engineering proceedings

Proceeding Paper

Modelling the Electric Field Distribution in Polyethylene Nano-Composite to Investigate Electrical Treeing Initiation Using Finite Element Method †

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† Presented at the 7th International Electrical Engineering Conference, Karachi, Pakistan, 25–26 March 2022.

Abstract: Electrical treeing is a type of dielectric breakdown in solid insulation when exposed to high voltage. It usually occurs due to non-uniform electric field, or by the presence of foreign particle (impurities) where partial discharge begins. Nanofillers improves dielectric strength by increasing the resistance to treeing. In this paper, the electric field distribution is simulated for polyethylene dielectric with needle-plane gap using finite element method in COMSOL Multiphysics simulation software. Using electric field distribution graphs, the electric stress at different points is computed. Filler addition makes the electric field uniform, and less intense which significantly improve electrical properties of polyethylene.

Keywords: dielectric breakdown; electric field distribution; electrical treeing; finite element method; nanofiller; polyethylene

Citation: Azhar, K.; Amin, S. Modelling the Electric Field Distribution in Polyethylene Nano-Composite to Investigate Electrical Treeing Initiation Using Finite Element Method. *Eng. Proc.* **2022**, *20*, 30. https://doi.org/10.3390/engproc2022020030

Academic Editor: Saad Ahmed Qazi

Published: 3 August 2022

1. Introduction

Polymers are frequently used for insulation purpose in high voltage (HV) equipments, due to excellent electrical, thermal and mechanical properties. When these HV equipment (cables, insulator etc.) are exposed to high electric fields, the electrical properties deteriorate and the dielectric becomes weak which ultimately degrades the performance of entire power system. Polyethylene (PE) is usually cross-linked to form cross-linked polyethylene (XLPE), during cross-linking space charges are produced in polymeric insulation material, when high voltage is applied across it the breakdown initiates in the form of electrical tree [1]. Since 1950s electrical treeing phenomena is been studied [2]. Electrical treeing has been studied under the effect of AC, DC and impulse voltage however, treeing due to DC voltage is under consideration due to evolvement of HVDC power transmission system. For both AC and DC stress the specimens used are commonly needle-plane, needle-rod and short cable used for initiation of electrical trees although earlier for AC test wire-plane configuration was used [3]. In high voltage dielectric materials (HVDMs) electric tree formation often occurs as a precursor to dielectric breakdown phenomena [4–7]. Therefore, studying the electrical tree phenomena and finding ways to inhibit it is the utmost requirement if we want to develop technologically more advanced HVDMs. Investigation of electrical treeing in solid dielectrics for high voltage applications was also discussed in [8]. Recently electrical treeing analysis in epoxy [9,10], and XLPE [11] under various nanofillers was investigated.

2. Methodology

Modelling the electric field distribution in PE dielectric under the effect of void and filler is implemented using finite element method (FEM). AC/DC electrostatic physics with proper geometry and boundary conditions is implemented in COMSOL Multiphysics. COMSOL is a powerful tool that implements the FEM by resolving Laplace equation. The detailed workflow is shown in Figure 1, which shows setting up geometry, assigning boundary conditions, and computations. The simulation area and mesh sizing is shown in Figure 2a,b respectively. The software computes the result for required area, once the model converged several plots were obtained shown in results section. COMSOL solves the following Equations (1) and (2), to compute the results in AC DC electrostatics module [12]. Table 1 shows the initial and boundary conditions used for electrical field distribution.

$$\nabla.D = \rho_V \tag{1}$$

$$E = -\nabla V \tag{2}$$

$$D = \varepsilon_0 \varepsilon_r E \tag{3}$$

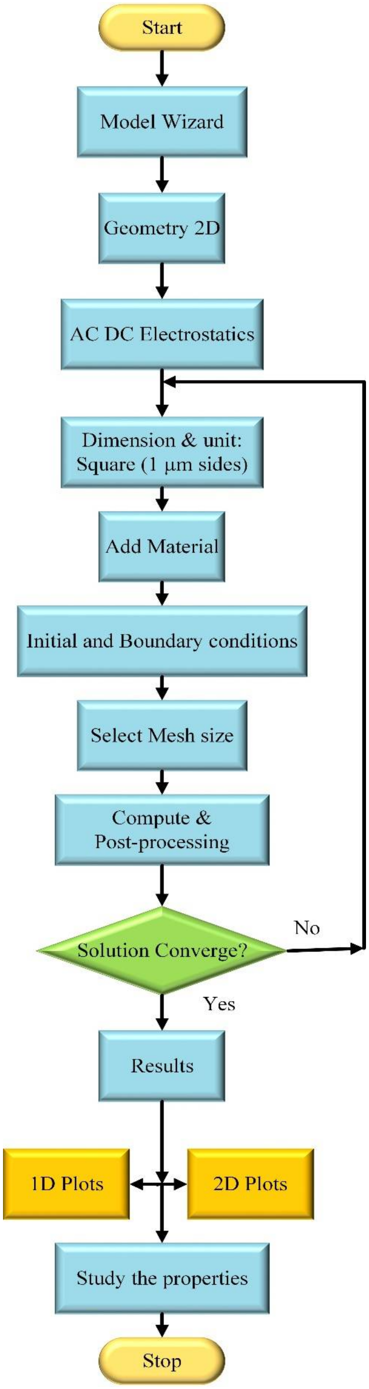
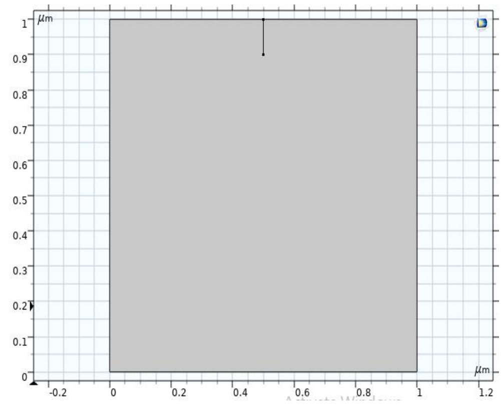


Figure 1. Workflow for electric field modelling.



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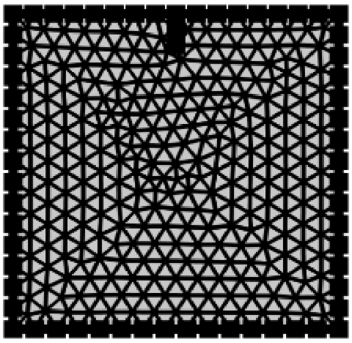

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Figure 2. (**a**) Polyethylene sample: a square of 1 µm each side. (**b**) Physics- controlled mesh size.

Table 1. Initial and boundary conditions for electric field modelling using FEM.

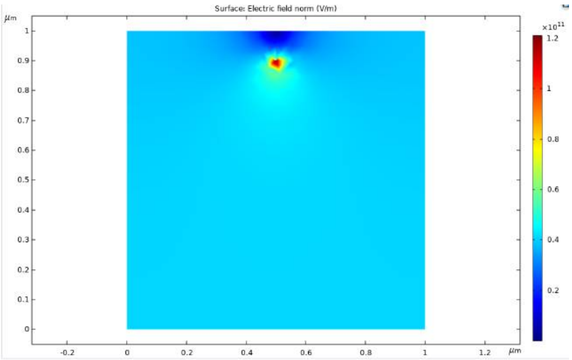
Initial Conditions	Boundary Conditions
1. Initial values applied to entire sample and potential is kept zero volts.	1. Charge conservation is applied to the sample with Equation (3). 2. Zero charge is assign to both horizontal sides. 3. Ground (0 V) is assigned to the bottom surface. 4. Electric potential is applied on the upper boundary.

3. Simulation and Results

PE is assigned as a base material, the sample is a square with area 1 µm × 1 µm. The dielectric strength of PE (base material) varies between 200–300 kV/cm and its permittivity is 2.2–2.3. HV is applied across the sample i.e., 40 kV between needle-plane electrode configurations. Voids of size 10 nm each filled with air are placed inside the sample domain to simulate the effect of void on electric field distribution. Filler of size 30 nm filled with TiO_2 are placed at nine different coordinates in the sample to simulate the effect of nanofiller on electric field distribution. The location of void and filler in the sample is presented in (x, y) coordinates as: (0.25, 0.25) (0.25, 0.5) (0.25, 0.75) (0.5, 0.25) (0.5, 0.5) (0.5, 0.75) (0.75, 0.25) (0.75, 0.5) (0.75, 0.75). The following sections will present the electric field distribution and electric field versus arc length line graph for raw PE, PE with air voids, and PE with nanofillers.

3.1. Electric Field Modelling in Raw Polyethylene

The electric field is maximum near to the sharp edge i.e., needle tip its value is 1.2×10^{11} V/m and minimum near to the plane i.e., 0.4×10^{11} V/m approximately. The electric field distribution is shown in Figure 3a, and Figure 3b shows electric field at each point of sample. Near 0.9 µm due to presence of needle or sharp edge the field is intense and nonuniform. Therefore, chances of electrical tree initiation occurs near the tip.



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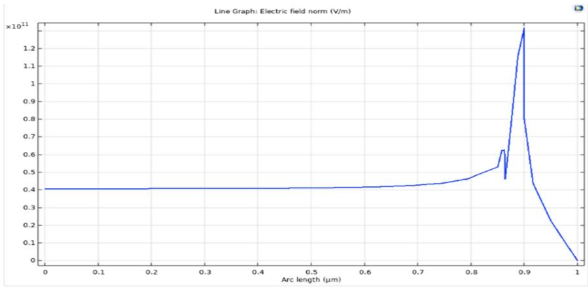

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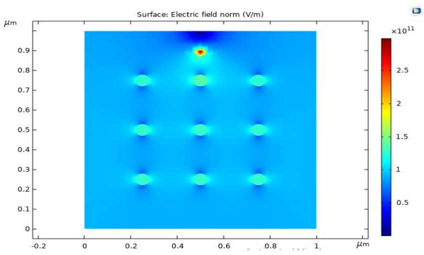
Figure 3. (**a**) Electric field distribution in raw PE. (**b**) Line graph Electric field v/s sample length for raw PE.

3.2. Electric Field Modelling in Polyethylene under the Effect of Air Filled Voids or Defects

The distribution of electric field inside the sample can be studied with the help of color code given by legends in COMSOL and presented in Figure 4a. Near the needle tip, electric field is intense and nonuniform, the maximum value of electric field stress is recorded here i.e., 2.5×10^{11} V/m, which is greater than dielectric strength of polyethylene. In the line graph of electric field versus sample length, at arc length 0.25 µm, 0.5 µm and 0.75 µm (where voids are present) the electric field is much intensified as shown in Figure 4b. Similarly, at 0.9 µm where needle is present the field is extremely intense and electrical tree usually initiate from that point.



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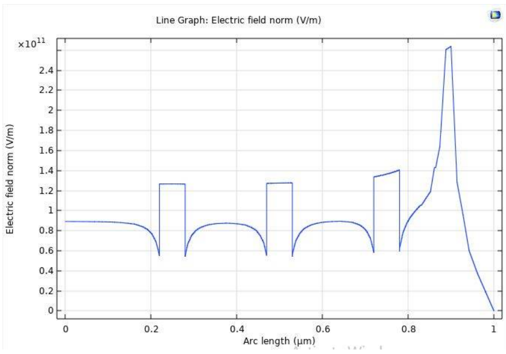

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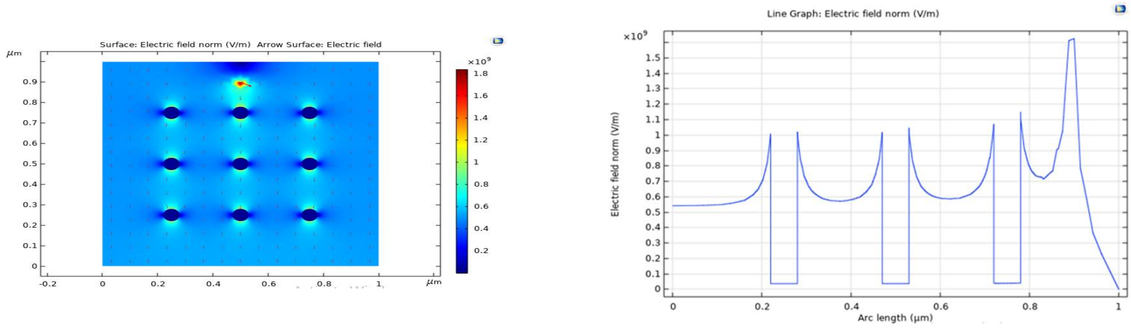
Figure 4. (**a**) Electric field distribution in PE with air voids. (**b**) Line graph Electric field v/s sample length for PE under air filled voids.

3.3. Electric Field Modelling in Polyethylene under the Effect of Filler Particle

Maximum electric field recorded adjacent to the needle tip is 1.8×10^9 V/m approximately, which is lower than previous cases as well as the dielectric strength of polyethylene. Therefore, the probability of tree initiation is very less when nanoparticles are added into the base matrix as the overall electric field become less intense. Consequently, the breakdown is delayed and the dielectric performance can be improved. Electric field distribution can be seen from Figure 5a across the 2D sample, the arrow surface is shown here to visualize the uniformity of electric field. As electrical filed is uniform and not intensified therefore, chances of treeing to occur is low. Moreover, the resistance to electrical treeing is also enhanced as the electric stress becomes less. Figure 5b shows how electric field changes along the sample length at 0.25 μm, 0.5 μm, and 0.75 μm respectively. The electric field stress is minimized due to the presence of filler particle. Therefore, the electrical properties of dielectric are enhanced and it can be used for improved HVDMs design.



(**a**) (**b**)

Figure 5. (**a**) Electric field distribution in filled PE. (**b**) Line graph Electric field v/s sample length for PE filled with nanofillers.

4. Discussion

It can be clearly observed from the numerical results that electric field is quite low inside the nanofiller. Similarly, electric field intensity within the nanoparticles is changed by changing the permittivity of nanoparticle. Table 2 presents a brief comparison between the electric field stress at needle and plate for raw PE, PE with air filled void, and PE filled with TiO_2 particle. It can be seen from Table 2, that the electric field is maximum for defected PE i.e., PE with air filled voids. However, when nanoparticles are added the electric stress and nonuniformity of electric field is minimized thus, it remains below the breakdown strength of base material and treeing is therefore inhibited. Figure 6, presents the electric field versus arc length line graph for the three cases mentioned in Table 2.

Table 2. Comparison of minimum and maximum electric field (E) to predict electrical tree initiation in PE.

Sr. No.	Dielectric Condition	E_{max} (V/m) (at Needle)	E_{min} (V/m) (at Plate)	Electric Field (E)	Electrical Tree Initiation
1.	Raw PE	1.2×10^{11}	0.4×10^{11}	Nonuniform, intense	√ Max E > Breakdown strength
2.	PE with air filled void	2.5×10^{11}	0.6×10^{11}	Extremely nonuniform, intense	√ Max E >> Breakdown strength
3.	PE filled with TiO_2 particle	1.8×10^{9}	0.1×10^{9}	Uniform, less intense	X Max E < Breakdown strength

The last column in Table 2 shows the chances of electrical tree initiation with a tick and cross sign, when the maximum electric field is greater than the breakdown strength the treeing is likely to initiate and the dielectric breakdown occurs which is shown as a tick mark in first two cases. Whereas, for the last case the cross represents that the electrical tree will not initiate as the maximum electric field is less than the dielectric strength so breakdown will not occur here.

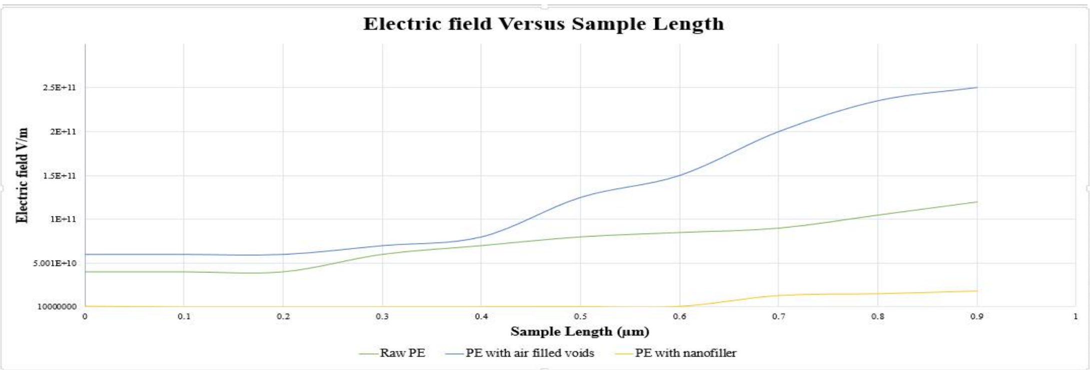


Figure 6. Electric field versus sample length.

5. Conclusions

The effect of nanofiller and void defects on the electric field distribution of polyethylene dielectric is analyzed in this paper. COMSOL Multiphysics is used to simulate the electric field distribution for needle-plane electrode configuration, and it is used to investigate the electrical tree initiation in solid dielectrics. Void makes the electric field so intense and nonuniform that it exceeds the breakdown strength of base material and electrical treeing is more likely to occur. The nanofiller increases the resistance to treeing therefore, the electric field is uniform and its magnitude is less than the breakdown strength of base material. It is concluded that by selecting suitable nanofiller, the resistance to treeing can be enhanced and the dielectric breakdown such as electrical treeing can be delayed. PE filled with nanofillers gives higher resistance to treeing therefore, it has high dielectric strength and improved electrical properties as compared to raw PE and PE with air filled voids.

Author Contributions: Methodology and original draft preparation K.A.; writing review and conceptualization S.A.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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