INVESTIGATION OF TREEING PROCESS IN NANOFILLED EPOXY MATERIAL BY FINITE ELEMENT METHOD

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Abstract: *Partial discharge is a localized electric breakdown due to the presence of micro size voids in the solid insulation of switchgear, cables, transformers etc. It is one of the main causes for electric breakdown of solid insulating material. High electric stress concentration due to the presence of voids/impurities leads to partial discharge which further leads to electrical treeing. The objective of this paper is to investigate the effect of nano fillers in inhibiting tree propagation. This is done by calculating electric stress at different points in pure epoxy and epoxy nano composite. For that various analyses are conducted viz. study the electric field stress distribution in base epoxy resin without and with void, the electric field stress distribution in base epoxy resin with three different nano materials added and probability of tree growth in base epoxy resin with filler nano materials . Simulations are done using Finite Element Method (FEM) in COMSOL software.*

Keywords*: Partial Discharge, Nano Fillers, Finite Element Method, Electric Field Distribution*

1. Introduction

Solid dielectric materials are used in high voltage electrical equipments to provide insulation between the conductors, between the conductor and ground and to provide mechanical support to conductors. 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 itself, the voltage across the cavity may exceed its breakdown value and initiate breakdown in the cavity. Once discharge happens inside the cavity the discharge channels penetrate towards the region of high electric field stress inside the dielectric and give rise to channel propagation like tree channels through the dielectric materials. The initial stage of tree channel inside the void starts with few branches and, later grows into bush-like tree channels which penetrate into the dielectric material. Many researchers from experiments have established the fact that electric field concentration and tree growth can be reduced by adding suitable nano fillers in the insulating material with suitable percentage. Desponina Pitsa et al. [1] discussed the treeing propagation in nano composites in simulation with the aid of Cellular Automata. The size and property of the nanomaterials added to the base material and its percentage have a large impact in the modification of electric field and tree growth. Epoxy resins are thermosetting types of solid dielectric materials with superior electrical and mechanical properties, which are used in insulators, bushing and other applications. The dielectric constant of the epoxy varies between 2.5 and 3.8 and to improve the dielectric strength of the base epoxy resins, they are loaded with fibre glass, fused silica and other nanofillers. Epoxy with nanofillers has higher dielectric strength and high value of resistance to electric discharge than base epoxy resin [2]. The electric field stress concentration depends on the applied voltage, distance between the electrodes, shape of the electrodes etc. The electric field distribution through the dielectric material when subjected to external applied voltage can be determined by using Laplace's equation [3].

The major factors influencing tree inception and growth are the non-uniformity of electric field distribution, which in turn depends on the distance between needle-plane electrodes, applied voltage, frequency, materials and temperature. Different combination of epoxy-based composites are developed with lower cost in the electric field applications for improving the dimensional stability, mechanical and thermal properties of the neat epoxy systems. But the dielectric strength of composite with micro fillers is lower than that of pure epoxy. For improvement in dielectric strength and longer time for breakdown, fillers like nano material are added in the base epoxy resin. Epoxy with nano-fillers has higher dielectric strength and high value of resistance to electric discharge than base epoxy resin and epoxy with micro size fillers [4, 5]. The breakdown time also is increased in nano composite than nano-micro composite and also micro composite. It was also observed that partial discharge resistance is higher in nano-micro-Al_2O_3/epoxy composite than micro-Al_2O_3/epoxy composite [6,7].The different electrode configuration like needle-plane, sphere-sphere, sphere-plane and parallel plate electrodes are used in the study of tree propagation [8]. The electrical tree growth based on electric field distribution process is simulated by employing the Finite Element Method (FEM) for different electrode system [9, 10]. The FEM provides solution over the entire region of interest by solving Laplace equation. The finite element analysis involves four steps namely (1) dividing solution region into a finite number of elements, (2) deriving main equation for each element, (3) assembling all the elements in the solution region of interest and (4) solving the system of equation obtained for solution region [11]. In this paper, by applying FEM, electric field distribution and probability of tree growth are studied with three different type of nanomaterial filled in epoxy using needle-plane electrode configuration.

2. Simulation of electric field

Most commonly used solid dielectric material in electrical applications is epoxy. In this simulation epoxy is considered as the base material which is having a dielectric strength of $5\,X\,10^7\,V/m$ and dielectric constant value of 2.8. For simulation the dimension of the sample selected is $5mm\,X\,3mm\,X\,2.5mm$. Needle and plane electrode configuration is selected to simulate the effects of nonuniform field. This sample is subjected to voltage of 125kV. When high voltage is applied across the sample, the electric field near to the needle tip is maximum and near to the plane is minimum. Fig.1. shows the simulated electric field distribution across the sample which is obtained when subjected to a voltage of 125kV and Fig .2. shows the same in the presence of a 1µm size void inside the sample near to the needle electrode. The void in the sample is filled with air and its permittivity value is considered as 1.The (x,y) coordinates of void location in the sample is $(25\,X\,10^{-4}\,m, 25\,X\,10^{-4}\,m)$. With the help of colour code the electric field distribution throughout the sample and near to the void are studied.

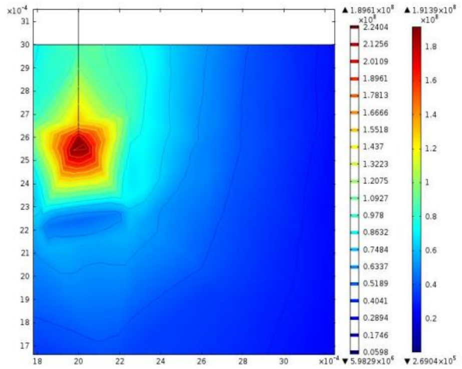

Fig .1. The electric field stress distribution (V/m) throughout the sample in ideal case.

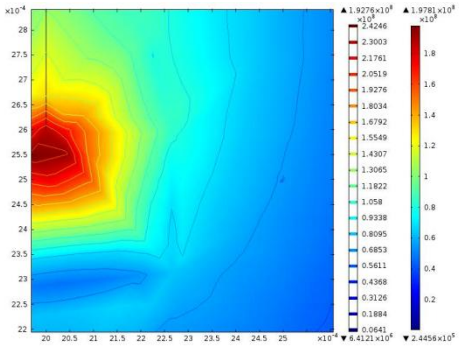

Fig. 2. The electric field stress distribution (V/m) throughout the sample with void.

In needle –plane electrode arrangement the electric field distribution is non-uniform. When 125kV is applied to the sample, the electric stress is more at void location than the other area where epoxy is present. Table.1 compares the electric stress at different coordinates in the presence and absence of void. As inferred from Table.1 the electric stress is higher in the void because the dielectric strength of the epoxy is very high than air. Due to high stress, breakdown occurs inside the void.

Table.1. Electric field value nearer to needle of sample without and with void.

X - axis (m)	**Y – axis (m)**	**EF stress (V/m) without void**	**EF stress (V/m) with void**
0.00248	0.00252	5.6219 E+07	5.7063 E+07
0.00248	0.00251	5.6073 E+07	5.6826 E+07
0.00248	0.0025	5.6879 E+07	5.36502 E+07
0.00248	0.00249	5.6689 E+07	5.6301 E+07
0.00249	0.00249	5.5807 E+07	5.5847 E+07
0.00251	0.00251	5.5131 E+07	5.5217 E+07
0.00252	0.00249	5.4767 E+07	5.3900 E+07
0.00252	0.00251	5.5035 E+07	5.4280 E+07
0.00252	0.0025	5.4918 E+07	5.4046 E+07
0.00253	0.0025	5.4819 E+07	5.3536 E+07
0.0025	0.0025	5.5135 E+07	7.4596 E+07

In this work, to demonstrate the influence of nano particles, epoxy with three different nano materials like Alumina (Al_2O_3), Boron Nitride (BN) and Fused Silica (SiO_2) are considered.

Alumina (Al_2O_3) is a widely used material in the field of high voltage insulators because of its excellent dielectric properties and good thermal conductivity [8,9]. Boron Nitride (BN) is a white solid material and it is having good electrical properties, low thermal expansion, thermal shock resistance, high electrical resistance, low dielectric constant and low loss tangent. Fused Silica (SiO_2) is a non-crystalline form of silicon dioxide and it is having low thermal expansion coefficient and good thermal shock resistance, low dielectric constant and low dielectric loss. Typical electrical properties of Alumina, Boron Nitride and Fused Silica are shown in Table.2 [12,13]. The size of the particles selected is 150nm.

The calculated number of particles for the selected volume percentage of the dimension of the sample selected is 1550 and it is dispersed as shown in Fig.3.

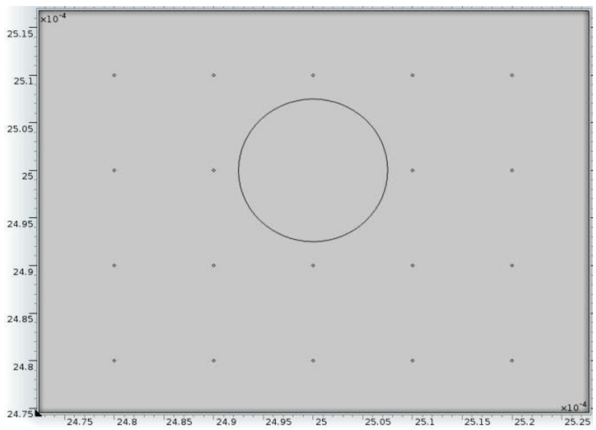

Fig.3. Zoomed region around the void with dispersed Alumina nano particals

Table.2. Typical electrical properties of nano materials

Nano material	**Dielectric Strength(kV/m)**	**Dielectric constant**	**Dissipation Factor**	**Volume Resistance(ohm.cm)**
Alumina	16.7	9.1	0.0007kHz	$>10^{14}$
Boron Nitride	95	4.6	0.0017GHz	$>10^{14}$
Fused Silica	30	3.82	0.00002MHz	$>10^{10}$

3. Results and Discussion

3.1 Simulation of electric field with different nano materials

To study the effect of dielectric constant of nano material on the electric field distribution and tree growth, simulation is repeated with nano materials with different dielectric constants. It is observed that with the addition of nano material, the electric field stress is reduced at different points. The electric stress obtained at different points with the three selected nanofillers is tabulated in Table.3. By comparing the values of electric stress in Tables 1 and 3, there is a clear reduction in stress with the addition of nanoparticles which is achieved by the high permittivity of the nano fillers. The nano material with high dielectric constant increases the polarization effect and reduces the electric field stress inside the nano material. It is inferred from Table.3 that electric field values of sample with different nano material around the void is reduced with the increased value of dielectric constant of nano material added.

Table.3. Electric stress values at some points with three different nano materials

X - axis (m)	Y – axis (m)	(Al_2O_3) εr = 9.1	(BN) εr = 4.6	(SiO_2) εr = 3.2
0.00248	0.00252	2.65 E+07	4.2174 E+07	4.6864 E+07
0.00248	0.00251	2.606E+07	4.1400 E+07	4.594 E+07
0.00248	0.0025	2.7086 E+07	4.2397 E+07	4.7369 E+07
0.00248	0.00249	2.848 E+07	4.4431 E+07	4.9259 E+07
0.00249	0.00249	3.0420 E+07	4.7929 E+07	5.3181 E+07
0.00251	0.00251	3.0249 E+07	5.9475 E+07	5.2470 E+07
0.00252	0.00249	2.47 E+07	3.8884 E+07	4.2689 E+07
0.00252	0.00251	2.6965 E+07	4.2653 E+07	4.7392 E+07
0.00252	0.0025	2.5606 E+07	4.0437 E+07	4.4790 E+07
0.00253	0.0025	2.5795 E+07	4.0532 E+07	5.1211 E+07

3.2 Simulation of tree growth with and without nano materials

After the occurrence of breakdown inside the void, discharge progresses through the insulator through points of maximum stress. To plot the growth of tree like discharge, the electric fields across finite elements in the x and y directions are computed. The tree starts from the void and progresses through points of maximum stress in the sample. Fig .4. shows tree growth nearer to needle tip and across the void. To study the effect of nano materials on tree growth, simulation is done with nano materials added into the base epoxy.Fig.5. and Fig.6. respectively represent the electric field stress distribution and tree around and inside the void without and with 0.5% of 150nm size Alumina nano materials, when the applied voltage is 125kV which is sufficient to cause tree propagation. The values of electric field stress inside and around the surface of void with and without nano materials and probability of tree growth are shown in Table .4.

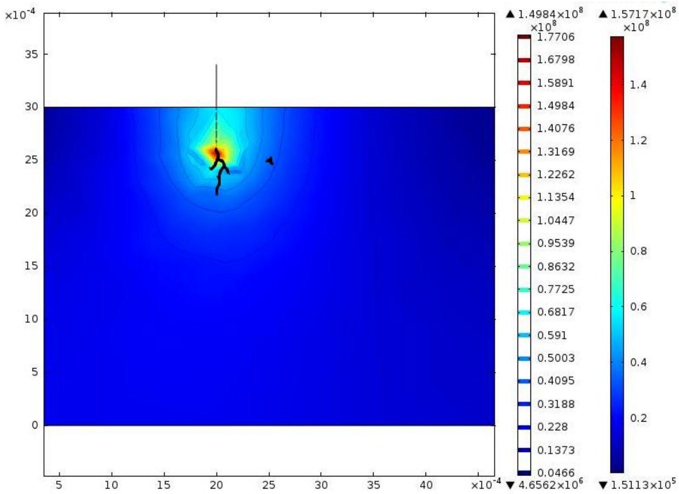

Fig .4. Electric tree growth (at needle tip and at void) based on the values given in Table 1.

It is clear from Table.4 that by adding high dielectric constant nano materials, the dielectric strength of epoxy- nano composite is improved and also probability of tree growth is restricted.

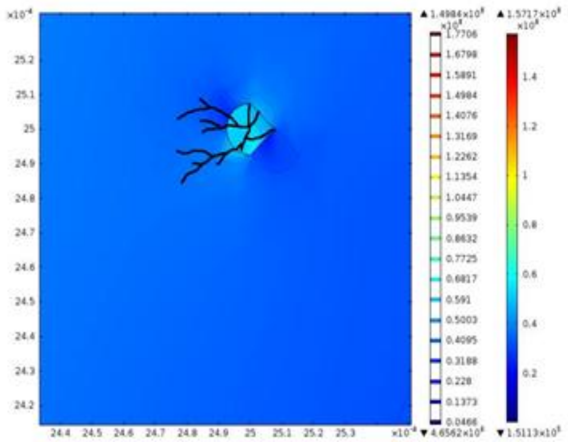

Fig. 5. Electric field distribution and tree growth around void in base epoxy

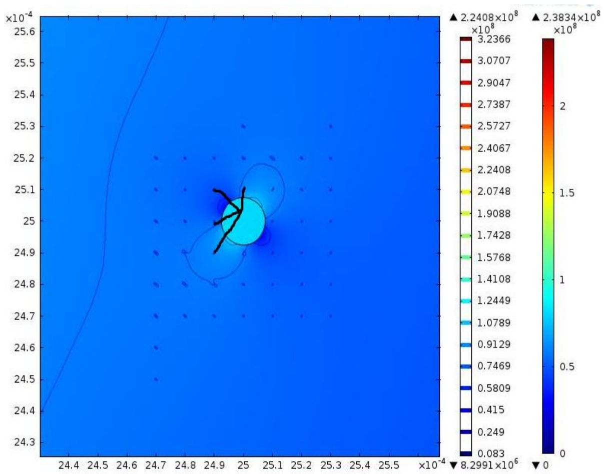

Fig.6. Electric field distribution and tree growth around void in base epoxy with Alumina nano material

Table.4. Electric Field stress and probability of tree growth with an applied voltage of 125kV

		Without Nano Materials		**With Nano Materials**	
x-axis (m)	**y-axis (m)**	**EF (V/m) inside the sample**	**Probability of Electrical tree growth**	**EF (V/m) inside the Nano Materials**	**Probability Electrical tree growth**
0.00249	0.00249	7.95E+07	YES	7.95E+07	YES
0.00249	0.00248	5.89E+07	YES	3.13E+07	NO
0.00249	0.00246	5.67E+07	YES	3.06E+07	NO
0.00249	0.00247	5.62E+07	YES	3.12E+07	NO
0.00248	0.00247	5.58E+07	YES	3.09E+07	NO
0.00248	0.00245	5.55E+07	YES	3.08E+07	NO
0.00247	0.00245	5.58E+07	YES	3.02E+07	NO

4. Conclusions

In this paper, the electric field stress and treeing pattern for different nanocomposite dielectrics with epoxy as the base material are analysed using Finite Element Method in COMSOL software. The nanofillers are selected based on the affinity to the base material. It is observed that the electric stress at different points in the nanocomposite is lower than that of pure epoxy in the presence or absence of void. It is also shown here that nanofillers with higher permittivity leads to much lower stress compared to fillers with lower permittivity. Hence the treeing process which leads to the breakdown of solid dielectric material is inhibited due to the lower electric stress at different points in the composite material. As a future work, experimental studies will be conducted to determine the breakdown strength and tree growth on the nanocomposite materials with the best filler and optimum percentage.

References

1. Desponina Pitsa, George Vardakis, Michael G. Danikas, Masahiro 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. Tuncer, E., Cantoni, C., More, K.L., James, D.R., Polizos G., Sauers, I., Ellis, A.R.: *Breakdown properties of epoxy nanodielectric*, Electrical Insulation and Dielectric Phenomena (CEIDP), 2010 Annual Report Conference on , p.1-4, 17-20 Oct. 2010

3. El-Zein.A.,Talaat.M., El Bahy M.M.:*A Numerical Model of Electrical Tree growth in Solid Insulation*, IEEE Transaction on Dielectric Electrical Insulation, Vol. 16, p. 1724-1733, 2009.

4.Peruani F., Solovey G., Irurzun M., Mola E.E., Marzocca A., Vicente J.L.: *Dielectric Breakdown Model for Composite Materials*, Physical Review E 67, 2003.

5. Mahajan A.,Seralathan K.E., Nandini Gupta: *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.

6.Zhi Li, Kenji Okamoto, Yoshimichi Tanaka and Toshikatsu Tanaka: *Effects of Nano-filler addition on Partial Discharge resistance and Dielectric Breakdown Strength of Micro-Al2O3/Epoxy composite*, IEEE on Transaction Dielectric Electrical Insulation, Vol. 17, p. 653-661, 2010.

7.Uneaki Kurimoto, Hitoshi Okubo, Katsumi Kato, Masahiro Hanai, Yoshikazu Hoshina, Masafumi Takei and Naoki 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.

8.Liu Jia-bin, Zhou Quan, Ye Di, Yang Tao, Liao Rui-jin, Chen Shi-jun: *Study on Propagation Characteristics of Electrical Trees in different Electrode System*, High Voltage Engineering and Application, 2008. ICHVE 2008. International Conference on , p.445-448, 9-12 Nov. 2008

9.June-Ho Lee, Gwan-Soo Park, Yi Dong-Young, Seong-Gyun Kim, Song-Yop Hahn and Min-Loo 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.

10.Hossam-Eldin A.A., Dessouky S.S., El-Mekkawy S.M.,.Abd El-Aal R.A.: *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.

11. Matthew.N.O.Sadiku.: *Elements of Electro magnetics*, Fourth Edition, Oxford University Press, p.721-740.

12.Stephanie Raetzke, Yoshimichi 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.Santanu Singha, Joy Thomas M.: *Dielectric properties of epoxy nanocomposites*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, p12-23, 2008.