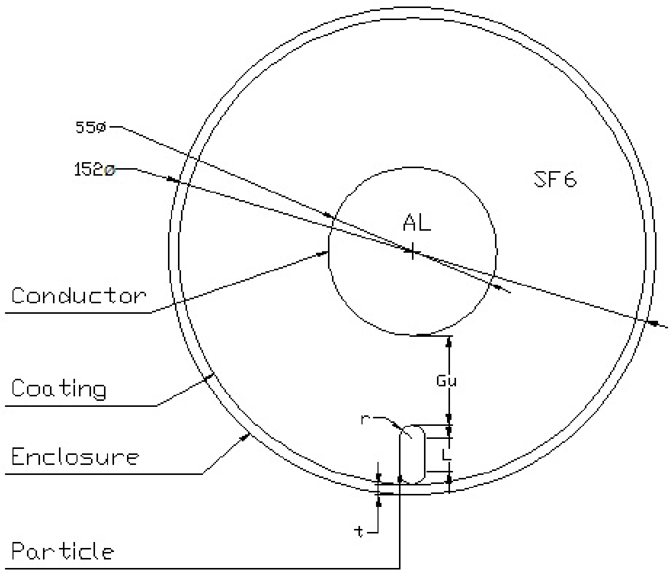


Figure 1. Gas insulated bus duct with filamentary wire contaminating particle in contact with dielectric coating of earthed enclosure

### 3.1. Effect of Dielectric Coating of Earthed Enclosure

The particle dimensions are taken as 10mm length and 0.5mm radius. The thickness of dielectric coating for earthed enclosure is taken as 2000 µm and epoxy material of relative permittivity ($\epsilon r$=4.5) is used for coating.

Figure 2 shows the electric field distribution along gap inside gas insulated bus duct with wire contaminating particle in contact with dielectric coating of earthed enclosure. It can be observed that the electric field is minimum value at lower tip of particle and maximum value at upper tip of it. The electric field decreases from upper tip of wire particle until it reaches a certain value but after that value, it returns to increase till reaches to a certain value 36V/m at inner conductor of gas insulated bus duct.

Figure 3 shows magnitude, normal and tangential components of electric field distribution along surface of wire particle. It can be observed that the tangential component of electric field is zero and the normal component of it increases gradually from zero until it reaches the maximum value at upper tip through negative side, so mathematically, the magnitude of electric field increases also from zero to 99.6V/m at upper tip of wire particle through positive side .

Figure 4 shows magnitude, normal and tangential components of electric field distribution along gap from upper tip of wire particle up to inner conductor of GIBD. It can be observed that normal component of electric field is zero. The tangential component and the magnitude of electric field is maximum value (≈99.6V/m) at upper tip of wire particle and decreases gradually along gap until it reaches a certain distance (7.8mm) from tip but after that value up to inner conductor, the electric field increases gradually until it reaches a certain value is about 36V/m.

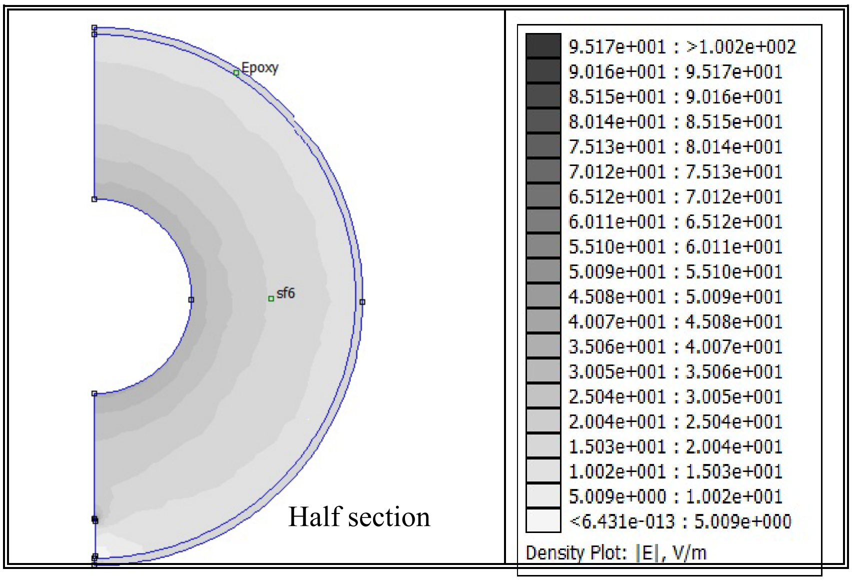


Figure 2. Electric field distribution along gap inside gas insulated bus duct with wire contaminating particle in contact with dielectric coating of earthed enclosure

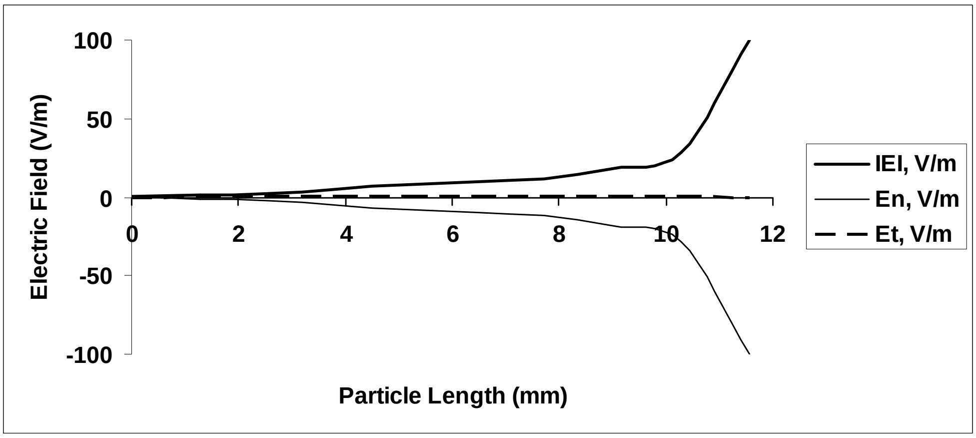


Figure 3. Electric field distribution along surface of wire particle

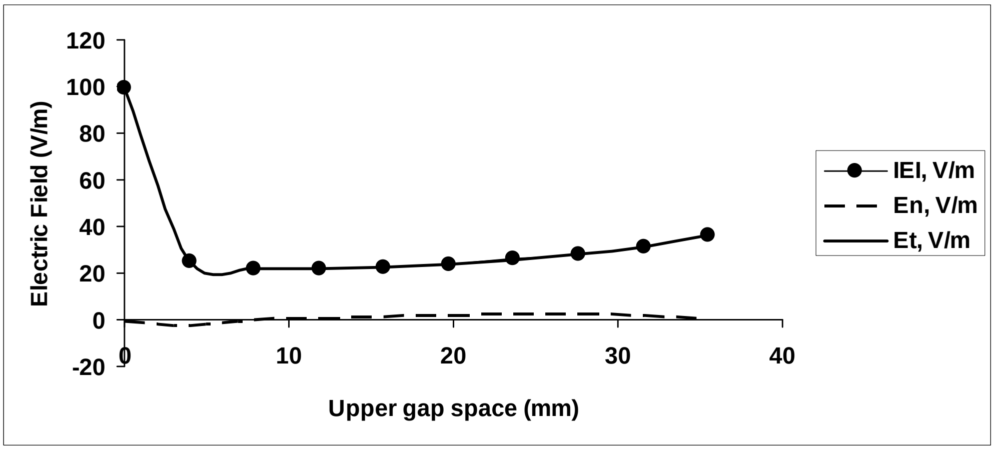


Figure 4. Electric field distribution along gap from upper tip of wire particle up to inner conductor of GIBD

## 4. MULTI-CONTAMINATING FIXED PARTICLES RESTED ON EARTHED ENCLOSURE

A study of CIGRE group suggests that 20% of failure in GIS is due to the existence of various metallic contaminations in the form of loose particles [6]. So, in this paper, we study the effect of multi-wire particles on the electric field.

Figure 5 shows Gas insulated bus duct with multi-wire contaminating fixed particles in contact with dielectric coating of earthed enclosure. The three wire contaminating particles are identical in length and radius. Consider that the middle particle length (L1) is taken as 5mm, outermost particles (L2) as 5mm and hemi-spherical radius of particles (r) are taken as 0.5mm. The spacing between middle particle and outermost particles is taken as 15mm. Gu1 is defined as upper gap space from upper tip of middle particle up to high voltage conductor and Gu2 is defined as upper gap space from upper tip of outermost particles up to high voltage conductor.

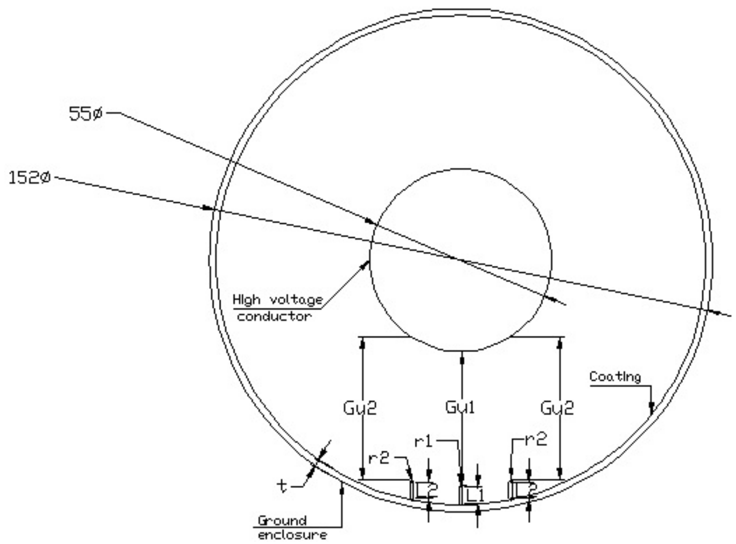


Figure 5. Gas insulated bus duct with multi-wire contaminating fixed particles in contact with dielectric coating of earthed enclosure

### 4.1. For Wire Particle of 5mm Length and of 0.5mm Radius

Figure 6 shows the electric field distribution along gap inside gas insulated bus duct with multi-wire contaminating particles resting on earthed enclosure. It can be observed that the electric field is minimum value at lower tip of middle and outermost particles and maximum value at upper tip of it but the maximum value of electric field at upper tip of outermost particles are slight increased from that at upper tip of middle particle. The electric field decreases from upper tip of wire particle till reaches a certain value but after this value, it returns to increase till reaches to the maximum value of electric field at inner conductor of GIBD in case of clean gap without any particle contamination.

Figure 7 shows electric field distribution along surface of middle and outermost particles. It can be observed that the electric field at upper tip of outermost particles is slightly greater than it at upper tip of middle particle and this is because the outermost particles which rested at ground enclosure is nearer to high voltage conductor than middle particle.

Figure 8 & Figure 9 show magnitude, normal and tangential components of electric field distribution along gap from upper tip of middle and outermost particles up to high voltage conductor. It can be observed that normal component of electric field is about zero and the tangential component of it decreases gradually from maximum value at upper tip of particle until it reaches a certain value but after that value, it returns to increase through negative side, so mathematically, the magnitude of electric field decreases gradually from 60.14V/m and 62.6V/m at upper tip of middle and outermost particles respectively until it reaches a certain value but after that value, it returns to increase as it approaches from high voltage conductor through positive side.

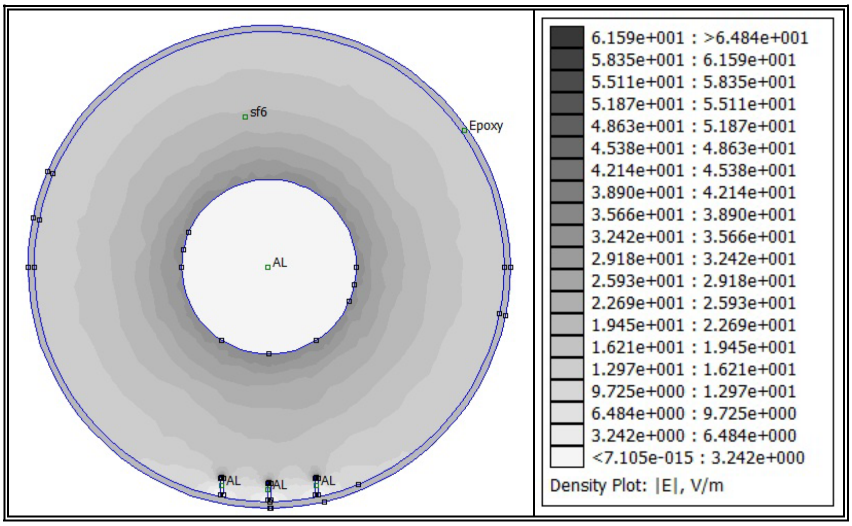


Figure 6. Electric field distribution along gap inside gas insulated bus duct with multi-wire contaminating particles resting on earthed enclosure

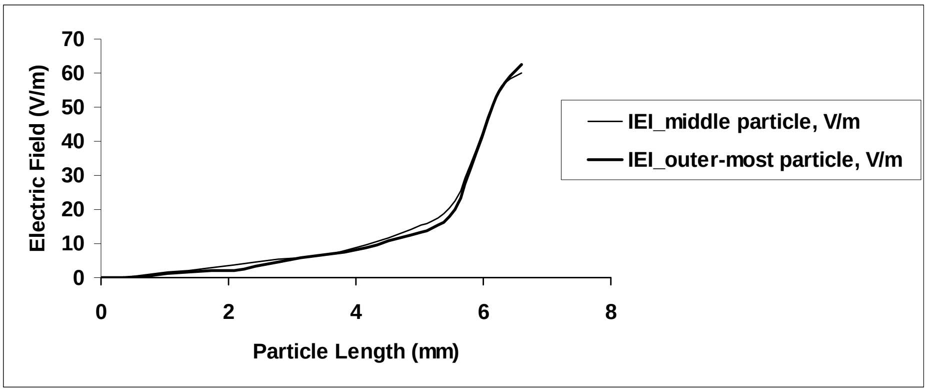


Figure 7. Electric field distribution along surface of middle and outermost particles

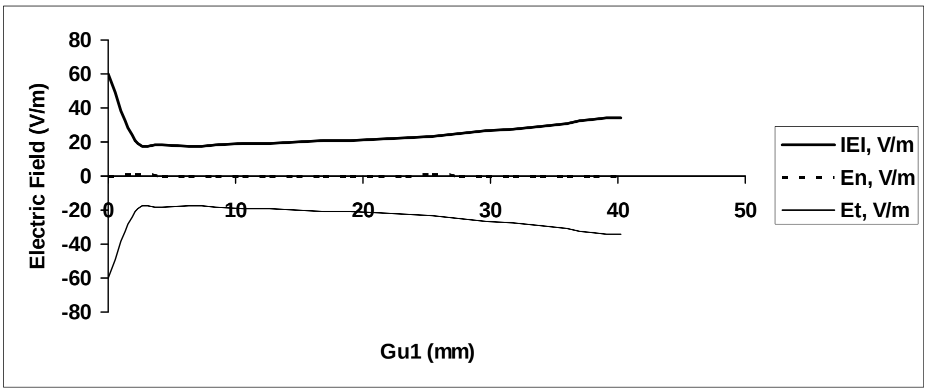


Figure 8. Electric field distribution along gap from upper tip of middle particle up to high voltage conductor

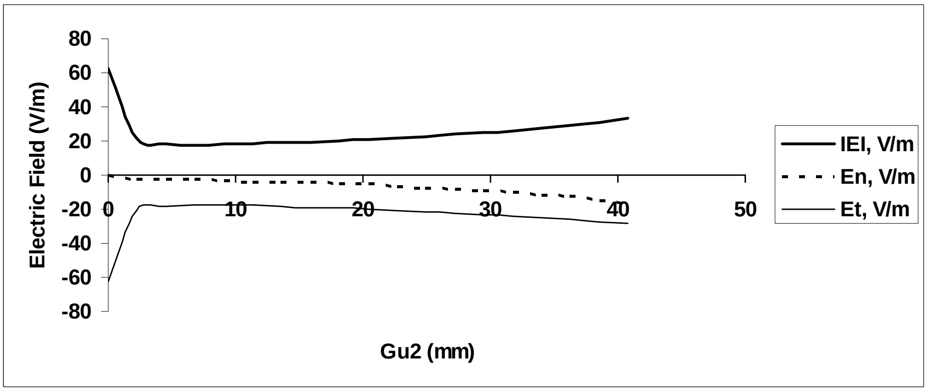


Figure 9. Electric field distribution along gap from upper tip of outermost particles up to high voltage conductor

### 4.2. Effect of Changing the Length of Middle Particle on the Electric Field Values

The variation of the electric field values at the upper tip of middle and outermost fixed particles with respect to the particles lengths at (r1,r2=0.5mm) is shown in Figure 10. When the dimensions of outermost particles are constant at 5mm length and 0.5mm hemispherical radius and change the length of middle fixed particle from 3mm to 12mm at constant 0.5mm radius, it can be observed that as length of middle fixed particle increases at constant length of outermost particles, the maximum electric field at upper tip of middle particle increases also but it slightly decreased at upper tip of outermost particles.

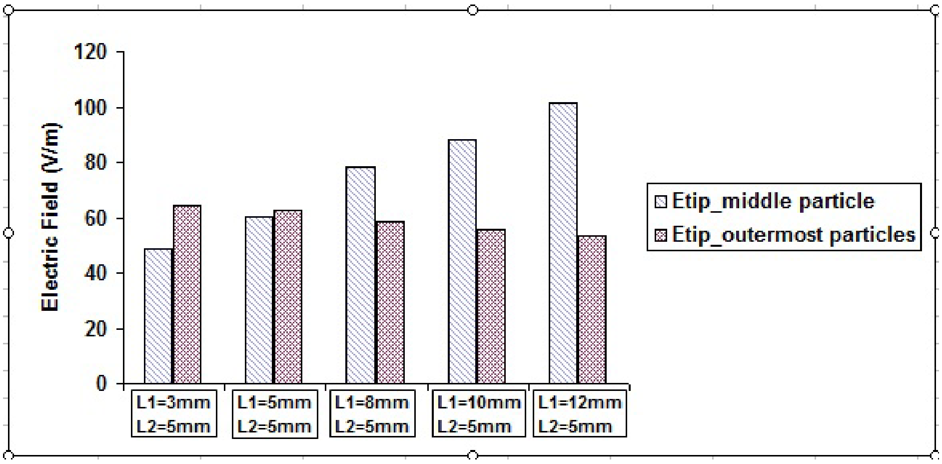


Figure 10. Variation of the electric field values at upper tip of middle and outermost particles versus particles lengths at constant radius.

### 4.3. Effect of Changing the Radius of Middle Particle on the Electric Field Values

The variation of the electric field values at the upper tip of middle and outermost fixed particles with respect to the particles radius at (L1,L2=5mm) is shown in Figure 11. When the dimensions of outermost particles are constant at 5mm length and 0.5mm hemispherical radius and change the radius of middle fixed particle from 0.2mm to 0.7mm at constant 5mm length, it can be observed that as radius of middle fixed particle increases at constant radius of outermost particles, the maximum electric field at upper tip of middle particle decreases and this means that the electric field is maximum at thin particles but it still approximately constant at upper tip of outermost particles.

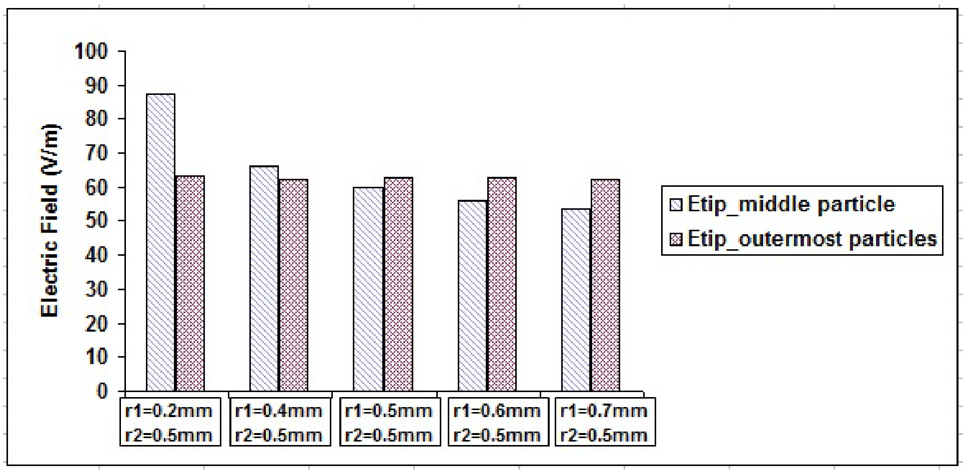


Figure 11. Variation of the electric field values at upper tip of middle and outermost particles versus particles radius at constant length.

## 5. 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 inside gas insulated bust duct for $SF_6$-gas mixture under DC voltage. The electric field around particles is satisfied in this paper 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 coefficients ($\bar{\alpha}$)[7-11].

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;

$$\int_0^{xc} \bar{\alpha}(x)\,dx \geq K \tag{7}$$

Where, $\bar{\alpha}(x)=\alpha(x)-\eta(x)$, $\alpha(x)$ 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 or triple junction point 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. In this study for breakdown voltages we take the value of K = 18.42 for $SF_6$ gas and $SF_6$-gas mixture [12].

## 6. BREAKDOWN VOLTAGE CALCULATIONS FOR GAS MIXTURES WITH SINGLE WIRE CONTAMINATING PARTICLE

Figure 12 shows the effect of gas pressure on the breakdown voltage for various fractional concentrations of $SF_6$-$N_2$-Air gas mixtures without coating of inner surface of earthed enclosure. We fixed the fractional concentration of $SF_6$ gas at 5% in these mixtures with various fractional concentrations of $N_2$ and Air to avoid disadvantages of $SF_6$ gas such as high costs and also obtain the optimum gas mixture. From this figure, it can be observed that, the breakdown voltage for ($SF_6$-$N_2$-Air) increases when fractional concentration of $SF_6$ gas is constant at 5% and with increasing fractional concentration of $N_2$ gas and with decreasing fractional concentration of Air. Also, the breakdown voltage for mixture is increased by about 500% as the pressure of mixture increases from 100Kpa to 700Kpa. From these mixtures, the optimum gas mixture is observed at 5%$SF_6$-80%$N_2$-15%Air.

Figure 13 shows the effect of gas pressure on the breakdown voltage for various fractional concentrations of $SF_6$-gas mixtures with and without particle contamination. From this figure, it can be observed that, the breakdown voltage for a mixture of (5%$SF_6$-80%$N_2$-15%Air) in case of gap with particle contamination decreased to about 43% from its value in case of clean gap, i.e without any particle contamination. Also, the breakdown voltage for a mixture of (5%$SF_6$-80%$CO_2$-15%Air) in case of gap with particle contamination decreased to about 40% from its value in case of clean gap.

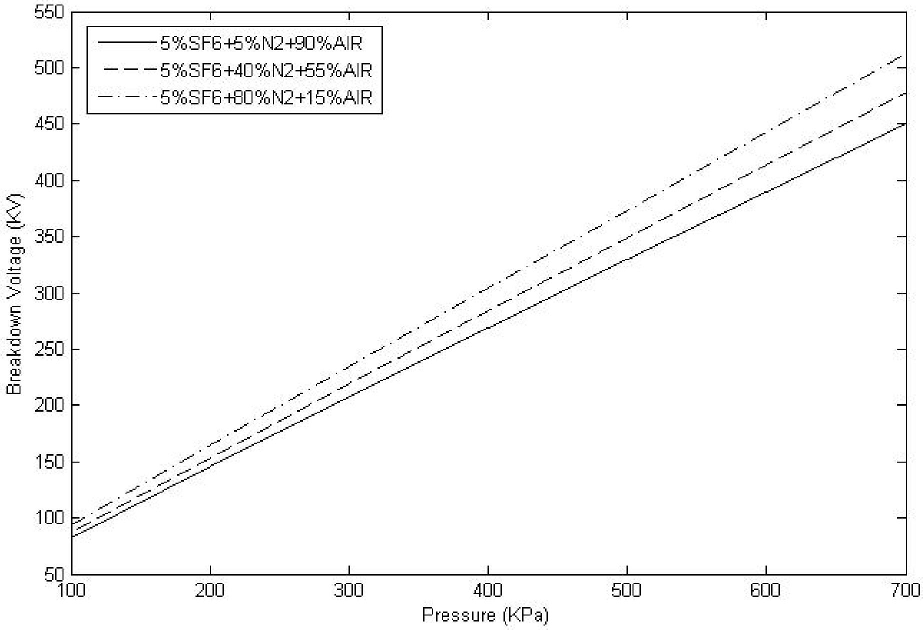


Figure 12. Effect of gas pressure on the breakdown voltage for various fractonal concentrations of $SF_6$-$N_2$-Air gas mixtures

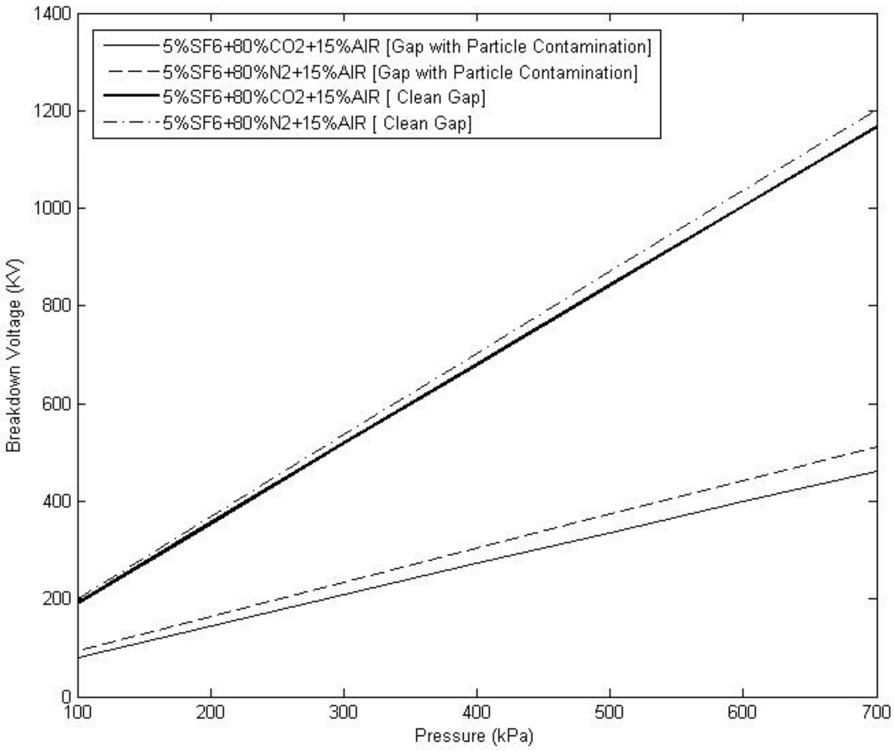


Figure 13. Effect of gas pressure on the breakdown voltage for various fractonal concentrations of $SF_6$-gas mixtures with and without particle contamination

Figure 14 shows the effect of gas pressure on the breakdown voltage for various fractional concentrations of $SF_6$-gas mixtures with and without coating of inner surface of earthed enclosure. The material which preferred for coating of earthed enclosure is Epoxy with 2000μm thickness. From this figure, it can be observed that, the breakdown voltage for a mixture of (5%$SF_6$-80%$N_2$-15%Air) in case of coating of inner surface of earthed enclosure increased to about 102% from its value in case of uncoating earthed enclosure. Also, the breakdown voltage for a mixture of (5%$SF_6$-80%$CO_2$-15%Air) in case of coating of inner surface of earthed enclosure increased to about 102% from its value in case of uncoating earthed enclosure. From this figure, it can be deduced that the optimum case is with coating the inner surface of earthed enclosure with 2000micro-meter thickness of epoxy material and with (5%$SF_6$-80%$N_2$-15%Air) mixture which it gives the higher breakdown voltage than other cases.

Figure 15 shows the effect of coating thickness of earthed enclosure on the breakdown voltage for various fractional concentrations of $SF_6$-gas mixtures. The gas pressure is taken as constant value 600kPa. From this figure, it can be observed that, the breakdown voltage is slightly increased as coating thickness increased from zero i.e. (without coating) to 2mm. The effect of coating thickness is small because charge accumulation on coating doesn't effect on field in case of coaxial gas gap. From this figure, the optimum gas mixture is (5%$SF_6$-80%$N_2$-15%Air) at different thickness of coating.

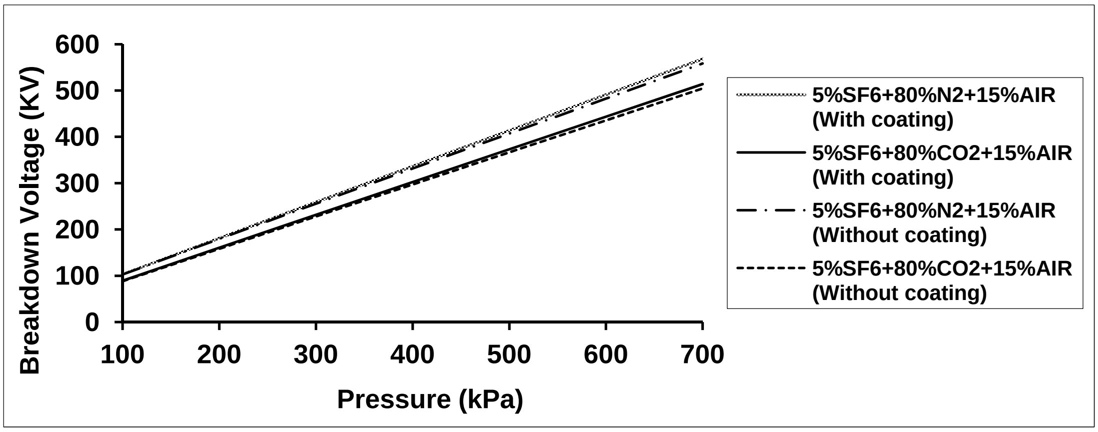


Figure 14. Effect of gas pressure on the breakdown voltage for various fractonal concentrations of $SF_6$-gas mixtures with and without coating of earthed enclosure

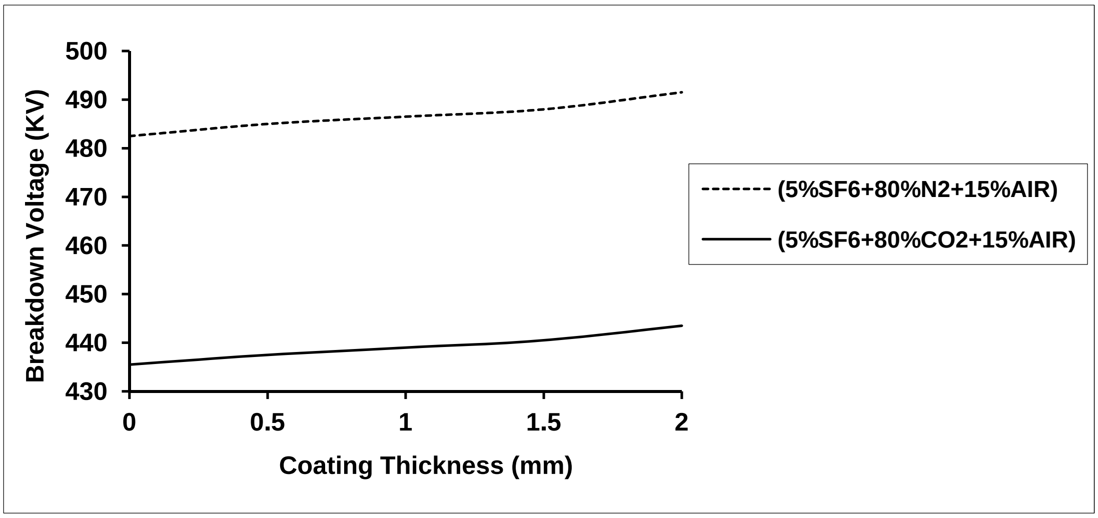


Figure 15. Effect of coating thickness of earthed enclosure on the breakdown voltage for various fractonal concentrations of $SF_6$-gas mixtures

## 7. BREAKDOWN VOLTAGE CALCULATIONS FOR GAS MIXTURES WITH MULTI-CONTAMINATING PARTICLES

Figure 16 and Figure 17 show the effect length of multi-contaminating particles on breakdown voltage with varing gas pressure at fixed hemispherical radius and 5%$SF_6$-80%$N_2$-15%Air mixture and 5%$SF_6$-80%$CO_2$-15%Air mixture respectively. From these figures, it can be observed that at constant length of outer most particles and increase length of middle particle, the breakdown voltage decreased. The probability of occuring breakdown for gas mixture in case of presence particles of dimensions L1=12mm and L2=5mm is higher than it in case of multi-particle of dimensions L1=5mm and L2=5mm. The most dangerous case is observed with multi-contaminating particles dimensions (L1=12mm and L2=5mm) which produced the minimum breakdown voltage.

Figure 18 shows the effect of length of middle particle on breakdown voltage for various $SF_6$-gas mixtures at fixed radius and length of outermost particles and at constant pressure 600kPa. From this figure, it can be observed that the breakdown voltage decreases as length of middle particle increases at fixed length of outermost particles. Also the breakdown voltage for 5%$SF_6$-80%$N_2$-15%Air mixture is greater than it for 5%$SF_6$-80%$CO_2$-15%Air mixture at different values of particle length.

Figure 19 and Figure 20 show the effect of hemi-spherical radius of multi-contaminating particles on breakdown voltage with varing gas pressure at fixed length and 5%$SF_6$-80%$N_2$-15%Air mixture and 5%$SF_6$-80%$CO_2$-15%Air mixture respectively. From these figures, it can be observed that at constant hemi-spherical radius of outer most particles and increase radius of middle particle, the breakdown voltage increased. The probability of occuring breakdown for gas mixture in case of presence particles of dimensions r1=0.2mm and r2=0.5mm is higher than it in case of multi-particles of dimensions r1=0.6mm and r2=0.5mm. The most dangerous case is observed with multi-contaminating particles dimensions (r1=0.2mm and r2=0.5mm) which produced the minimum breakdown voltage.

Figure 21 shows the effect of hemi-spherical radius of middle particle on breakdown voltage for various $SF_6$-gas mixtures at fixed radius and length of outermost particles and at constant pressure 600kPa. From this figure, it can be observed that the breakdown voltage increases as hemi-spherical radius of middle particle increases at fixed radius of outermost particles. Also the breakdown voltage for 5%$SF_6$-80%$N_2$-15%Air mixture is greater than it for 5%$SF_6$-80%$CO_2$-15%Air mixture at different values of particle radius.

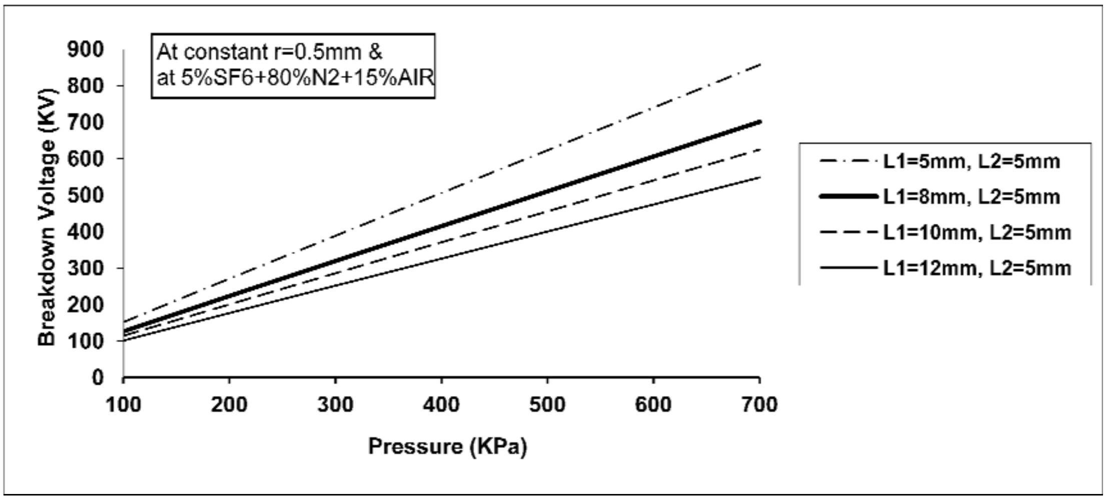


Figure 16. Effect of length of multi-contaminating particles on breakdown voltage with varing gas pressure at fixed hemispherical radius and 5%$SF_6$-80%$N_2$-15%Air mixture

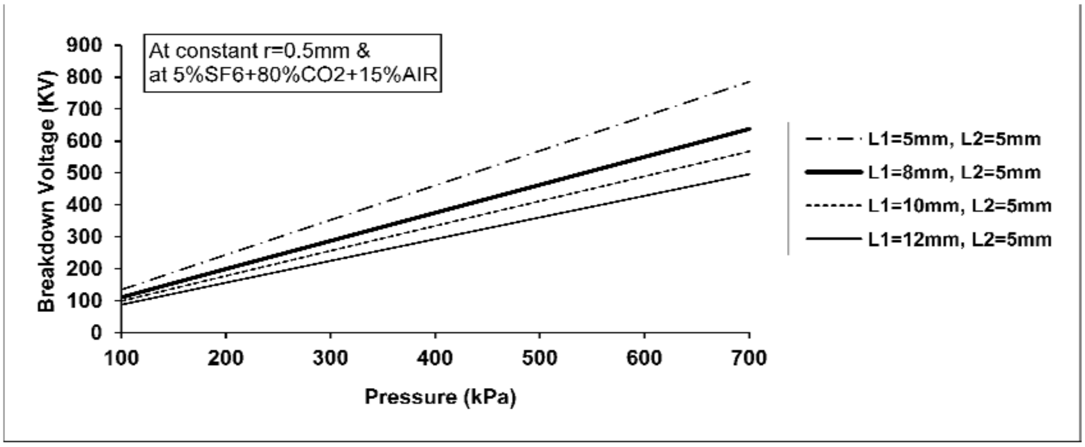


Figure 17. Effect of length of multi-contaminating particles on breakdown voltage with varing gas pressure at fixed hemispherical radius and 5%$SF_6$-80%$CO_2$-15%Air mixture

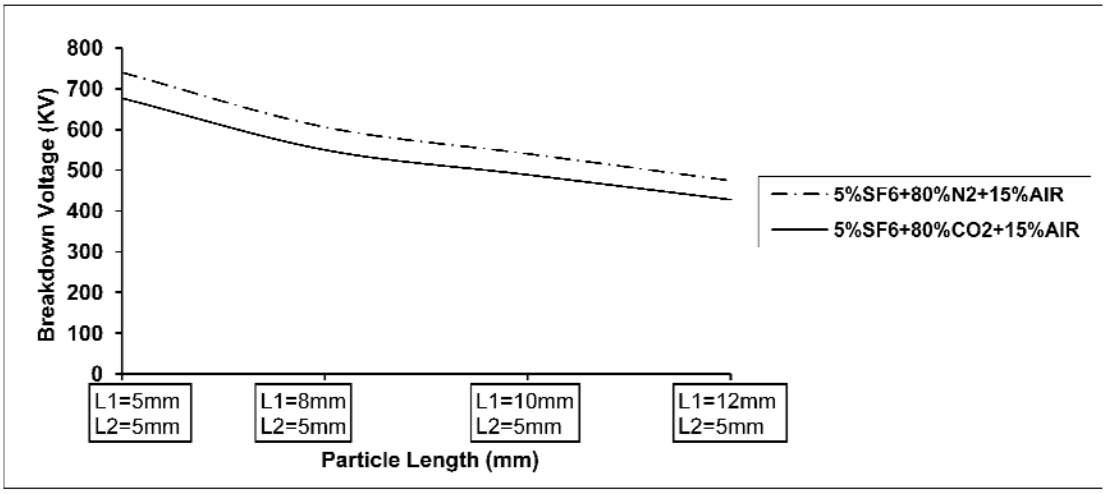


Figure 18. Effect of length of middle particle on breakdown voltage for various $SF_6$ gas mixtures at fixed radius, length of outermost particles and at constant pressure 600kPa

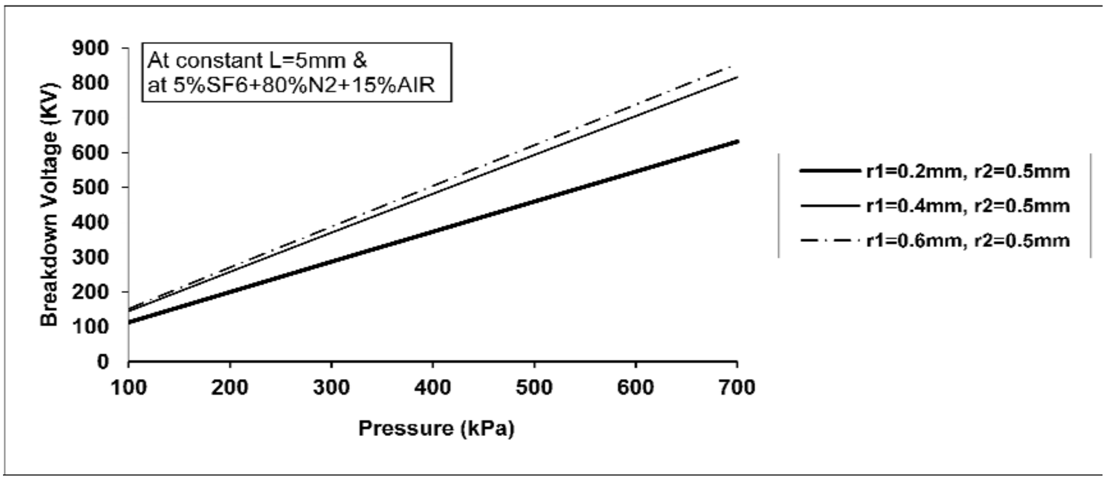


Figure 19. Effect of hemi-spherical radius of multi-contaminating particles on breakdown voltage with varing gas pressure at fixed length and 5%$SF_6$-80%$N_2$-15%Air mixture

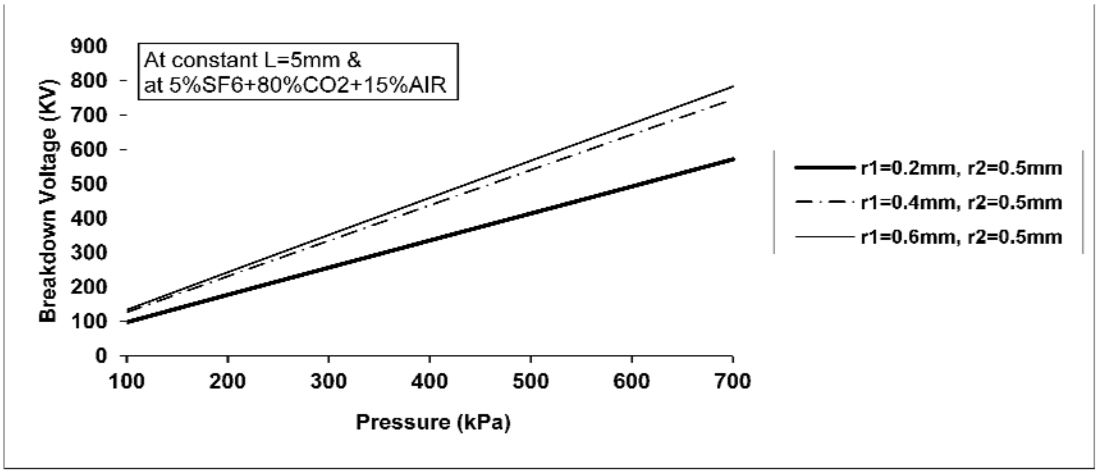


Figure 20. Effect of hemi-spherical radius of multi-contaminating particles on breakdown voltage with varing gas pressure at fixed length and 5%$SF_6$-80%$CO_2$-15%Air mixture

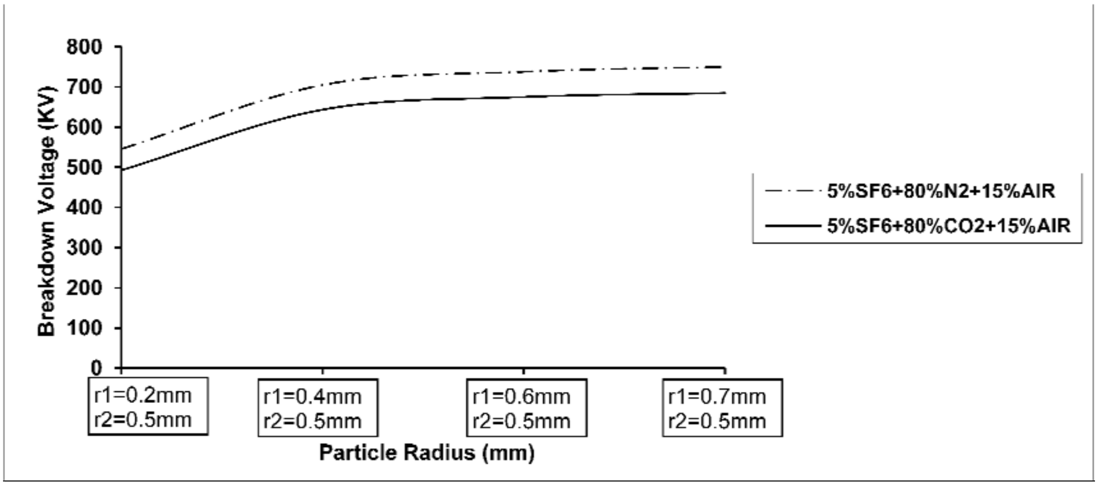


Figure 21. Effect of hemi-spherical radius of middle particle on breakdown voltage at fixed radius and length of outermost particles and at constant pressure 600kPa

## 8. CONCLUSION

In this study, modeling of gas insulated bus duct with coating of earthed enclosure is presented. The effect of single and multi-contaminating particles on electric field and breakdown voltage values are also presented in this paper. From this work, in case of gas insulated bus duct with multi-contaminating particles, it can be observed that the electric field is minimum value at lower tip of middle and outermost particles and maximum value at upper tip of it but the maximum value of electric field at upper tip of outermost particles are slight increased from that at upper tip of middle particle because of its nearer to high voltage conductor. The maximum electric field at upper tip of middle particle decreased when the radius of middle particle increased while the electric field is still approximately constant at upper tip of outermost particles when its radius is constant. The breakdown voltage for gas mixture is increased by about 500% as the pressure of mixture increased from 100Kpa to 700Kpa. The optimum gas mixture is observed at 5%$SF_6$-80%$N_2$-15%Air when it compared with different $SF_6$-gas mixtures. The breakdown voltage for (5%$SF_6$-80%$N_2$-15%Air) in case of gap with particle contamination decreased to about 43% from its value in case of clean gap without any particle contamination. The breakdown voltage for (5%$SF_6$-80%$N_2$-15%Air) in case of coating of inner surface of earthed enclosure increased to about 102% from its value in case of not presence coating for earthed enclosure. From different case studies in this work, the optimum case is observed with coating the inner surface of earthed enclosure with 2000micro-meter thickness of epoxy material and with (5%$SF_6$-80%$N_2$-15%Air) mixture which it gives the higher breakdown voltage than other cases. The breakdown voltage is slightly increased as coating thickness increased from zero i.e. (without coating) to 2mm. The effect of coating thickness is small because charge accumulation on coating doesn't effect on field in case of coaxial gas gap. The probability of occuring breakdown for gas mixture in case of presence particles of dimensions L1=12mm and L2=5mm is higher than it in case of multi-particle of dimensions L1=5mm and L2=5mm. The most dangerous case is observed with multi-contaminating particles dimensions (L1=12mm and L2=5mm) which produced the minimum breakdown voltage. The probability of occuring breakdown for gas mixture in case of presence particles of dimensions r1=0.2mm and r2=0.5mm is higher than it in case of multi-particles of dimensions r1=0.6mm and r2=0.5mm. The most dangerous case is observed with multi-contaminating particles dimensions (r1=0.2mm and r2=0.5mm) which produced the minimum breakdown voltage.

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