MODELING OF ELECTRIC FIELD DISTRIBUTION IN EPOXY NANOCOMPOSITES USING FINITE ELEMENT METHOD

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Abstract

Electrical treeing gets initiated from voids or impurities present in the volume of the solid insulating material where partial discharge occurs due to the enhanced stress. Breakdown of the insulation can be delayed if the insulation gives higher resistance to the propagation of the discharge in the form of an electrical tree. It is well understood from some of the reported experimental results that addition of nanoparticles improves the electrical properties of a base insulating material. The shape, size and percentage loading etc. of the nanoparticles play a good role in deciding the properties of the nanocomposites. Theoretical analysis for determining the influence of fillers and the dependence of its size, shape and composition on the electrical properties of the composite is limited in the literature. In this work, the electric field stress of different nanocomposites at different points in the matrix is found using Finite Element Method (FEM). From the determined stress, the propagation of electrical treeing is analysed for different nanocomposites and the properties of the fillers required for enhanced resistance to electrical treeing is identified.

***Keywords**: Electrical treeing, nanocomposites, electric field distribution, Finite Element Method (FEM).*

1. Introduction

Epoxy resins are well-known solid dielectric materials with superior electrical and mechanical properties. Practical solid dielectric systems often contain voids or cavities within the dielectric materials or on boundaries between the solid dielectric and the electrodes. These cavities are filled with a medium of lower dielectric strength and dielectric constant value than the solid dielectric

materials, which causes the field intensity in the cavity to be higher than that in the dielectric. Under normal working stress of the dielectric system the voltage across the cavity exceed the breakdown value and may initiate breakdown in the cavity. Once discharge happened inside the cavity the discharge channels penetrate towards the region having high electric field stress inside the dielectric and gives rise to channel propagation like tree growth through the dielectric materials. The electric field intensity of the dielectric material depends on the applied voltage and distance between the electrodes [1].

Epoxy composites with nanofillers can be used as insulating materials with greater electrical, mechanical and thermal properties than unfilled base epoxy. Epoxy loaded with nanofillers has higher dielectric strength and high value of resistance to electric discharge than base epoxy resin and epoxy with micro size fillers. It has been demonstrated in various studies that insulating nanomaterials like nano-sized titanium dioxide (TiO_2), zinc oxide (ZnO), alumina (Al_2O_3), calcium carbonate ($CaCO_3$) and layered silicates when added to base epoxy resins in different weight percentages alters the dielectric properties of the resin. At low nanofiller concentration (≤ 5% by weight) a significant change in the electrical properties of the epoxy nanocomposites[2].Imai et al with 5wt% filler concentration of layered silicate and TiO2 had lower breakdown strength than base epoxy and higher breakdown strength for epoxy silica nanocomposites. A slight reduction of ac dielectric strength was observed in epoxy – alumina nanocomposites at 0.1wt% and 1wt% nanofiller loading. The ac dielectric strength was higher for 5wt% nano alumina and was lowered further as nano – alumina content increased to 10wt% and 15wt% [3,4].

When the sample is subjected to high voltage, there is a probability of electrical tree growth occurring in the material due to the stress concentration inside the sample. Most of the literature on the treeing phenomena is based on experimental studies. Zein and Lee et al simulated the field distribution process employing the Finite Element Method (FEM) for different electrode system [5,6]. The FEM provides solution over the entire region of interest by solving Laplace equation. However, simulation models of electrical tree grown based on electric field distribution have not yet been reported. In this paper electric field distribution and probability of tree growth in epoxy nanocomposites were simulated using FEM. The effect of type (alumina, silca, calcium carbonate and layered silicate), size (50nm and 200nm), shape and content (0.5 and 2.5 weight %) of nanoparticles on the electric field distribution and tree growth were investigated using needle-plane electrode configuration. The COMSOL simulation software was used for FEM analysis.

2. Simulation of electric field distribution in unfilled base epoxy with and without void.

In this simulation epoxy was considered as the base material as sample. The dimension of sample used in simulation was 40mmx40mmx2.5mm.The dielectric strength of base epoxy varies between $18\ and\ 25X10^{6} V/m$ and dielectric constant is 2.8. This sample was subjected to breakdown voltage of 45kVrms between needle-plane electrode configurations. When high voltage was applied across the sample, the electric field was maximum near to the needle tip and minimum near to the plane. Fig.1. shows the simulated electric field distribution across the 2D sample when subjected to a voltage of 45kV. To understand the effect of a small void on electric field distribution, a void of size 0.5µm diameter filled with air was created near the needle electrode in the sample. The (x,y) coordinates of void location in the sample is $(25\ X10^{-4}m, 25\ X10^{-4}m)$. With the help of colour code the electric field distribution throughout the sample and near to the void were studied and is presented in Fig. 2.

There was non-uniformity in the electric field distribution throughout the sample. The maximum electric field stress was at the needle tip at $7.967\ X\ 10^{7}\ V/m$. This value was greater than dielectric strength of base epoxy. Also, the electric field stress at void was greater than the dielectric strength of air filled in the void. Due to this overstress at the tip of needle and void, partial discharge took place leading to electrical treeing. The electrical tree penetrates towards the point at which electrical stress is maximum.

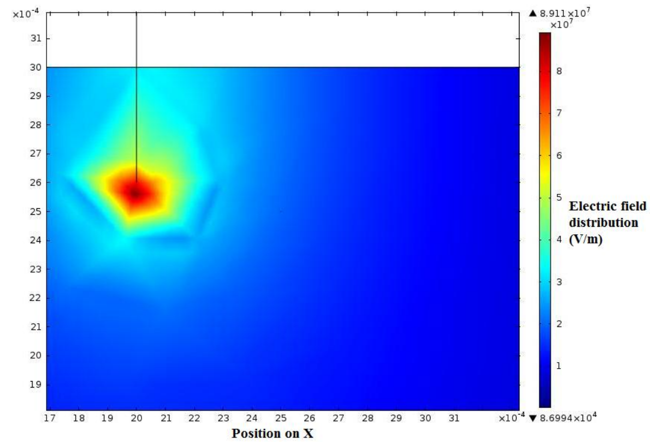


Fig. 1. Electric field distribution in unfilled epoxy sample without void

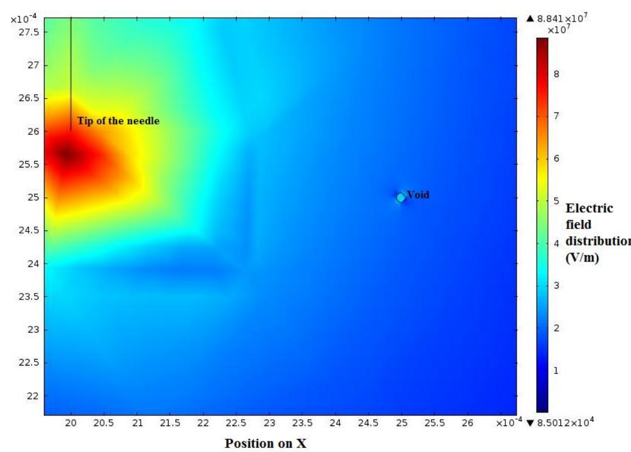


Fig. 2. Electric field distribution in unfilled epoxy sample with void

3. Effect of different nanoparticles on electric field distribution

To improve the insulation properties, nanoparticles were added to the base epoxy. The physical and electrical properties of nanomaterials influence the insulation properties of nanofilled epoxy. The properties that affects the insulation properties are the shape (spherical or layered i.e. 3 dimensional or 1 dimensional), size (diameter and length), the weight percentage and permittivity of the nanoparticles.

3.1 Estimation of interparticle distance between nanoparticles.

It is important to understand inter particle distances as a function of filler sizes and shape as well as filler surface areas to discuss the characteristics of the interaction between the nano-particles. The inter particle distance between nanomaterial for various wt% are tabulated based on Tanaka equation [7].

$$D = [\left\{\frac{\pi}{6}\frac{\rho_m}{\rho_n}\frac{100}{wt\%}\left[1-\frac{wt\%}{100}\left(1-\frac{\rho_m}{\rho_n}\right)\right]\right\}^{1/3}-1]\ d \quad \text{----- (1)}$$

D – Interparticle distance(nm), ρ_n – Specific gravity of nanocompound(g/cm^3), ρ_m - Specific gravity of epoxy resin(g/cm^3), d – Diameter of the nano compound(nm). For a given epoxy nanocomposites, the inter particle distance depends on weight percentage, specific gravity of a nanoparticlesas well as size of nanoparticle. For the same weight percentage as the size of nanoparticle increases the inter particle distance also increases. If base epoxy is loaded with 2.5wt% of nanomaterials, the inter particle distance betweennanoparticle is less thanthat with0.5wt% of loading. The inter particle distance between the nanomaterials reduces with the increasing nanofiller content. Table 1 summarizes the interparticle distance computed for different nanoparticles at different size and weight percentage

Table 1: Inter particle distance

Sample	**Permittivity**	**Interparticle distance (D) nm**			
		0.5wt%		**2.5wt%**	
		50nm	**200nm**	**50nm**	**200nm**
$CaCO_3$	4.5	357	503	122	209
TiO_2	100	258	404	63	151
Layered Silicate	3.2	392	791	58	379
Al_2O_3	9.1	302	401	119	151

As it can be seen from the Table 1, the inter particle distance decreases with increase in wt% of the nanoparticle. Also, for the same wt% value, the inter particle distance of layered silicate is greater when compared to other samples. Layered silicates are plate like structures having aspect ratio much higher than spherical nanoparticles like $CaCO_3$, TiO_2 and Al_2O_3. With increase in the filler concentration the inter-particle distance decreases and the interface become highly immobile.It may be concluded that the interparticle distance has a significant effect on the surface induced degradation and internal discharge [7].

3.2 Simulation of electric field distribution in epoxy nanocomposites

The electric field distribution was simulated by FEM using the software COMSOL. In this analysis field distribution was estimated for materials of different permittivity, different weight percentages and particle sizes. Four different nanomaterials like $CaCO_3$, TiO_2, Al_2O_3 and layered silicate are considered. For each of these nanoparticles two different size of particle 50nm and 200nm are considered for field estimation. Table 2 gives the value of field strength at selected location for different nanoparticles with 50nm size for 0.5 wt% and 2.5wt% loading. Irrespective of the size and shape of nanomaterials used, the electric field stress inside nanoparticles reduced with increased value of permittivity of nanoparticle. It was observed from Table 2 that the electric filed value at the same location is different due to the wt% loading of nanofillers into the base material.

3.3 Effect of size and shape of nanomaterial on electric field

The nanoparticles were placed around the void with different size like 150nm and 200nm into the base epoxy. The nanoparticles used in simulation have different shapes like spherical and layered structured. In simulation the nanoparticles are placed as per estimated inter particle distance. When the sample is subjected to maximum stress the electric field inside the nanomaterial mainly depends upon the permittivity value. As per equation

$$E_2 = \frac{\varepsilon 1}{\varepsilon 2}E_1 \quad \text{------- (2)}$$

E_2 is the electric field stress inside the nanomaterial which decreased with high value of permittivity. As referred Table 2 the electric field stress value inside the nanomaterial is same irrespective of the size and shape of the nanomaterials.

Table 2: The electric stress value at void and inside nanofiller with different permittivity .

nanosize		50nm							
Permittivity		(TiO_2) 100		(Layered silicate) 3.2		($CaCO_3$) 4.5		(Al_2O_3) 9.1	
Position on X(mm)	Position on Y(mm)	0.5wt%	2.5wt%	0.5wt%	2.5wt%	0.5wt%	2.5wt%	0.5wt%	2.5wt%
0.0025	0.0025	2.84E+07	2.84E+07	2.82E+07	2.83E+07	2.82E+07	2.83E+07	2.82E+07	2.83E+07
0.00249	0.0025	1.15E+06	1.15E+06	1.88E+07	2.22E+07	1.56E+07	1.56E+07	9.79E+06	9.72E+06
0.00248	0.0025	1.20E+06	1.20E+06	1.90E+07	2.25E+07	1.58E+07	1.58E+07	9.83E+06	1.98E+07
0.00251	0.0025	1.14E+06	1.14E+06	1.83E+07	2.17E+07	1.52E+07	1.52E+07	9.54E+06	9.46E+06
0.00252	0.0025	1.13E+06	1.13E+06	1.93E+07	2.14E+07	1.93E+07	1.50E+07	1.93E+07	9.25E+06
0.00252	0.00251	1.94E+07	1.16E+06	1.94E+07	2.15E+07	1.94E+07	1.51E+07	1.94E+07	9.44E+06
0.00251	0.00251	1.96E+07	1.15E+06	1.96E+07	2.18E+07	1.96E+07	1.53E+07	1.96E+07	9.61E+06
0.0025	0.00251	1.15E+06	1.15E+06	2.04E+07	2.20E+07	1.55E+07	1.55E+07	9.71E+06	9.77E+06
0.00249	0.00251	2.01E+07	1.01E+06	2.01E+07	2.23E+07	2.01E+07	1.57E+07	2.01E+07	9.77E+06
0.00248	0.00251	2.04E+07	1.04E+06	2.04E+07	2.26E+07	2.04E+07	1.59E+07	2.04E+07	9.93E+06
0.00248	0.00249	2.02E+07	1.02E+06	2.02E+07	2.24E+07	2.02E+07	1.57E+07	2.02E+07	9.85E+06
0.00249	0.00249	1.15E+06	1.15E+06	1.99E+07	2.21E+07	1.99E+07	1.55E+07	1.99E+07	9.69E+06
0.0025	0.00249	1.12E+06	1.12E+06	1.97E+07	2.18E+07	1.97E+07	1.54E+07	9.67E+06	9.69E+06
0.00251	0.00249	1.95E+07	1.15E+06	1.94E+07	2.16E+07	1.94E+07	1.51E+07	1.97E+07	9.50E+06
0.00252	0.00249	1.92E+07	1.12E+06	1.92E+07	2.14E+07	1.92E+07	1.50E+07	1.94E+07	9.37E+06

4. Simulation of tree growth with and without nanofillers

After the occurrence of breakdown inside the void, discharge progresses in dielectric material through the points of maximum stress [8-10]. To plot the growth of tree like discharge, the electric fields across finite elements in the x and y directions were computed. The tree starts from the void and progresses through points of maximum stress in the sample. Fig.3. shows the penetration of electrical tree growth towards the maximum stress point in unfilled epoxy. The study of electrical tree growth based on the electric field distribution throughout the epoxy 2.5wt% loading (50nm size) nanocomposite were shown in Fig. 4. For more understanding the cube was considered, which contained void and nanofillers in base epoxy. According to the dielectric constant value of nanofiller the field stress inside the nanocomposite was varied. Even though Layered Silicate has very low value of permittivity, due to layered shape it restricted the penetration of tree growth at interface. Due to high permittivity value, the electric stress inside the TiO_2 nanoparticles was minimum. It was observed that the field distribution inside of TiO_2 nanofiller is very low compared with other nanofillers is shown in Fig. 4.b. Based on the value of electric field the tree growth penetrate inside and at interface of nanofiller further.

According to Tanaka equation 2.5wt% loading of nanofillers in base epoxy have very less inter particle distance than 0.5wt% loading. The inter particle distance also very important consideration of penetration of tree growth.

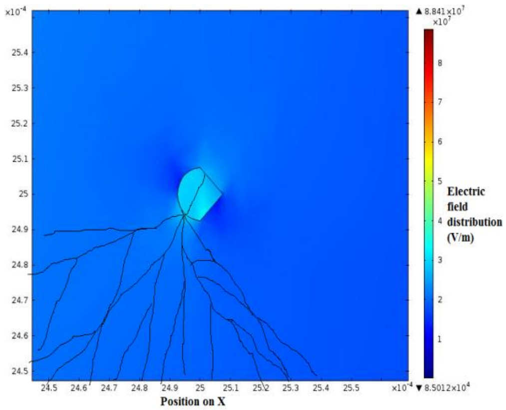
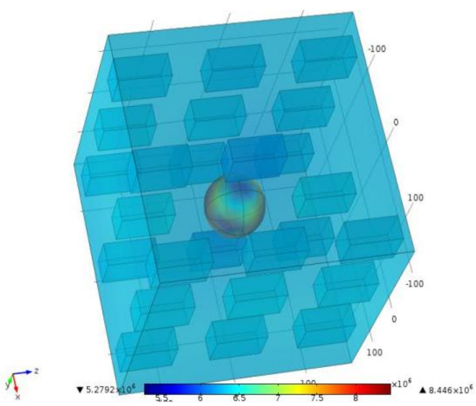
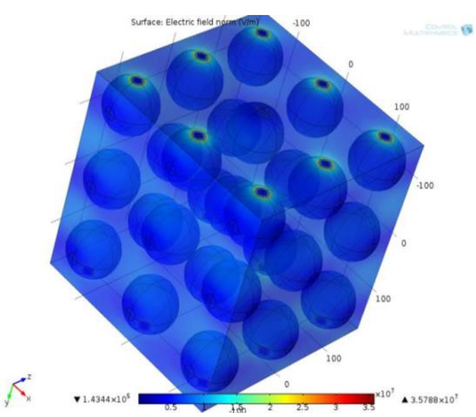


Fig . 3. The penetration of electrical tree growth towards the maximum stress point in unfilled epoxy.



(a) Epoxy Layered Silicate nanocomposites



(b) Epoxy TiO_2 nanocomposites

Fig.4. The electric field distribution in epoxy nanocomposites

5. Discussion

It was observed from the simulation, the electric field distribution inside the nanoparticles is independent of the size of the nanoparticle (50nm and 200nm). This indicates that field distribution is affected by permittivity of the nanoparticles and weight percentage added to base epoxy. A permittivity of a nanocomposite containing a filler with high permittivity will be higher. For example, titania has the highest permittivity and the epoxy – titania nanocomposites is expected to have higher dielectric loss and lower breakdown strength. Among the different nanofillers considered, nanoclay has the lowest permittivity. Hence the discharge path is restricted to within the nanoclay itself and is not propagated much into the polymer matrix.

The penetration of tree growth inside the nanoparticles got restricted based on the electric stress value which intern depends on permittivity value of nanoparticles [11-13]. These simulation results establishes that the percentage of nanoparticle to be added depends upon the permittivity of the nanoparticle selected. It is likely that there is an optimum weight percentage that gives the best resistance to treeing based on the permittivity of nanoparticles.

6. Conclusion

The effect of nanoparticle on an electric field distribution when added to base epoxy is analysed in this paper. Four different types of nanoparticles namely Layered Silicate, TiO_2, $CaCO_3$, Al_2O_3 added to base epoxy with 0.5wt% and 2.5wt% loading. The sample is placed in needle plane electrode configuration without and with void is considered for field analysed using COMSOL simulation software based on FEM. It was observed that the electric field distribution is influenced by permittivity of the nanoparticle and percentage weight rather than size and shape of the nanoparticle. For different permittivity nanoparticle, the variation of field distribution is not directly depended on percentage weight. It is concluded that selecting suitable nanoparticle, both permittivity and percentage weight are to be considered together.

Reference

1. D. Pitsa, G. Vardakis, Michael G. Danikas, M. Kozako, *Electrical Treeing Propagation in Nanocomposites and the role of Nanofillers-simulation with the aid of Cellular Automata*, Journal of Electrical Engineering, Vol. 61, p. 125-128, 2010.
2. P. Preethaand M. Joy Thomas, Influence of Nanofillers on the Surface Electrical Discharge Resistance of Epoxy Insulation Used in HV Power Apparatus, International Journal of Emerging Electric Power Systems, Vol. 12, Iss. 2, Article 1, pp.1-18, June 2011.
3. P. Gonon and A. Boudefel, Electrical properties of epoxy/silver nanocomposites, J. Appl. Phys., Vol. 99, pp. 024308(1)-024308(8), 2006.
4. P. Preetha and M. Joy Thomas, AC Breakdown Characteristics of Epoxy Nanocomposites, IEEE Transactions on Dielectrics and Electrical Insulation. Vol. 18, Issue 5, pp. 1526-1534, October 2011.
5. A.El-Zein.,M.Talaat, and M.MElBahy,*A Numerical Model of Electrical Tree growth in Solid Insulation*, IEEE Transaction on Dielectric Electrical Insulation, Vol. 16, p. 1724-1733, 2009.
6. J.H. Lee, G.S. Park, Y.D.Young, S.G. Kim, S.Y Hahn and M.L Han, An Accurate Method for Numerical Simulation of Electrical Tree growth process by Finite Element Method, in conference of the 1992 IEEE International Symposium on Electrical Insulation, Baltimore, 1992.
7. T. Tanaka, Dielectric Nanocomposites with Insulating Properties,IEEE Trans. Dielectr. Electr. Insul., Vol. 12, No. 5, pp. 914-928, 2005.
8. A.Mahajan, K.E.Seralathan, G.Nandini, *Modeling of Electric Tree Propagation in the Presence of Voids in Epoxy Resin*, in 2007 International Conference on Solid Dielectric, Winchester, p. 138-141, 2007.
9. U. Kurimoto, H. Okubo, K.Kato, M. Hanai, Y. Hoshina, M. Takei and N.Hayakawa, *Dielectric Properties of Epoxy/Alumina Nanocomposite influenced by Control of Micrometric Agglomerates*, IEEE Transaction on Dielectric Electrical Insulation, Vol. 17, p. 662-670, 2010.
10. J. Lee, G.S. Park, Y.D.Young, S.G. Kim, S.Y. Hahn and M.L. Han, *An Accurate Method for Numerical Simulation of Electrical Tree growth process by Finite Element Method*, in conference of the 1992 IEEE International Symposium on Electrical Insulation, Baltimore, 1992.
11. A.A.Hossam-Eldin , S.S.Dessouky ,S.M. El-Mekkawy ,R.A.Abd El-Aal,*Analysis and simulation of field distribution in micro cavities in solid insulating materials*, IEEE Annual report conference on Electrical Insulation and Dielectric Phenomena, p. 792-796, 2007.
12. S.Raetzke, Y. Ohki, Takahiro Imai, Toshikatsu Tanaka, Josef Kindersberger: *Tree Initiation Characteristics of Epoxy Resin and Epoxy/Clay Nanocomposite*, IEEE Transaction on Dielectric Electrical Insulation, Vol. 16, p. 1473-1480, 2009.
13. D.Kavitha ,T.K. Sindhu andT.N.P. Nambiar, Investigation of treeing process in nano filled epoxy material by Finite Element Method**”,** Journal of Electrical Engineering, Universitatea Politehnica din Timisoara, Volume 14, Number 1, p.344-349 (2014).