Analysis of Dielectric Behavior of Various Components at Rated Impulse Voltages

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Abstract: In this paper the validity of a finite element method based analysis with simulation tool, Maxwell software, has been demonstrated to Calculate the electric field distribution in different configuration like plane-plane and point plane, here the diversity in distribution of field stress can be seen due to uniform field distribution and non-uniform field distribution, with the analysis of plane-plane configuration the theory of higher the capacitance higher the charge storing capacity can be checked.

***Keywords*: Electric field intensity, dielectric material, permittivity, capacitance**

I. INTRODUCTION

The electric field here classified on the basis of 'Uniformity' and 'Non-uniformity'. In the Uniform field the potential is linearly distributed and the electric field intensity is constant throughout the space between the two electrodes. The characteristic of this type of uniform electric field is that the insulation breakdown takes place without any partial discharge preceding the breakdown. Similarly, if we deal with non-uniform field then, there is an extreme nonlinear distribution of potential in the space between two point (needle) electrodes. The characteristic of non-uniform field shows that the insulation breakdown takes place after stable partial discharge (pre discharge) are set. These pre discharges are remains unstable only just before the breakdown. [2] The electric field distribution in high voltage equipment is a key aspect in electrical design. However, it is generally costly to employ testing to evaluate electric field distribution. In many cases, it is impossible to carry out measurements without affecting the electric field. In the last two decades, finite element analysis (FEA) has been increasingly used in all fields of engineering to aid in simulating various practical problems, including electric field analysis. Experience suggests this is the way to generate rapid and accurate models of high voltage apparatus in an efficient and effective manner [1]. In this paper, finite element analysis is used to help study the diversity in electric field stress distribution due to point plane and plane configuration. Thus to implement in the real world the 3D configuration is used using Maxwell software. The electric field distribution is used in high voltage equipment.

Essentially there are three type of numerical methods employed in high voltage engineering application. The methods are:-

- Finite Element Method (FEM)
- Charge simulation method(CSM)
- Surface charge simulation method (SSM)/ Boundary Element method(BEM)

Here in this paper for simulation in Maxwell we used Finite Element method (FEM) has a dominant position because it is versatile, having a strong interchangeability and can be incorporated into standard programs. "FEM is a computer aided mathematical technique for obtaining approximate numerical solutions to the abstract equations of calculus that predict the response of physical systems subjected to external influences."

II. SIMULATION & ANALYSIS DISCUSSION

1) Analysis of Plane-Plane configuration:

Configuration 1

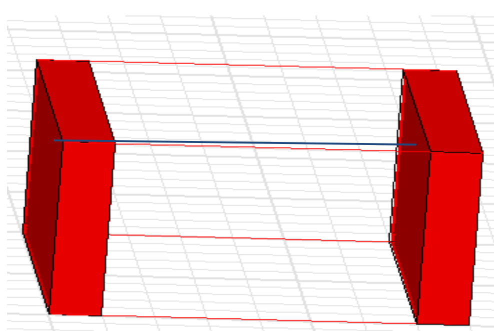


Fig. 1. Configuration with air as dielectric material between two plates

Distance between two plates (60mm), blue line shows its path.
This distance remains constant for all configurations

Here the basic configuration of plane –plane is taken as two plates as shown in above figure with one plate as 1 volt and another as a 0 volt.
Capacitance between two copper plates is 0.73829 pF by simulation.
Capacitance between two copper plates is 0.7378 pF by calculation
For calculation,

$$C=\epsilon_0 \epsilon_r * A/D$$

Where, $\epsilon_0 =$ Permittivity of free space/vacuum ($8.854*10^{-12}$)
$\epsilon_r =$ Relative permittivity

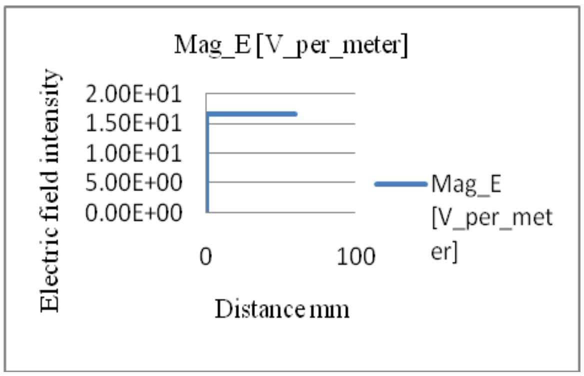


Fig. 2. Electric field intensity v/s Distance mm

This results shown by simulating but also its theoretically also result should be same through its equation E=V/D where V=1 volt and D=60mm, so E=16.66v/m so here we show its simulation result also 16.66v/m.

This is a voltage variation graph

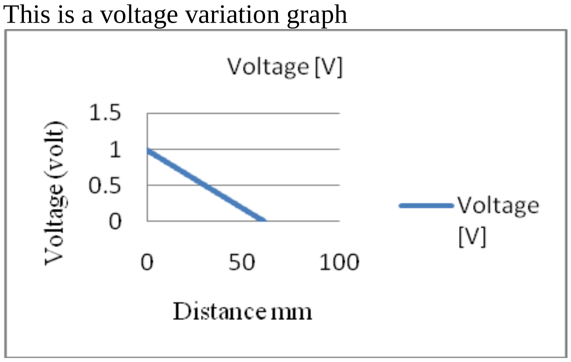
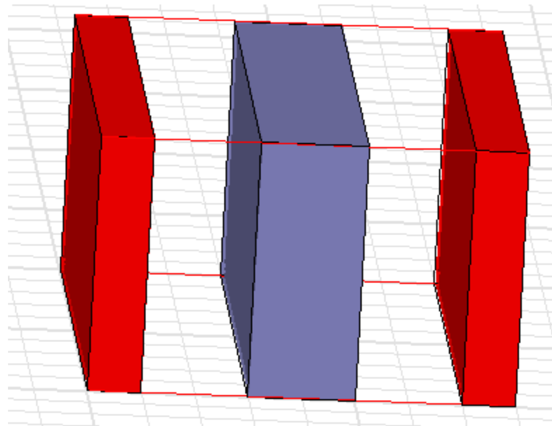


Fig. 3. Voltage v/s Distance

Configuration 2

Now in another configuration in which we are providing one material between two plates. This is given below:



Dielectric plate (permittivity 2, 3, 4 respectively)

Copper conductors

(Note: Distance between materials is 30mm).
Fig. 4. Configuration with one material between two plates

Object	NO. of object	Length (mm)	Height (mm)	Thickness (mm)
Plate	2	50	100	10
Dielectric	1	50	100	20
Air gap	2	50	100	40

Table. 1. Dimension for objects

By theoretically we can find it out its capacitance value

$$1/C = [\{(D-t)/ \epsilon_0 \epsilon_r * A\} + \{t/\epsilon_0 \epsilon_r * A\}]$$

t = thickness of dielectric material
A = Area of Copper plate

From below table we can show its simulated & theoretical value will be same.

Sr. NO	Permittivity	Capacitance* Theoretically (pF)	Capacitance* Simulated (pF)
1	2	0.8854	0.88584
2	3	0.94864	0.94915
3	4	0.98377	0.98432

Table. 2. These capacitances are between two copper plates

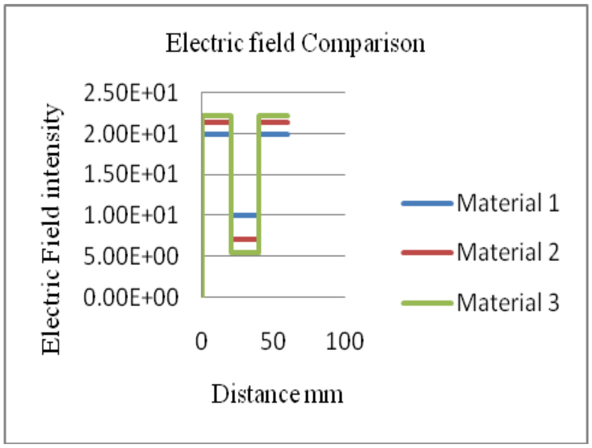


Fig. 5. Electric Field intensity v/s Distance

Here the electric field intensity graph is shown as using three material as described dielectric material act as a barrier, more the permittivity higher will be electric field stress outside the material as it will not allow to pass the electric field lines through it thus more field line will get outside the material on both the side thus electric field intensity is high outside the material and inside the material field intensity is very less.

Region	Material	Q(pC)	N	C(pF)
Region 1	Air	0.871129	5444556.25	2.21235
Region 2	Material (Per2)	0.88580	5536295	4.427
Region 3	Air	0.83994644	5249665.25	2.21235
Regions	**Material**	**Q(pC)**	**N**	**C(pF)**
Region 1	Air	0.933384	5833651.58	2.21235
Region 2	Material (Per3)	0.9642	6026250	6.6405
Region 3	Air	0.9541955	5963721.87	2.21235
Regions	**Material**	**Q(pC)**	**N**	**C(pF)**
Region 1	Air	0.96797	6049827.52	2.21235
Region 2	Material (Per4)	1.0157	6348539.35	8.854
Region 3	Air	0.98455	6153488.49	2.21235

Table. 3. Regions

As we know the charge storing capacity of a capacitor is known as Capacitance. Thus above table shows that high the capacitance high the charge particle thus it proves the theory.

Here,

Region 1 is the Region between 1v plate and Dielectric material (20mm).

Region 2 is the Region inside the dielectric material (20 mm)

Region 3 is the Region between dielectric material and 0V plate. (20 mm)

Q= Total charge in the given region.

N=Number of electrons in the region

N=$1.60*10^{-19}$ coulomb

C=Capacitance between two surface around region

Configuration 3

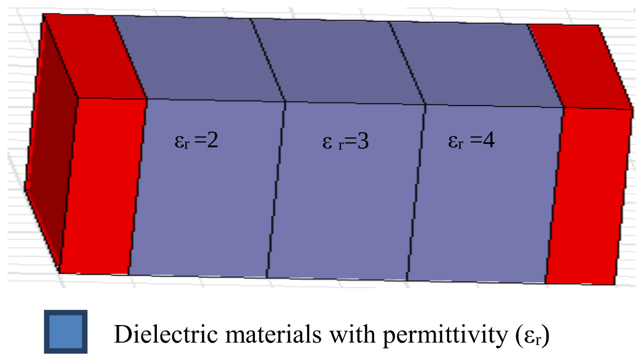


Fig. 6. Configuration with three materials between two plates

It shows composite dielectric material figure with the three material of 2, 3, 4 permittivity.

Capacitance between two copper plates is 2.0432 pF by simulation

Capacitance between two copper plates is 2.0433pF by calculation

For calculation:

$$C= (t_1 /\varepsilon_{r1} * \varepsilon_0 * A) +(t_2 / \varepsilon_{r2} * \varepsilon_0 * A)+(t_3 / \varepsilon_{r3} * \varepsilon_0 * A)$$

$t_{1, 2, 3}$ =Thickness of dielectric plate 1, 2, 3 respectively.

$\varepsilon_{r1,2,3}$ =Relative permittivity of dielectric materials 1,2,3 resp.

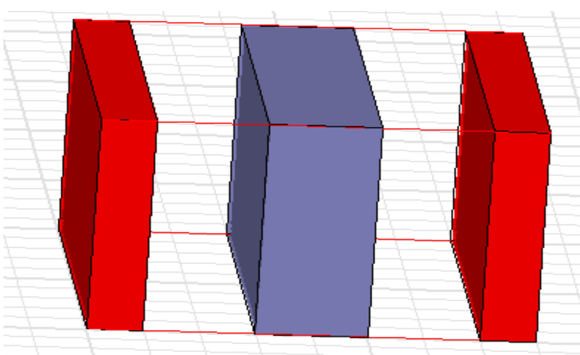
Regions	Material	Q(pC)	N	C(pF)
Region 1	Material(Per2)	2.010	12565486.1	4.427
Region 2	Material (Per3)	2.0268200	12667625	6.6405
Region 3	Material (Per4)	2.130493	13315585.9	8.854

Table. 4. Regions

Again,
Q= Total charge in the given region.
N=Number of electrons in the region.
N=1.60*10^{-19} coulomb
C=Capacitance between two surface around region
Region 1 is the Region inside the dielectric material having ε_r =2. (20 mm)
Region 2 is the Region inside the dielectric material having ε_r =3. (20 mm)
Region 3 is the Region inside the dielectric material having ε_r =4. (20 mm)

Configuration 4

From first conductor to material distance is 10mm & for second 30mm and for that the analysis graph is shown below:



Dielectric materials with permittivity (ε_r)
Copper conductor
Fig. 7. Configuration with single material having different distance between two plates

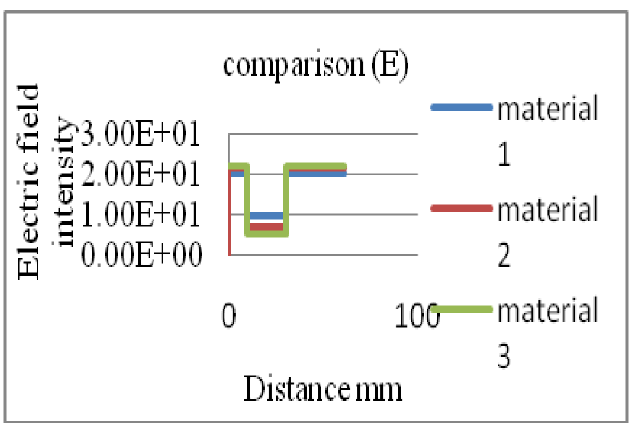


Fig. 8. Electric field v/s Distance

Here the electric field intensity using three materials as describe dielectric material act as a barrier more the permittivity higher will be electric stress and inside the field intensity is very less.

Dielectric material	C1	C2	C3	Q1	Q2	Q3	N1	N2	N3
Material (Per.2)	4.427	4.427	1.475	0.8606	0.8889	0.8920	5378750	5555625	5575000
Material (Per.3)	4.427	6.640	1.475	0.9334	0.9488	0.9532	5833750	5930000	5957500
Material (Per.4)	4.427	8.854	1.475	0.9680	0.9916	0.9872	6050000	6197500	6170000

Table. 5. Dielectric materials

As we know the charge capacitance is equal to charge storage capacity. Thus above table shows that high the capacitance high the charge particle.

Dielectric material	C1	C2	C3	Q1	Q2	Q3	N1	N2	N3
Material (Per.2)	4.427	4.427	1.475	0.8606	0.8889	0.8920	5378750	5555625	5575000
Material (Per.3)	4.427	6.640	1.475	0.9334	0.9488	0.9532	5833750	5930000	5957500
Material (Per.4)	4.427	8.854	1.475	0.9680	0.9916	0.9872	6050000	6197500	6170000

Table. 6. Dielectric materials

Here,
Per. =permittivity
Region 1 is the Region between 1v plate and Dielectric material (10mm).
Region 2 is the Region inside the dielectric material (20 mm)
Region 3 is the Region between dielectric material and 0V plate. (30 mm)
V1=Voltage across region 1
V2=Voltage across region 3
C1, C2, C3=Capacitance across region 1, region 2, region 3 respectively.
Q1, Q2, Q3=charge inside the region 1, region 2, region 3 respectively.
N1, N2, N3=Number of electrons in the region 1, region 2, region 3 respectively.

2) Point plane configuration:

Mostly there are irregular shapes and edges are there due to which there is non uniform field distribution So to understand the phenomena we are using point plane configuration Plane is used as a earthing plate. As mostly every instrument mostly enclosed with the plane sheet of steel. As described dielectric material acts as a barrier, more the permittivity higher will be electric field stress between metallic plate and dielectric material and electric field intensity inside the dielectric material is less as shown in above figure.

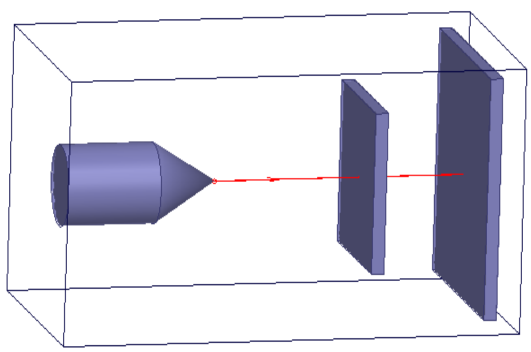


Fig. 9. Distance between point and dielectric material

Here,

D = Distance between point and dielectric material which has been taken 5mm, 10mm&15mm.

Dielectric material is placed between point and plane and is of different Point and plane are made of copper material.Point has given 1volt & plane has given 0volt & red line shows path

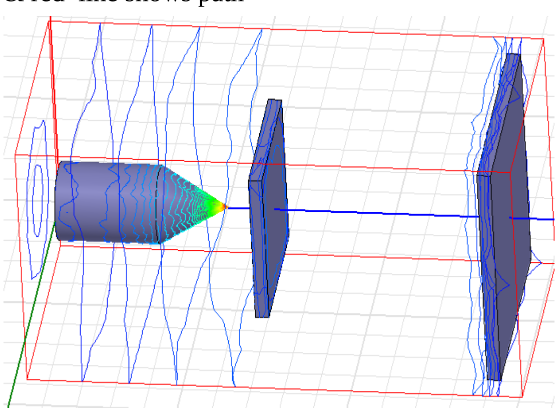


Fig. 10. Isolines

Isolines are shown in above graph .isolines are normal vector to the electric field line red indicates higher voltage level & blue indicate lowest voltage level. As we have applied 1volt & the 0volt at earth surface or plate.

After giving different material between point & plane like polyamide, Fr4 epoxy, Bakelite, Mica, silicon we can get different results for electric field intensity.

We have taken the readings of E max by putting the dielectric material at different places and also with different Dielectric materials. In above figure the value of E_{max} is shown at the tip of point due to its sharp edge. This is shown in below table:

Permittivity of different material as shown below:

Polyamide=4.3, Fr4 epoxy=4.4, Bakelite=4.8

Mica=5.7,Silicon=11.9

Distance	Polyamide	Fr4 epoxy	Bakelite	Mica	Silicon
5mm	239.83	239.992	240.258	240.874	242.892
10mm	202.337	202.375	202.512	202.758	203.513
15mm	182.497	182.523	182.618	183.241	183.783

Table. 7. Distance v/s E max (v/m) with different materials

Here with the help of above table we can see the maximum value of field stress using different dielectric material for the different gap spacing. This study will be helpful in providing the insulation at different distances. The ideal material should have higher dielectric strength with lower relative permittivity. It shows that with the increase the permittivity the dielectric strength of the material increase

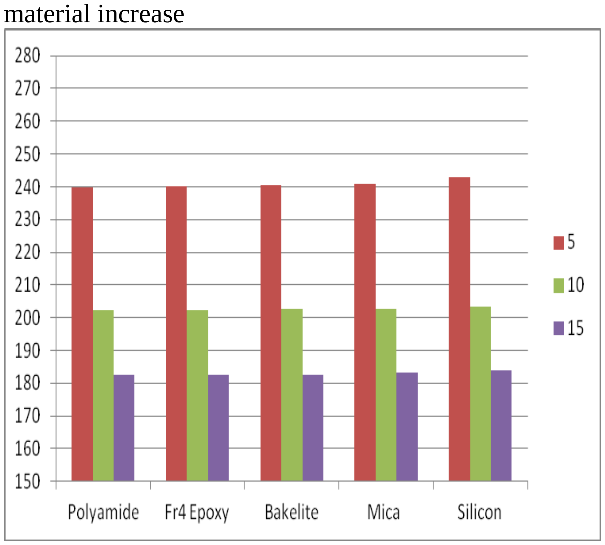


Fig. 11. Comparision

As we know dielectric material act as a barrier thus as permittivity increases the electric field stress increases at the point surface. When dielectric material is near the point i.e. on the 5mm the electric field value is maximum. as more amount of the field lines are obstructed compare to the other distances i.e. 10&15mm.& as we know higher the permittivity more Emax .In such cases it can be seen that the insulating material does not get puncture but due to high stress value in outside region a partial discharges path takes form and it make get fail.

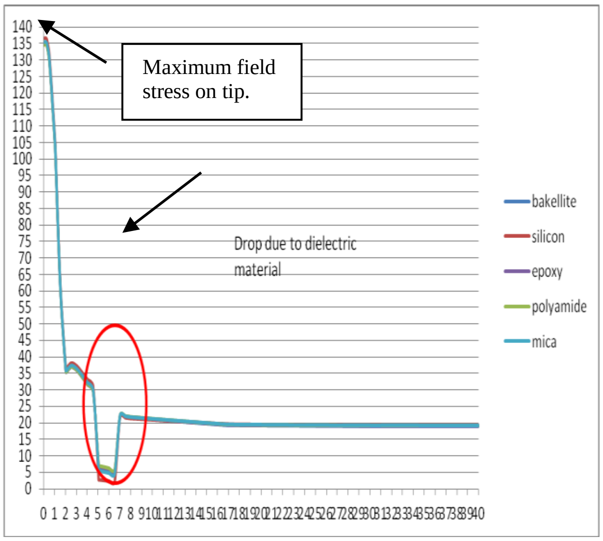


Fig. 12. Maximum field stress in tip

As from the above graph we can see that near the point show the maximum field stress. Inside the dielectric material there is lowest value of Emax. After passing through the dielectric material there will be two plane forming one of dielectric plate and of ground plate due to which it shows uniform distribution of electric field intensity as shown in earlier configuration.

III. CONCLUSION:

From the above paper we can conclude that the plane-plane is an example of uniform field distribution and point plane is an example of non-uniform field distribution. It also proves how the charge storing capacity of a capacitor increases with selecting higher relative permittivity material. We can also see how dramatically change in electric field intensity changes due to edge factor. As it can concluded that E=V/D as smaller will be the distance more will be electric field intensity it is in the case of point surface's or in edges cases. So it makes importance of smoothening the edges of high voltage apparatus in order to decrease the electric field stress and proper clearance has to be provided with proper grading of insulating material.

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