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Influence of Wire and Cone Particle Contamination on Maximum Electric Field for Rod-Plane Gaps

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Abstract—Non uniform gap like rod-plane gap and its electric field distribution has a great importance in high voltages. The maximum electric field of rod-plane gap is strongly affected by geometry (shape and dimentions) of two electrodes and the distance between them. The Finite Element Method (FEM) has been used throughout this work, for its favorable accuracy, to calculate the electric field distribution for rod-plane gaps.This paper studied the effect of the rod diameter, the plane diameter and the gap space on the maximum electric field of rod-plane gap. Influence of wire and cone particle contamination that settled on the grounded electrode on the electric field distribution of rod-plane gap is carefully researched in this paper as well. Effects of wire particle length and radius on the maximum electric field are also studied. Finally, effect of cone particle length on the maximum electric field is implemented.

Index Terms— Cone particle, electric field, FEM, plane diameter, rod-plane gap, tip of the rod and wire particle.

1 INTRODUCTION

Study of electric field distribution in non-uniform gaps like rod-plane gaps is very important in high voltage studies. One of the most important factors which affect the breakdown voltage of the dielectric material is the field distribution inside and around the material when stressed by high voltage [1], [2], [3].

The electric field calculations are complex and it is so difficult to find an exact solution. Several numerical techniques have been increasingly implemented to solve such practical problems since the availability of high performance computers [4], [5].

The finite element method (FEM) is used in many researches for its favorable accuracy, when applied to high voltage problems [6],[7], [8],[9], [10], [11].

2 ELECTRIC FIELD CALCULATIONS

FEM is one of the most efficient techniques for solving electric field problems and it is used to implement and simulate electric field distribution of the modeling rod-plane gap. FEM concerns itself with minimization of the energywithin 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 [12]:

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

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

Furthermore, for rod-plane 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 arealimited system is now given according to [12]:

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

Where (W/φ) is thus an energy density per elementary 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

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

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 [12]:

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

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 [12]:

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

The electric field is calculated with aid of Finite Element Method (FEM) throughout this work. FEMM is a finite element package for solving 2D planar and axi-symmetric problems in electrostatics and in low frequency magnetic [13].

In this study, the voltage on the high voltage conductor of the configurations considered is taken as 1V, for any applied voltage the values of the electric fields can be proportioned.

3 Modeling Of Rod-Plane Gap

Here, Fig. 1, shows a rod-plane air gap, where the plane disc diameter is (d_p), plane thickness (t_p) is 10 mm and has a curved edge of radius r_2 =3 mm. While the rod diameter is (d_r) with a curvature r_1=4 mm and a hemispherical end. Diameter of upper surface of rod (d_u) is taken as 10 mm, length (L_1) as 25 mm and length (L_2) as 45 mm. The gap space (S) is taken from the rod tip to the plane surface.The plane electrode is grounded.

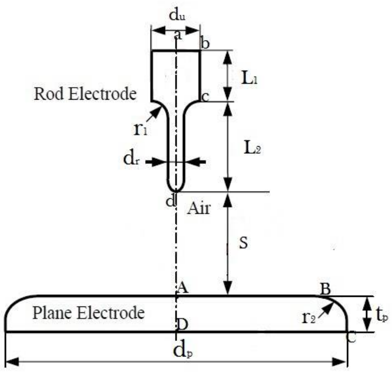

Fig. 1. rod-plane air gap configuration

3.1 Electric Field Distribution of Rod-Plane Gap

Fig. 2, shows the drawn geometry of rod-plane gap where the rod diameter (d_r) is taken as 2 mm. The plane diameter (d_p) and thickness (t_p) are 70 mm and 10 mm respectively at fixed gap space 50 mm.

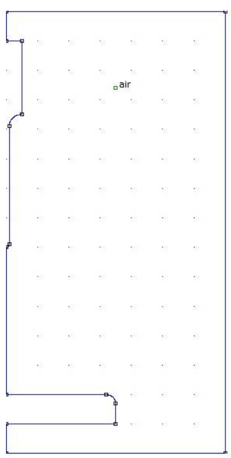

Fig. 2. Problem definition of rod-plane air gap

Fig. 3, shows computed electric field distribution in rod-plane gap.Results obtained from FEM analysis show that the maximum electric field is at tip of the rod (the point facing the grounded plane). Electric field is also concentrated at the plane hemispherical edge.

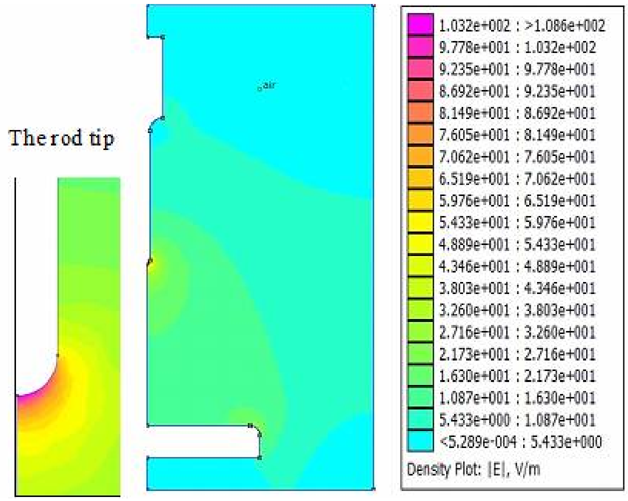

Fig. 3. Electric field distribution of rod-plane gap

3.1.1. Electric Field Distribution along the Gap Axis from the Rod to the Plane Electrode

Fig. 4 shows distribution of the electric field along the gap axis from the rod electrode to the plane. The gap between the rod and the plane is 50 mm. The electric field has its maximum value at tip of the rod and decreases gradually as moving away from the rod and then it roughly trends to be stable (at the distance 5 mm away from the rod reaching to the plane). The decrement percentage is nearly 85 %(from the rod to the plane surface). The normal component of electric field is around zero but its magnitude and tangential components have the same direction and value.

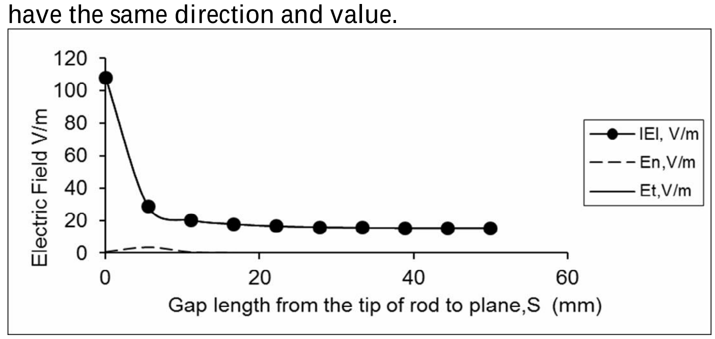

Fig. 4. Electric field distribution along the axis of rod-plane gap

3.1.2. Electric Field Distribution along the Surface Length of Rod Electrode

Fig. 5, describes electric field distribution along the rod surface, where the electric field roughly stays constant along the upper surface of the rod (from a to b as shown in fig. 1) and then it decreases at the hemispherical curvature at (c) but it sharply increases at the lower curvature of the rod until it reaches to its maximum value at the lower tip of rod (d).

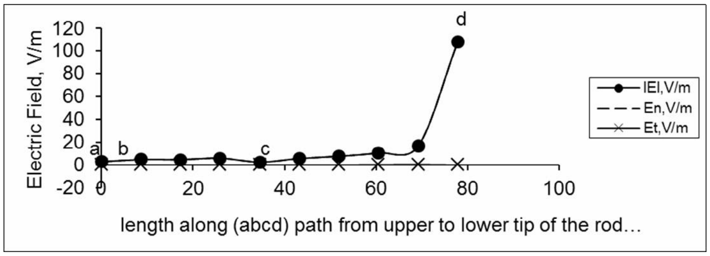

Fig. 5. Electric field distribution along the surface length of rod electrode

3.2. Effect of the Rod Diameter on the Maximum Electric Field

Electric field computations are carried out for different rod diameters(dr) between 2 mm and 12 mm,plane diameter is taken as 70 mm and a distance between the rod and the plane of 50 mm.

Fig. 6 illustrates the variation of maximum electric field with the rod diameter (d_r) in rod-plane gap. It's clear that the maximum electric field decreases with increasing in the rod diameter. The percentage of decrease is about 56% (for rod diameters from 2 mm to 12 mm). The decrement is much higher for small rod diameters than that for bigger rod diameters (greater than 6 mm) where the electric field becomes approximately constant with increase in the rod diameter.

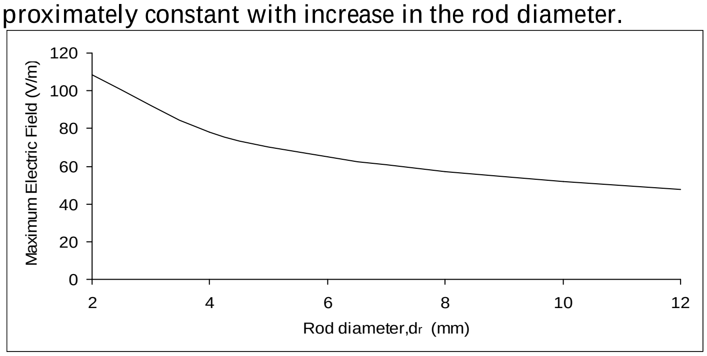

Fig. 6. Maximum electric field versus the rod diameter

3.3. Effect of the Plane Diameter on the Maximum Electric Field

Electric field calculations are implemented for different plane diameters between 50 mm and 200 mm at a 50 mm fixed gap space and the rod diameter is taken as 2 mm.

Fig. 7 clarifies effect of the plane diameter on the maximum electric field. It illustrates that the maximum electric field increases with increasing in the plane diameter where the gap becomes more non-uniform. The increment percentage is about 19 %(for plane diameters from 50 mm to 200 mm). The value of the maximum electric field gets steady with increasing in plane diameter greater than 150 mm.

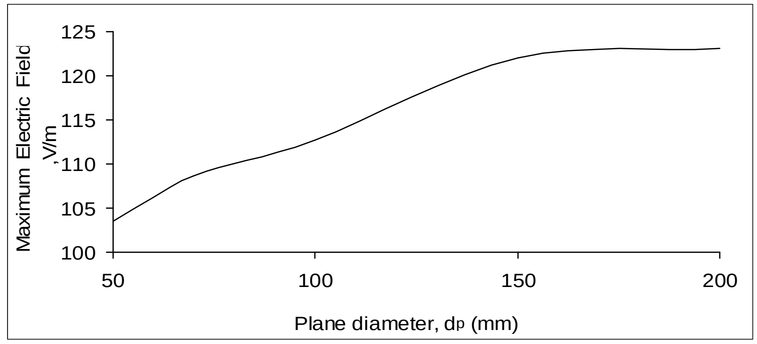

Fig. 7. Maximum electric field versus the plane diameter

3.4. Effect of the Gap Length on the Maximum Electric Field

FEM analysis is carried out for different gap lengths between 10 mm and 50 mm changed by 10 mm steps, where the rod diameter and plan diameter are taken as 2 mm and 70 mm respectively.

Fig. 8 shows the dependence of the maximum electric field on the gap length obtained in rod-plane gap. From Fig. 8, it results that the maximum electric field decreases with the increase in the gap space (S) as the charges accumulated on the rod decrease. The percentage of decrement is approximately 43 % (from 10 mm to 50 mm gap length).

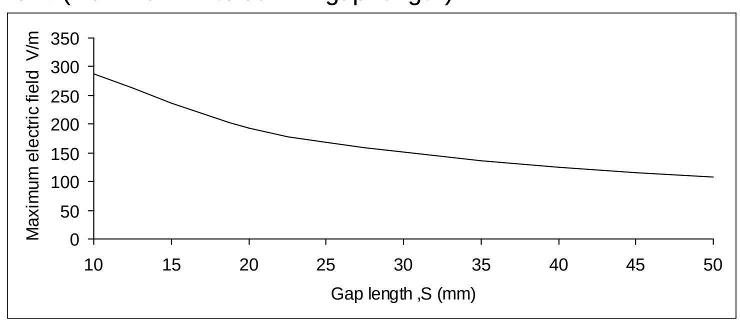

Fig. 8. Maximum electric field versus the gap length

4 Effect of Wire Particle Contamination (Rested on the Plane) on the Electric Field Distribution

4.1. Electric Field Distribution around Rod-Plane Gap with a Wire Particle Contamination

Fig. 9, shows the drawn geometry of rod-plane gap with a wire particle contamination of radius (r_p) taken as 0.1 mm and length (L_p) taken as 5 mm. The plane diameter is 70 mm, the rod diameter is 2 mm and the distance between them is 50 mm.

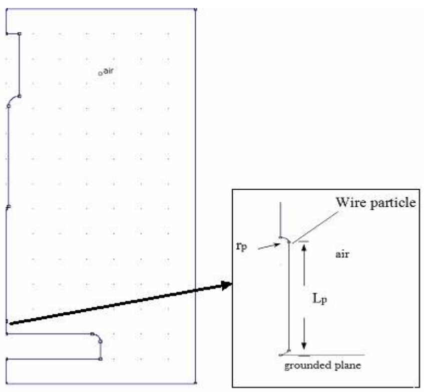

Fig. 9 .Problem definition of rod- plane gap with wire particle contamination

In fig. 10, the obtained electric field distribution in the gap with presence of a wire particle contamination, electric field at the rod tip and at the wire particle are shown. The difference in the field distribution is illustrated where the wire particle changes the field in the gap. The electric field has the maximum value at the wire particle hemispherical tip and it has high value at the rod tip. The radius of the wire particle tip is extremely thin so that the electric field is stronger and more concentrated at the wire particle hemispherical tip than that at the rod tip.

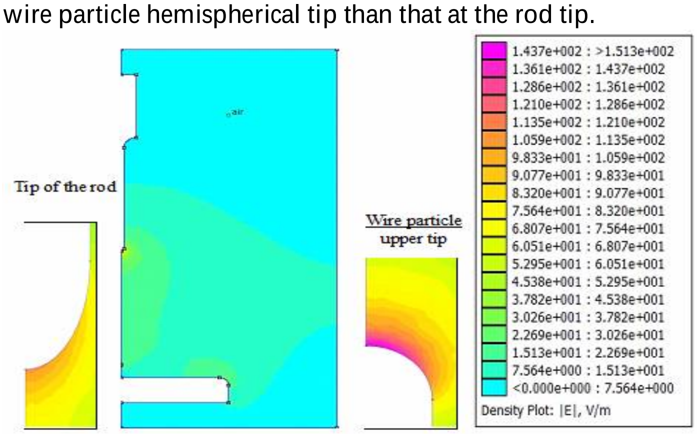

Fig. 10 .Electric field distribution in rod-plane gap with wire particle contamination

4.2. Electric Field Distribution along the Gap Axis from the Rod to the Plane

Fig.11. describes the electric field distribution along the gap axis from the rod electrode to the plane surface. Electric field intensity decreases as moving away from the rod and then it is roughly stable from distance 5 mm away from the rod until it reaches to the wire particle hemispherical tip where it increases sharply to reach to its maximum value. After that it decreases gradually until it reaches to zero at the plane centre.

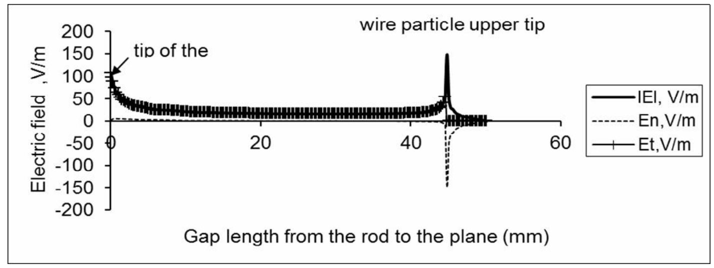

Fig. 11. Electric field distribution along the axis of rod-plane gap with a wire particle contamination

4.3. Effect of the Wire Particle Radius on the Maximum Electric Field

In this study, radius of the wire particle (r_p) is changed from 0.1 mm to 1 mm, its length (L_p) is taken as 5 mm and it's laid on the plane surface. Plane diameter is taken as 70 mm, the rod diameter as 2 mm and distance between the rod and the plane of 50 mm.

Fig. 12 clears up influence of increasing wire particle radius (r_p) on electric field intensity at the wire particle tip (E_2) and electric field intensity at the rod tip (E_1). Electric field at the wire particle tip E_2 decreases with increasing its radius and the reduction percentage is nearly 60 %(for wire particle radius from 0.1 mm to 1 mm). But electric field intensity at the rod tip (E_1) is almost constant with the wire particle radius. The maximum electric field is observed at the wire particle tip for wire particle radius less than or equal to 0.2 mm but it is observed at the rod tip for wire particle radius greater than 0.2 mm.

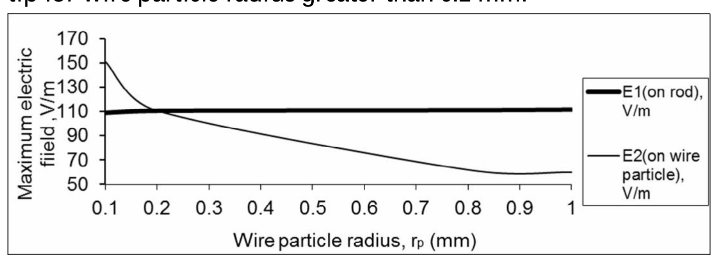

Fig. 12. Maximum electric field versus wire particle radius

4.4. Effect of the Wire Particle Length on the Maximum Electric Field

In this analysis, length of the wire particle (L_p) is changed from 5 mm to 12 mm, its radius (r_p) is taken as 0.5 mm and it's laid on the plane surface. Plane diameter is taken as 70 mm, the rod diameter is 2 mm and distance between the rod and the plane of 50 mm.

As shown in fig. 13, the maximum electric field, at the rod tip,(E_1) increases slightly with length of the wire particle. The percentage of increment in maximum electric field is about 5.5 %(from 5 mm to 12 mm wire particle length). And the electric field intensity at the wire particle contamination (E_2) increases as length of the wire particle increases, the percentage of increase is nearly 53 % (for wire particle length from 5 mm to 12 mm). And the electric field intensity at the wire particle contamination (E_2) is equal to the maximum electric field at the rod tip (E_1) for wire particle contamination length 12 mm as shown in fig. 13.

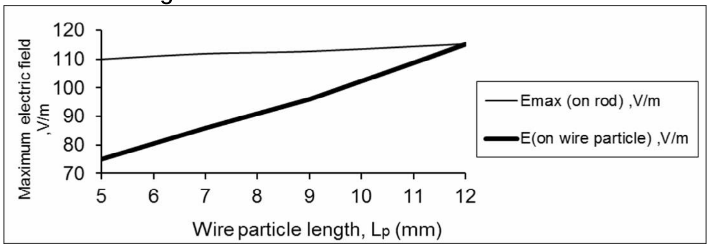

Fig. 13. Maximum electric field versus wire particle length

5 Effect of Cone Particle Contamination (Rested on the Plane Surface) on the Electric Field Distribution

5.1. Electric Field Distribution around Rod-Plane Gap with a Cone Particle Contamination

Fig. 14. shows the drawn geometry of rod-plane gap with a cone particle contamination with a radius (r_c) taken as 0.5 mm and 12 mm length. Plane of 70 mm diameter is at 50 mm distance from the rod and the rod diameter is taken as 2 mm.

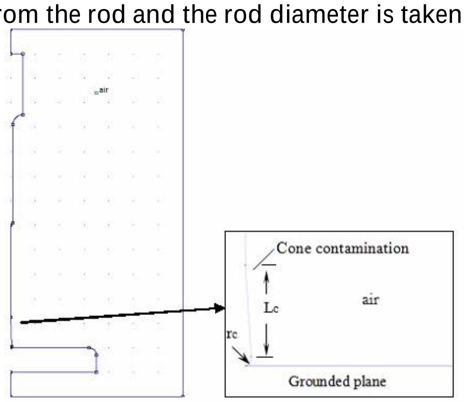

Fig. 14. Problem definition of rod- plane gap with cone particle contamination

In fig. 15, the obtained electric field distribution in rod-plane gap with presence of a cone particle contamination, electric field at the rod tip and at the cone particle tip are shown. The maximum electric field is at the cone particle tip as it has a needle tip and the field is very intense at the rod tip as well.

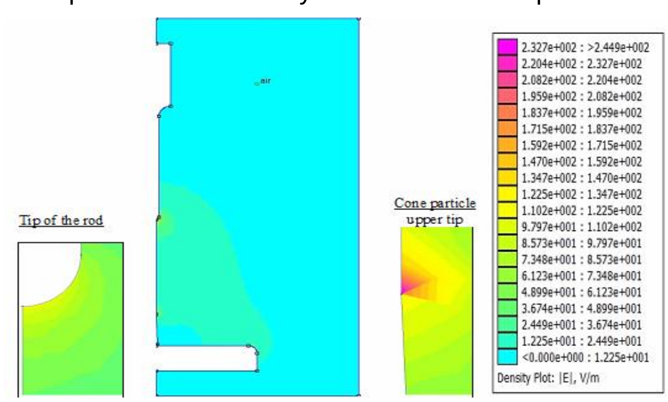

Fig. 15. Electric field distribution in rod -plane gap with a cone particle contamination

5.2. Electric Field Distribution along the Gap Axis from the Rod to the Plane

Fig. 16. explains the electric field distribution along the gap axis from the rod electrode to the plane. The gap between the rod and the plane is 50 mm. The electric field decreases gradually as moving away from the rod tip and then it is nearly steady at distance greater than 5 mm away from the rod until it reaches to the cone particle on the surface of the plane where it increases strongly to reach to the maximum value of the electric field in the whole gap and returns to decrease before reaching to zero at the plane surface.

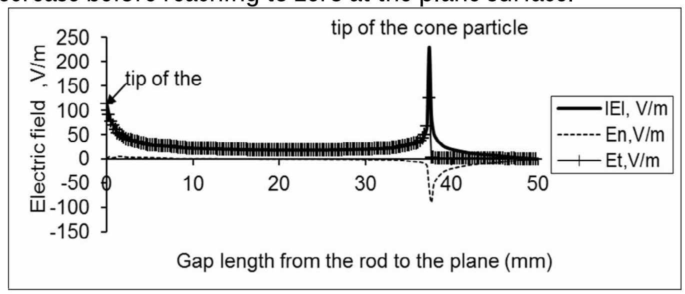

Fig. 16. Electric field along the axis of rod-plane gap with a cone particle contamination

5.3. Effect of Cone Particle Length on the Maximum Electric Field

In this analysis, length of the cone particle (Lc) is changed from 5 mm to 12 mm, its radius (rc) is taken as 0.5 mm and it's placed on the plane surface. Plane of 70 mm diameter is at 50 mm distance from the rod and the rod diameter is taken as 2 mm.

As shown in fig. 17, the maximum electric field (at the cone particle tip) increases with the increase in length of the cone particle. The percentage of increment in maximum electric field is about 36 %(from 5 mm to 12 mm cone particle length) and the electric field on the rod tip is nearly fixed with length of the cone particle as shown.

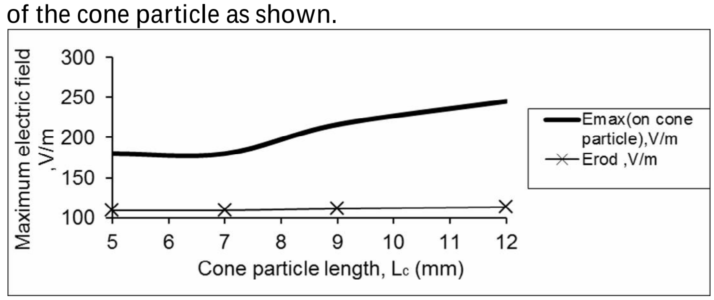

Fig. 17. Maximum electric field versus the cone particle length

6 Conclusion

According to the analysis made in this paper by using Finite Element Method for models of rod-plane air gaps, conclusions have been arisen:

- Thin rod electrodes result relatively high electric field intensity in rod-plane gap.
- Small plane electrodes result relatively low electric field intensity in rod-plane gap.

- Small gap space produces relatively high electric field intensity in rod-plane gap.
- Thin wire particle contamination with large length causes the electric field strength in rod-plane gap to increase.
- Increasing in length of the cone particle contamination causes the electric field strength in rod-plane gap to increase and the maximum electric field would be at its needle tip.
- The most dangerous case for rod-plane gap with a wire particle contamination is at wire particle length and radius 12 mm and 0.1 mm respectively.
- The most dangerous case for rod-plane gap with a cone particle contamination is at cone particle length 12 mm.

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