International Journal of Engineering & Technology, 7 (3.36) (2018) 127-133

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Analysis of Electric Field and Current Density for Different Electrode Configuration of XLPE Insulation

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Abstract

The most important aspect influencing the circumstance and characteristics of electrical discharges is the distribution of electric field in the gap of electrodes. The study of discharge performance requires details on the variation of maximum electric field around the electrode. In electrical power system, the insulation of high voltage power system usually subjected with high electric field. The high electric field causes the degradation performance of insulation and electrical breakdown start to occur. Generally, the standard sphere gaps widely used for protective device in electrical power equipment. This project is study about the electric field distribution and current density for different electrode configuration with XLPE barrier. Hence, the different electrode configuration influences the electric field distribution. This project mainly involves the simulation in order to evaluate the maximum electric field for different electrode configuration. Finite Element Method (FEM) software has been used in this project to perform the simulation. This project also discusses the breakdown characteristics of the XLPE. The accurate evaluation of electric field distribution and maximum electric field is an essential for the determination of discharge behavior of high voltage apparatus and components. The degree of uniformity is very low for pointed rod-plane when compared to other two electrode configurations. The non- uniform electric distribution creates electrical stress within the surface of dielectric barrier. As a conclusion, when the gap distance between the electrodes increase the electric field decrease.

Keywords: *current density; cross linked polyethylene (XLPE); electric field; electrodes configuration; Finite Element Method (FEMM) software*

1. Introduction

In wide field of high voltage applications, the understanding of electric field and current density are very important be-cause the analysis of electric field provides crucial roles for the evolution of design and analysis of high voltage equipment. The perfect and secure condition systems to the consumers always become the important feature for engineers. The fundamental characteristic of electrical breakdown should understand and examine to design the high voltage cable, transmission lines, substation equipment and various solid insulated high voltages equipment. Hence, the study of electric field also provides better understanding of discharge characteristics of electrode configurations (Michealrakis, 2015). The typical complication in this application is to find the electric field and current density between two electrodes. The electric field in the gap of two electrodes will be examined using Finite Element Method (FEM) software. Besides, electric fielnd also has been examined using Quickfield software (Rosli,H., Othman,N.A., Jamail, N.A.M., Ismail,M.N. (2017)). Solid insulator particularly cross-linked polyethylene (XLPE) used as dielectric barrier in this application. The electric field propagation and current density in electrode configurations depend upon the arrangement of the electrodes (Ravindra Arora & Wolfgang Mosch, 2011). The behavior of the solid insulator directly related to the electrode configurations. In addition, different configurations of electrode will be used in this research to observe the variation of the electric field and current density which usually impact the insulation part. Different electrode configurations such as rod-plane, plane-plane, pointed electrode- plane as testing objects will be used to determine the electric field and current density which influence the XLPE. This project con-sists of experimental set up and software simulation. FEM software used to simulate the model for electric field and current density to analyze the region of maximum electric field, Emax. For the experimental set-up, TERCO measuring spark gap circuit which used to determine air breakdown characteristic in sphere gaps. In real life, the sphere gaps are very important in high voltage engineering as it generally used to measure peak values of high voltage. IEC and IEEE choose the sphere gap as calibration device. Other than that, the standard sphere gaps are widely used for protective device in electrical power equipment. In Malaysia, the biggest electric provider is Tenaga Nasional Berhad (TNB). The gap overhead transmission lines in TNB are applied to minimize or prevent sag of an overhead transmission line. Greater gap is applied give less chances to breakdown and this will provide more safety condition on the overhead transmission line.

2. Electrode Configuration

Electrode configuration is array of electrodes used to measure the electric field distribution, voltage distribution and current density. Insulation design power equipment must be done by considering to the estimated maximum electric field intensity. It will be possible to achieve a high degree uniformity of fields by choosing suitable electrode configurations. Non- uniformity in fields can cause uneconomical and non-reliable of the dielectric. The more non-uniformity results in high electric stress in the dielectric which causing dielectric damage. The acceptable electric stress in electrodes is interrelated with total electric field distribution in the space between electrodes and the electric strength of insulating material in use. To obtain higher degree of uniformity of electric field, the electrode configuration must well- designed in overall aspect. The figure 1 shows the some typical of electrodes configurations which generally using for measuring electric field distribution in the gap or on electrode. The sphere-sphere usually used for measuring the peak voltages in high voltage engineering field (Lee & Lee, 2018).

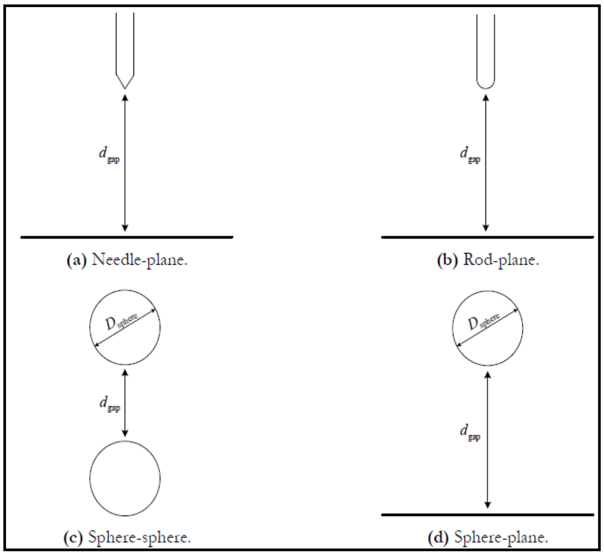


Figure 1 Typical configuration of electrode for testing electric field intensity (Michealrakis, 2015)

In Figure 2, the curves 1 and 2 represent curved shaped electrodes, curves of 3,4 and 5 are for cylindrical electrodes and 6,7 and 8 for spherical electrodes. From the curve, it is shown that the different electrodes systems depend on the value of degree of uniformity, η. The curve is revealed the fields between cylinder electrodes system; cylinder – plane, concentric cylinders, cylinder-cylinder, etc. have higher value of η that is they are more uniform than the fields in spherical electrode system; sphere-plane (Sasamoto, Nomiyama, Izawa, & Nishijima, 2017), concentric sphere. The curves also explain that symmetrical electrode such as sphere-sphere or cylinder-cylinder has higher value of η than the unsymmetrical electrode which is cylinder-plane or sphere plane. In addition, the field between two identical electrodes that placed adjacent to each other has higher value of η than when the electrodes are placed in concentric formation. So as to control electric stress in high voltage apparatus, sharp points and edges should be avoid. Instead, symmetrical, smoothly shaped and large electrodes are preferable to use. (R.E James & Q.Su, 2008). The Schwaiger curve established that the degree of uniformity, η as a function of geometrical characteristic, p for an electrode configuration.

$$p = (r+d)/r \qquad (1)$$

$(1 \leq p < \infty)$ and

$$\eta = f(p) \qquad (2)$$

Where d is the shortest gap distance between the two electrodes under consideration and r is the curvature of the sharpest electrode.

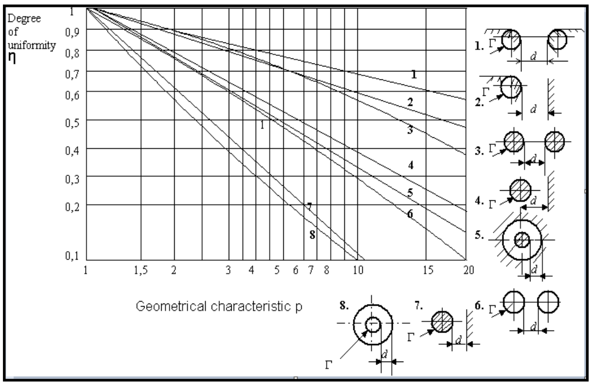


Figure 2 Schwaiger curves for fields with spherical, cylindrical, and curved electrode (R.E James & Q.Su, 2008).

3. Coulomb's Law

This law states the computation of force, F between electric charges, q which act as a source and another random electric charges, q. Both of the charges are seemed to be in movement as time function. When the source charge is in stationary position while the rest of charges are moving, then this phenomenon considered as electrostatic case. In this study, the force, F between source charges and random moving charges can be calculated by Coulomb's law:

$$F = \frac{1}{4\pi\varepsilon_o}\frac{q_s q_x}{r^2} \qquad (3)$$

Where, r is the distance between the two charges, ε_o is the permittivity of free space and $\hat{r}$ is position vector. The Coulomb's law is followed by superposition principle in the case when the source charge comprises of multiple point charges,

$$F = F_1 + F_2 + F_3 + \ldots F_n \qquad (4)$$

4. Electric Field

The electric field is defined in two ways in electrostatic. The one triggered by point charges and the other triggered by continuous distributions such as surface, volume and line charges. The electric field from several point charges is provided y,

$$E\ (\boldsymbol{r}) = \frac{1}{4\pi\varepsilon_o}\sum_{i=1}^{n}\frac{q_i}{r_i^2} \qquad (5)$$

r_i is the distance between the point charges q_i and the point where the electric field is computed. The equation that illustrates the continuous charge distribution is

$$E\ (r) = \frac{1}{4\pi\varepsilon_o}\int\frac{d_q}{r^2}\,\hat{r} \qquad (6)$$

d_q = amount of the distributed charge.

5. Uniform Distribution and Non-Uniform Distribution

Uniform distribution of electrostatic field described field between two parallel, infinite and opposite charged plates and the principle behind uniform electrostatic field distribution is pretty easy. The electric field that never get distract and directs from positive-charge plate to negative-charge plate considered the field distribute uniformly on the surface of electrode. The voltage along the gap, d decreases from top to bottom plate, the gradient of voltage will be constant. The Figure 3 shows the uniform electric field distribution between electrodes. This kind distribution usually provided by symmetrical electrode system such as plane-plane, sphere-sphere.

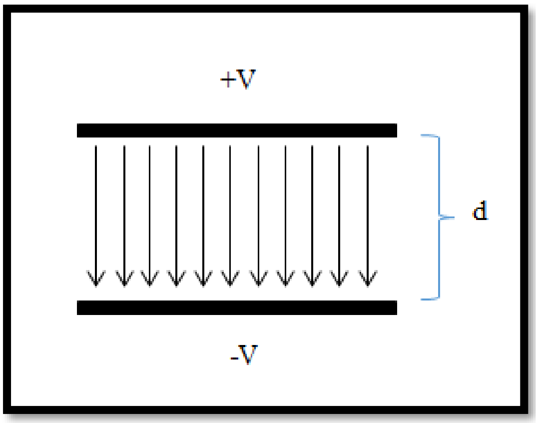


Figure 3 Electric field distribute uniformly on surface of ground electrode.

The non-uniform electrostatic field distributions occur in almost all the electrode configurations as it become more realistic approach. The maximum electric field usually occur in the tip of the needle because of its sharpness and the tip become place of concentration of high electric field and at the same time rapid fall in the place of it as shown in Figure 4. The gradient of voltage kept constant and voltage decrease from the top to bottom of electrode.

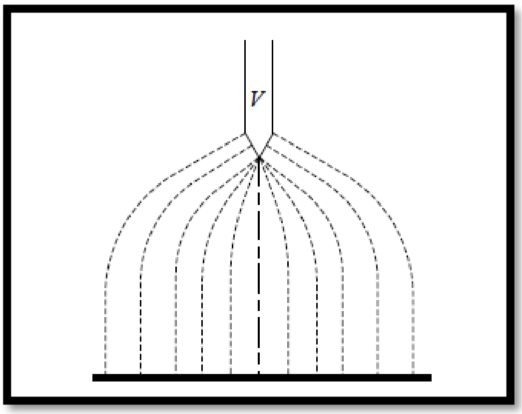


Figure 4 Non-uniform electric field distribute in needle-plane configuration (Michealrakis, 2015)

6. Cross Linked Polyethylene (XLPE)

XLPE is a shortened form of cross-linked polyethylene. It is one kind of solid insulation which protects the power equipment from damage and able to increase the life span of equipment. It has an excellent electrical property compared to many other solid dielectrics such as paper insulation. It has very low relative permittivity, “ε_r” and also very low loss tangent, “tan δ”, both of which are almost independent of temperature and frequency (R.E James & Q.Su, 2008). The dissipation factor or tan δ is an indication of condition of dielectric. The higher the value, the worse condition of insulation will be. For better insulation, tan δ is of the order of 1-3× 10^{-3}, even for dry oil- impregnated paper at room temperature (R.E James & Q.Su, 2008). The value for XLPE is much lower, perhaps 0.3× 10^{-4}. XLPE is usually use for medium and high voltage cables due to their low dielectric loss and moderately high electric strength.

7. Simulation Procedure

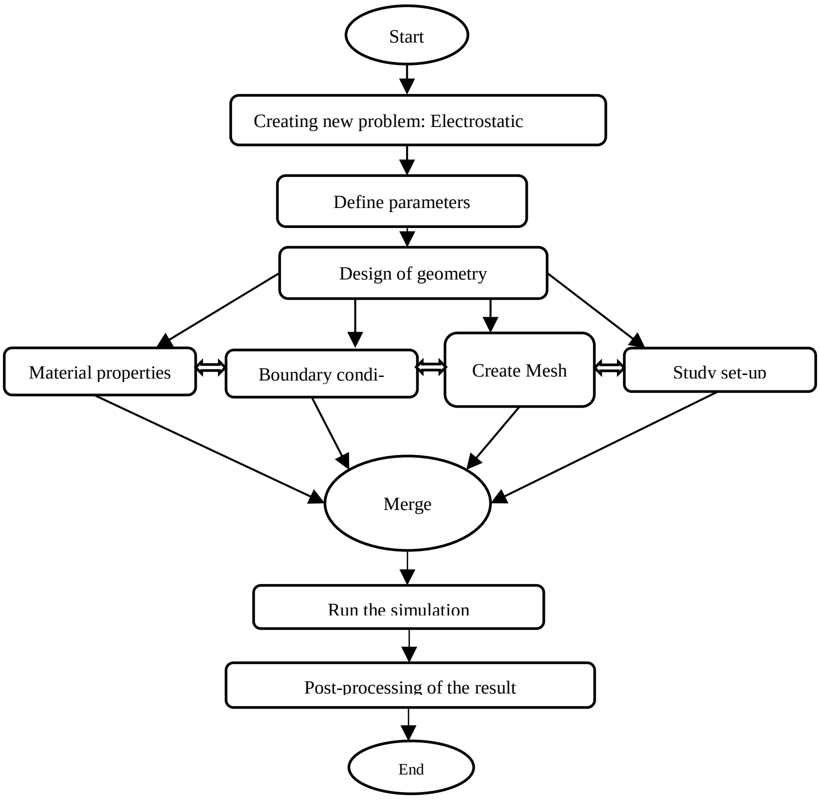
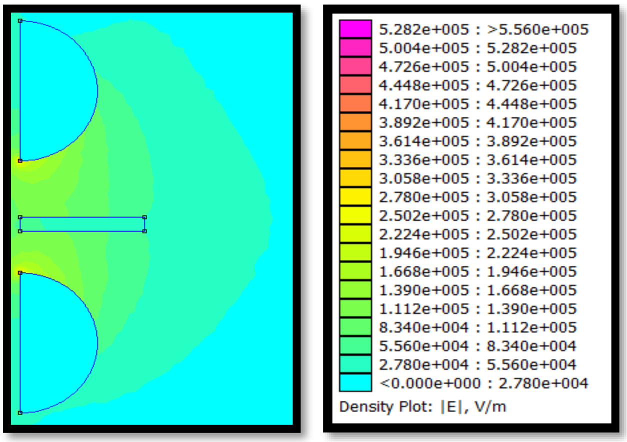


Figure 5 Flowchart of simulation

This project deals with FEM software where modelled the electrostatic problem to simulate and produce the results. The fundamental steps in simulation procedure are described. The basic steps that involved for the simulation in FEMM are electrostatic preprocessor and postprocessor. The drawing geometry, defining materials and defining boundary conditions involved in preprocessor. In postprocessor, the view of solution and generated results are involved. The selections of appropriate parameters are playing important roles in order to generate result with great accuracy and precision. Otherwise, errors and incorrect results occur in the end of simulation.

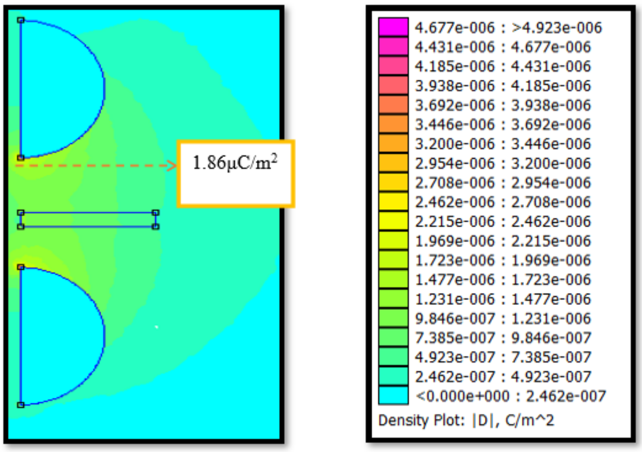
8. Results and Discussion

The result obtained for sphere-sphere electrode configuration from FEM software. It reveals the maximum electric field distribution occurs at the bottom of the sphere as shown in Figure 6. The bottom of sphere becomes highly concentration area for flux density which expressed in Figure 7. It can be observed the equipotential lines are symmetrical in the gap which shows the electric field distribution is in uniform in the gap and the equipotential lines not pass through the dielectric barrier as shown in Figure 8.



(a) (b)

Figure 6: (a) Maximum electric field region (b) Electric field range



(a) (b)

Figure 7: (a) Maximum current density region (b) Current density range

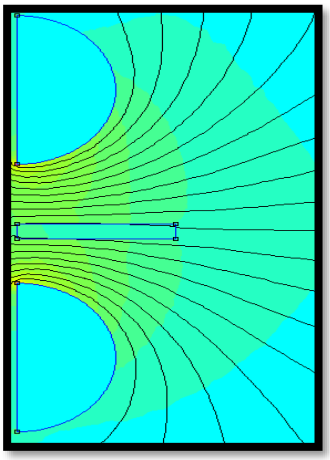


Figure 8 Equipotential lines

The graph obtained for electric field and flux density with the gap spacing in the sphere electrodes. From the graph, it can be concluded that the electric field and flux density decreasing when the gap distance increasing. The small gap distance can lead to obtain higher electric field which said to be critical point of view. The electric field graph drops deeply at gap length of 2 cm and rises back at the gap length of 2.5 cm as shown in Figure 9. The flux density graph fluctuates in the gap distance of 2 cm until 2.5 cm as depicted in Figure 10.

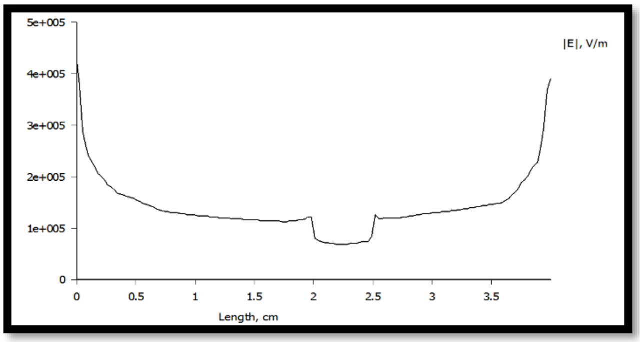


Figure 9: The graph of electric field versus gap spacing

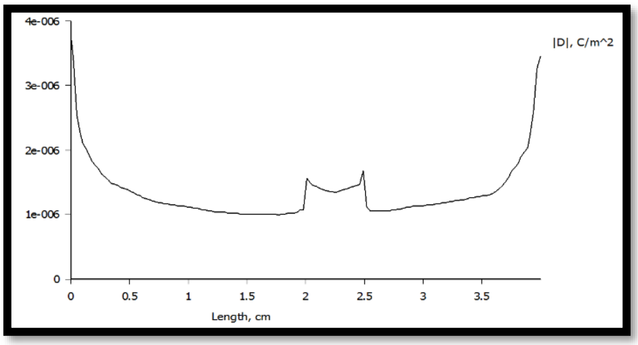
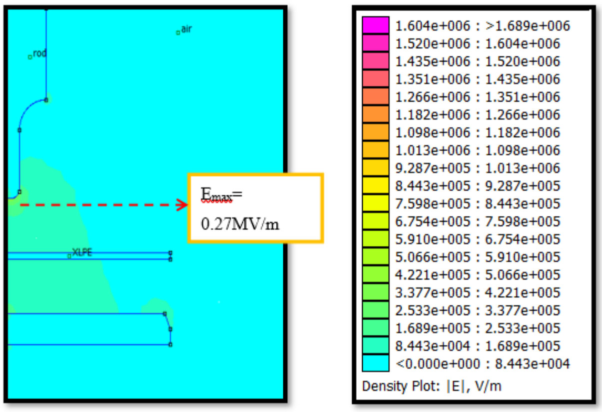


Figure 10: The graph of flux density versus gap spacing

From the result, the electric fields reach its maximum value at the end of the rod which pointing towards the plane electrode as shown in Figure 11. The electric field distribution in the gap of rod-plane electrodes is non-uniform and the equipotential lines are passing across the dielectric barrier and the equipotential lines condense at the end of rod as illustrated in Figure 12. The non-uniform electric field in the gap of electrodes can cause the breakdown of the dielectric barrier easily because of electric stress. The electrical strength of dielectric barrier rapidly reduces when the applied voltage exceeds the breakdown voltage. The high amount of flux concentrated at the end of rod as shown in Figure 13.



(a) (b)

Figure 11: (a) Maximum electric field (b) Electric field region

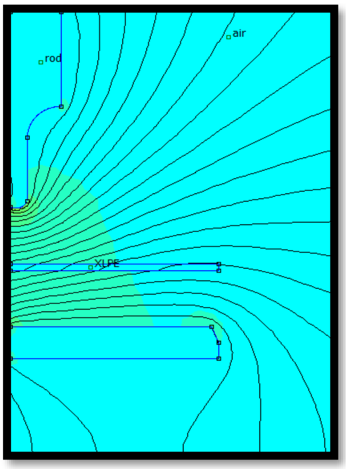
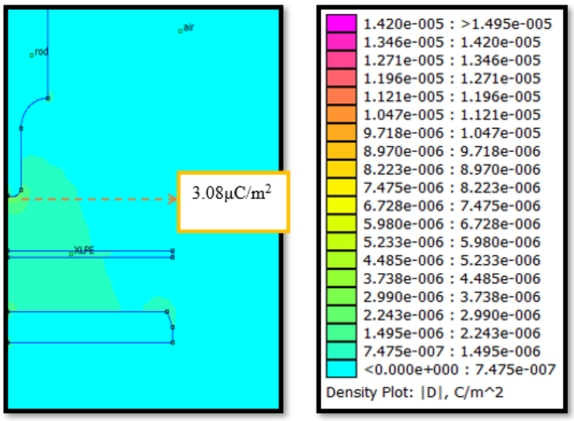


Figure 12: Equipotential lines



(a) (b)

Figure 13: (a) Maximum flux density (b) Flux density range

The graphs depicted the increase of gap distance between the rod-plane resulting in the drop of electric field in the gap spacing as shown in Figure 13.

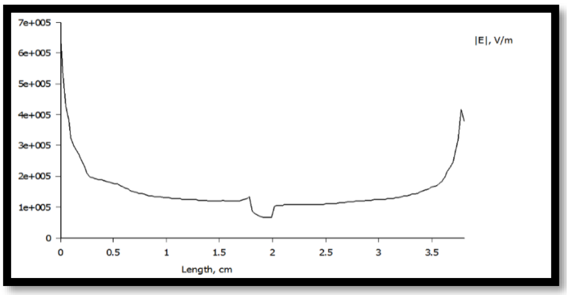


Figure 14: The graph of electric field versus gap spacing

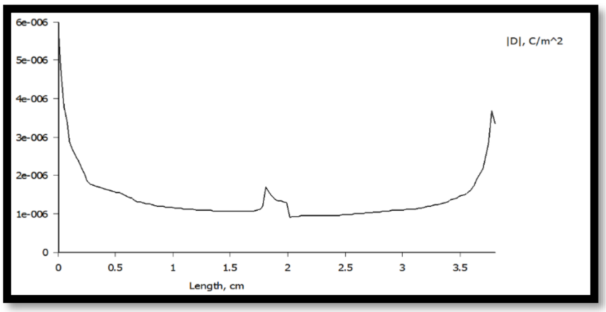
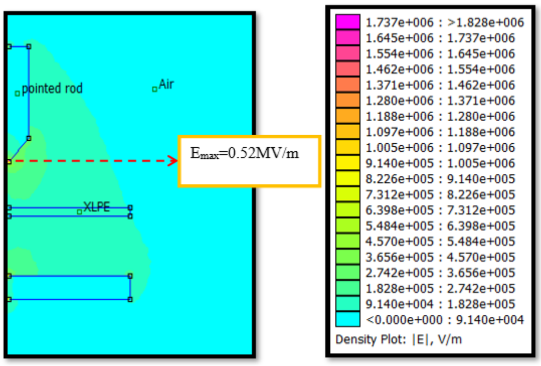


Figure 15: The graph of flux density versus gap spacing

The simulation results reveal that the maximum electric field found at the sharp point and edges of pointed electrode as shown in Figure 15. This is because the electric field usually accumulated at sharp and edges surfaces in high amount. Thus, the electrodes should design with smooth surface and make sure the electrode should not have edges and sharp appearances. The electrical distribution is in non-uniform and the equipotential lines pass across the dielectric barrier as shown in Figure 16. The high amount of flux also focused at sharp point region and edges region as shown in Figure 17.



(a) (b)

Figure 16: (a) Maximum electric field (b) Electric field region

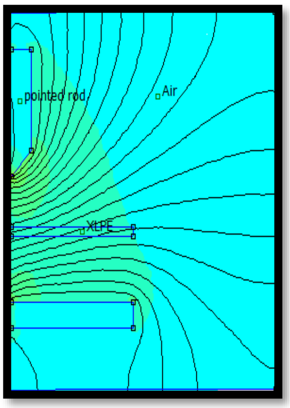
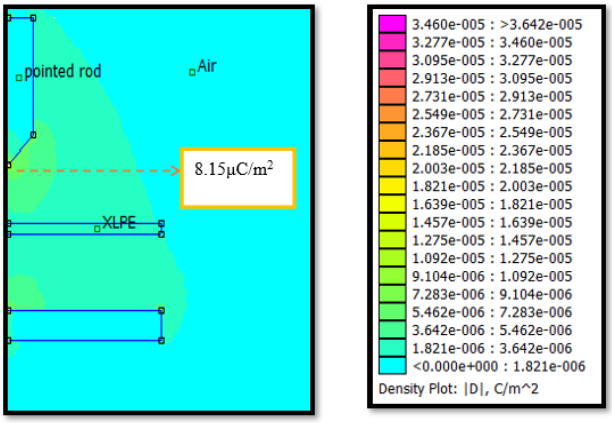


Figure 17: Equipotential lines



(a) (b)

Figure 18: (a) Maximum flux density (b) Flux density range

The electric field decreases gradually when the gap distance increases as shown in Figure 18. The flux density also decreases as the gap distance increase as shown in Figure 19.

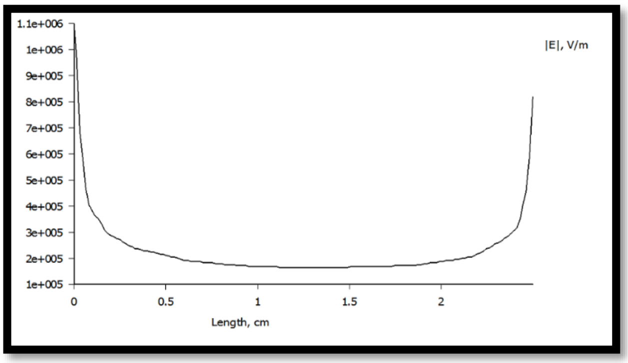


Figure 19: Electric field versus gap distance

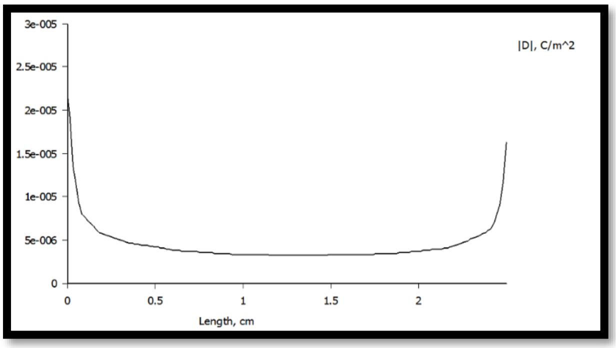


Figure 20: Flux density versus gap distance

When differentiate three electrode configurations, it can be observed that the symmetrical electrodes configuration such as sphere-sphere provide uniform distribution. The electrical strength of dielectric barrier is great when the uniform electric field distribution expose on it. This means the resistance of dielectric barrier will not reduce rapidly in uniform electric field distribution on it. Unlike, the unsymmetrical electrodes configuration such as rod-plane and pointed electrode-plane produce the non-uniform electric field distribution where the dielectric barrier tends to damage rapidly. The degree of uniformity is high for the symmetrical electrodes but low for the unsymmetrical electrodes. The degree of uniformity is very low for pointed rod-plane when compared to other two electrode configurations. The non- uniform electric distribution creates electrical stress within the surface of dielectric barrier. Consequently, the electrical breakdown which said to be electrical tree growth will occur. From the overall observation, when the gap distance between the electrodes increase the electric field decrease.

Furthermore, in all three electrode configurations, it can be observed that, the electric field and flux density increases when the gap distance is 2 cm. This is because positive charge is attracted more to the ground electrode. This can be related to the lightning phenomena. The high voltage terminal can be related to the cloud and the ground can be related to ground terminal. Maximum electric field can occur anywhere when conductor is being place close to it.

9. Conclusion

When differentiate the three electrodes configuration, it can be observed that the symmetrical electrodes configuration such as sphere-sphere provide uniform distribution. The electrical strength of dielectric barrier is great when the uniform electric field distribution expose on it. This means the resistance of dielectric barrier will not reduce rapidly in uniform electric field distribution on it. Unlike, the unsymmetrical electrodes configuration such as rod-plane and pointed electrode-plane produce the non-uniform electric field distribution where the dielectric barrier tends to damage rapidly. The degree of uniformity is high for the symmetrical electrodes but low for the unsymmetrical electrodes. The degree of uniformity is very low for pointed rod-plane when compared to other two electrode configurations. The non- uniform electric distribu-tion creates electrical stress within the surface of dielectric barrier. Consequently, the electrical breakdown which said to be electrical tree growth will occur. From the overall observation, when the gap distance between the electrodes increase the electric field decrease.

Acknowledgement

The authors gratefully acknowledge the Research Management Centre of Universiti Tun Hussein Onn Malaysia under grant GPPS vote H025, Research Fund, UTHM, Kvolt Focus Group Team and High Voltage Laboratory UTHM for the equipment support.

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