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Investigating Electrical Treeing Initiation in Polyethylene Through Electric Field Modelling with the Finite Element

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Abstract

This study addresses the critical need to understand the initiation of electrical treeing in polyethylene dielectrics, particularly in cross-linked polyethylene (XLPE), which is widely used in high-voltage insulation systems. Traditional experimental methods for monitoring and predicting electrical treeing are time-consuming, costly, and often lack detailed insight. To overcome these limitations, this research utilizes Finite Element Method (FEM) software to simulate electric field behavior. This approach provides a comprehensive understanding of how high electric field stress, nanofillers, and void defects influence the initiation and progression of electrical treeing in XLPE dielectrics. The Finite Element Method (FEM) enables the prediction of electrical tree behaviour under diverse conditions, which is vital for creating more reliable and long-lasting insulating materials. This research aims to model the geometry and material properties of cross-linked polyethylene (XLPE) in COMSOL, examine various parameters such as voltage stress, and analyze tree development in polyethylene. The methodology involves creating precise geometry, applying relevant physics interfaces, and running simulations to capture electric field distributions and tree growth patterns under varied conditions. Quantitative findings indicate that the likelihood of tree initiation is significantly reduced, approaching 0.3 x 10^7 V/m electric field, when nanoparticles are introduced into the base. This is attributed to the overall electric field becoming less intense compared to raw polyethylene and polyethylene with air voids. This research enhances polyethylene with nanoparticles such as titanium dioxide providing valuable insights for improving electrical insulation system design and reliability.

1. Introduction

Dielectric refers to an insulating material that poorly conducts electric current. Electric treeing begins and spreads when a dry dielectric material experiences prolonged exposure to high and diverging electrical field stress. Tree growth can be characterized by factors such as voltage stress, temperature, and material qualities. Dielectric treeing is a critical failure mode in electrical insulation systems, and understanding the components that advance their growth is critical to ensuring the reliability and safety of electrical equipment [1]. Polyethylene (PE) is a variable crystalline thermoplastic well known for its versatility [2]. Polyethylene is a dielectric material commonly used in high-voltage power lines and capacitors. There are five types of polyethylene which are LDPE (Low-Density), LLDPE (Linear Low Density), HDPE (High Density), UHMWPE (Ultra-high-molecular-weight), and XLPE

(Cross-linked) [3]. In this project, High-density cross-linked polyethylene (XLPE) will be used as the material. It's hydrolysis-resistant and potable water-approved with excellent abrasion resistance and electrical properties [4]. However, since electric trees appear in different shapes, such as bush and branch shapes, the appearance of curved tree branches complicates tree image segmentation, leading to high misclassification rates during segmentation [5]. Hence, this project employs modern computational techniques like the Finite Element Method (FEM) to conduct more comprehensive analyses.

Electrical treeing is a type of electrical discharge that occurs in high voltage (HV) insulation materials, especially in cables and transformers. It is characterized by the formation of tree-like structures within the insulation material, which can eventually lead to the breakdown of the material and failure of the electrical system [6]. The statistical models adapt the data gathered from experiments to statistical distributions, such as the Median, Wiener, and Gaussian Filtering Techniques [7] and Hybrid Multi Scale Line Tracking Algorithm [8] to illustrate the breakdown of solid dielectrics. However, the life of XLPE-insulated cables can be limited by electrical treeing, a damaging phenomenon caused by partial discharges. It is extensively utilized in HV cables and power distribution systems due to its exceptional breakdown resistance, superb dielectric features, and ability to withstand electrical treeing and partial discharges [9-11].

Cross-linked polyethylene (XLPE), renowned for its excellent mechanical and electrical properties in high-voltage insulation systems, is vulnerable to electrical treeing under high electric fields, leading to potential dielectric failure. The introduction of nanofillers into polyethylene dielectrics aims to improve their electrical properties, yet the exact mechanisms affecting the electric field distribution remain unclear. This study seeks to explore how various types and concentrations of nanofillers, along with defects like air voids and cavities, impact the electric field distribution and the initiation of electrical treeing. Traditional experimental methods for monitoring and predicting electrical tree growth in polyethylene are limited due to being time-consuming, costly, and lacking detailed insight. To address these limitations, this research will utilize finite element method (FEM) software to simulate electric field behaviour, providing a comprehensive understanding of how high electric field stress, nanofillers, and void defects influence the initiation and progression of electrical treeing in XLPE dielectrics.

2. Methodology

Fig. 1 depicts the detailed procedure, which is divided into three stages. The first stage is "developing a computer model," discussing the setup of the geometry in COMSOL Multiphysics. The second stage, "processing," involves providing boundary conditions and running the simulation to obtain results. Finally, the last stage, "post-processing," involves analyzing the results and performing computations.

Modeling the electric field distribution in polyethylene (PE) dielectrics under the influence of voids and fillers is carried out using the finite element method (FEM). This simulation have three condition which is firstly, raw polyethylene, then polyethylene with air voids, and lastly polyethylene with titanium dioxide filler. This process is implemented in COMSOL Multiphysics, employing AC/DC electrostatic physics with appropriate geometry and boundary conditions. The simulation area and mesh sizing are depicted in Figures 2a and 2b respectively. COMSOL solves the following Equations (1) and (2) within the AC/DC electrostatics module to compute the results . Table 1 outlines the initial and boundary conditions applied for the electric field distribution analysis.

$$\nabla . D = \rho_{\mathrm{V}} \tag{1}$$

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

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

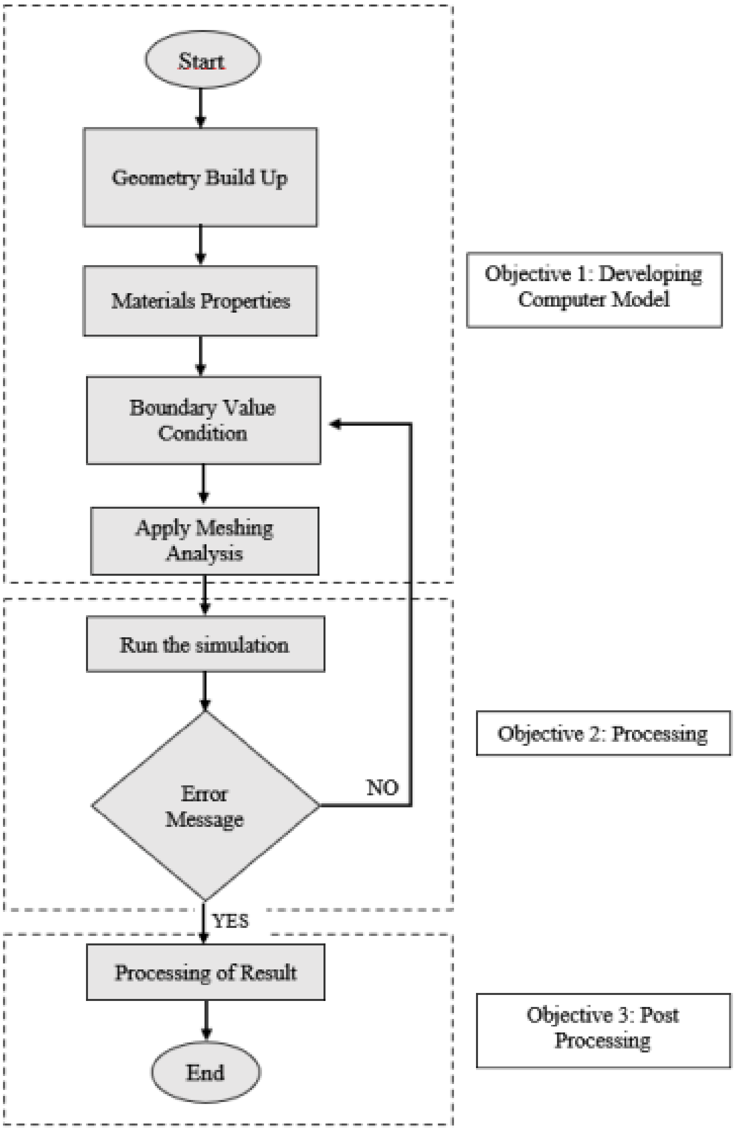


Fig. 1 *Flowchart of electric field modelling*

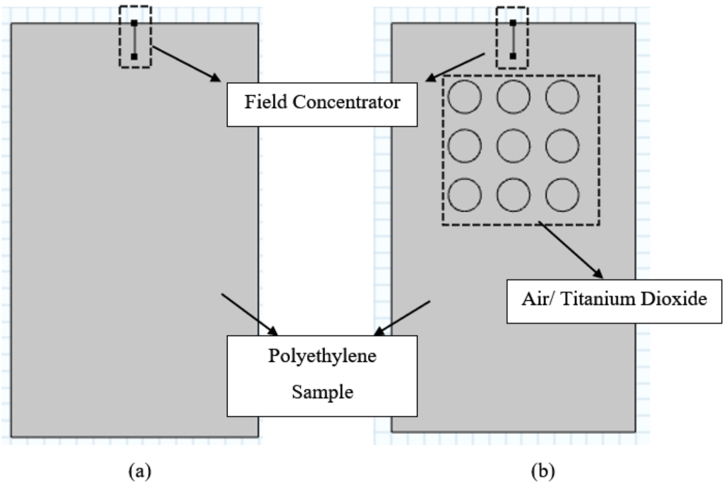


Fig. 2 *The overview of the geometry development computer model for (a) XLPE with field concentrated; (b) XLPE with air/ titanium dioxide filler*

Table 1 *Initial value and Boundary Conditions for the Computer Model*

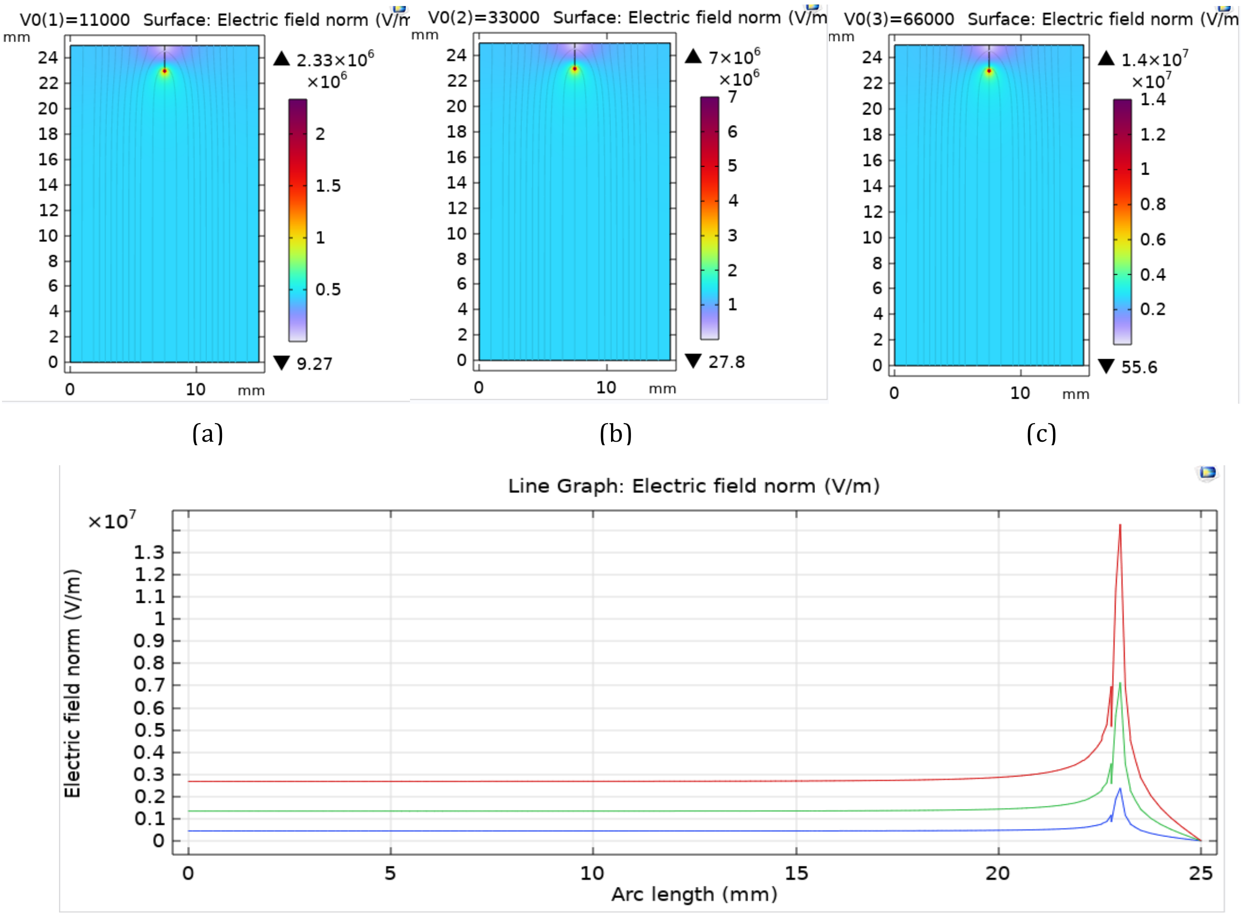
Initial condition	Boundary condition
Potential kept at zero voltage at entire sample	1. Equation 3 applies charge conservation to the sample. 2. Both horizontal sides are assigned zero charge. 3. The bottom surface is grounded (0V). 4. Upper boundary applied to electric potential.

3. Simulation and results

In this project, there will be two computer model setups as depicted in Fig. 2(a) and 2(b). Fig. 2(a) shows the overall development setup for the XLPE sample with dimensions of 15mm x 25mm, using a needle-plane configuration as the high voltage (HV) source. This schematic illustrates the loading setup of the XLPE dielectric, incorporating a field concentrator. Fig. 2(b) presents the setup for the XLPE sample of the same size, featuring nine circular voids (air) and fillers at specific positions: (4.5, 20.5), (7.5, 20.5), (10.5, 20.5), (4.5, 17.5), (7.5, 17.5), (10.5, 17.5), (4.5, 14.5), (7.5, 14.5), and (10.5, 14.5). This schematic also illustrates the loading setup of the XLPE dielectric with a field concentrator but includes voids or fillers. The following sections will present the electric field distribution and the electric field versus arc length line graph for raw polyethylene (PE), PE with air voids, and PE with nanofillers.

3.1 Modeling of the Electric Field in Unprocessed Polyethylene (Raw PE)

The electric field reaches its highest intensity near the sharp edge of the needle. At the needle area, the values are approximately 2.33 x 10^6 V/m for 11 kV, 7 x 10^6 V/m for 33 kV, and 1.4 x 10^6 V/m for 66 kV. The electric field distribution within polyethylene, which has a relative permittivity of 2.3, displays distinct characteristics due to its dielectric nature. With a relative permittivity higher than that of a vacuum, polyethylene undergoes polarization when subjected to an electric field, causing the concentration of electric flux within its volume. As a result, the electric field strength within polyethylene is reduced compared to vacuum conditions. Understanding the electric field behaviour in polyethylene with a relative permittivity of 2.3 is crucial for the strategic design and optimization of electrical systems and components that use this material for insulation or related applications. The electric field distribution and the electric field graph line in COMSOL Multiphysics are shown in Fig. 3(a) to 3(d).



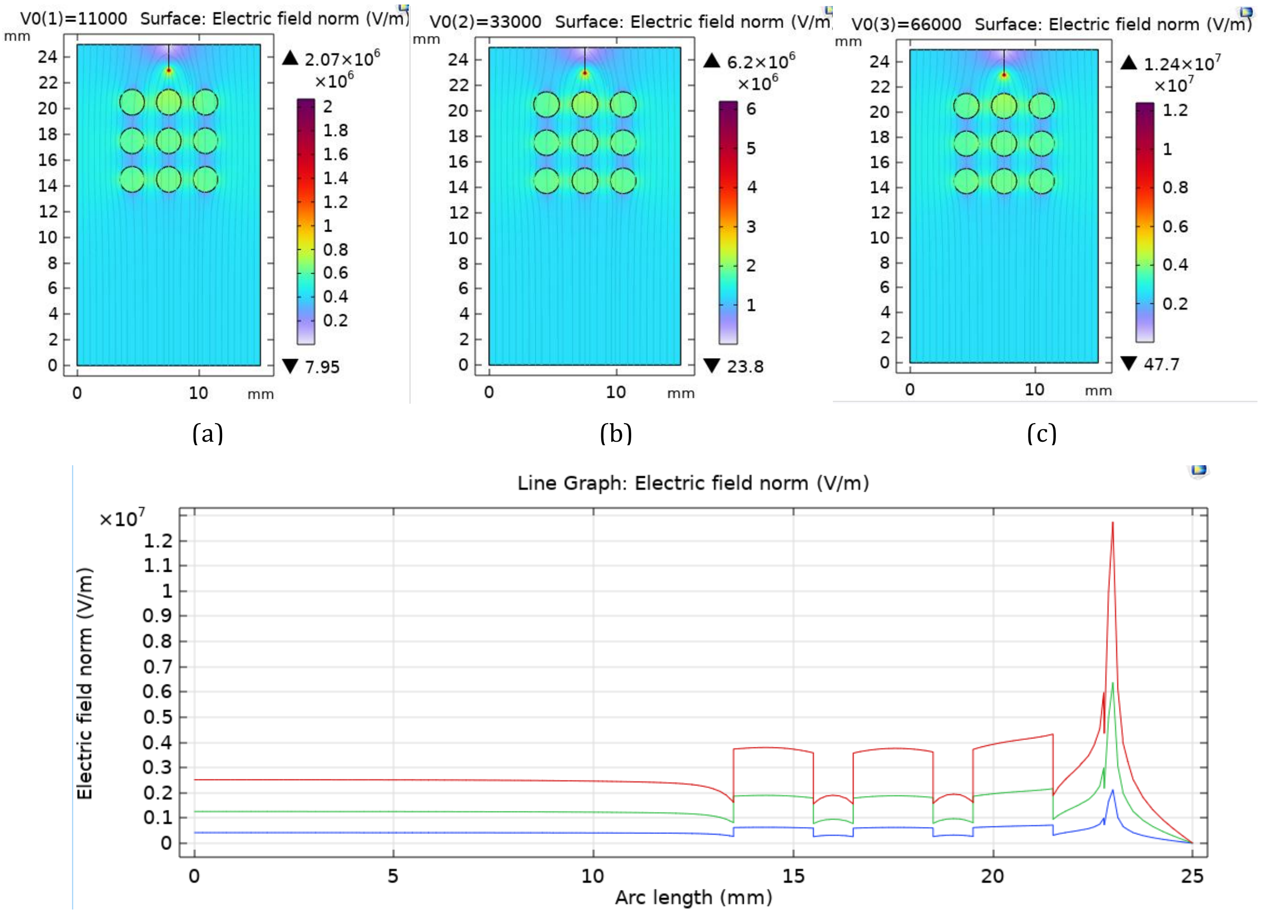
(a) (b) (c)

(d)

Fig. 3 *Electric field in COMSOL Multiphysics for raw polyethylene: (a) 11kV; (b) 33kV; (c) 66kV; Line Graph for electric field in COMSOL Multiphysics (Raw polyethylene)*

3.2 Modeling the electric field in polyethylene with air

The electric field distribution within the sample can be illustrated using a color-coded representation, as shown in Fig. 4, with legends provided by COMSOL. Near the needle area, the electric field is characterized by high intensity and non-uniformity. The maximum electric field stress values recorded are approximately 2.07 x 10^6 V/m for 11 kV, 6.2 x 10^6 V/m for 33 kV, and 1.24 x 10^7 V/m for 66 kV, respectively. These values remain below the dielectric strength of polyethylene. The electric field distribution and the electric field graph line in COMSOL Multiphysics are shown in Fig. 4(a) to 4(d).



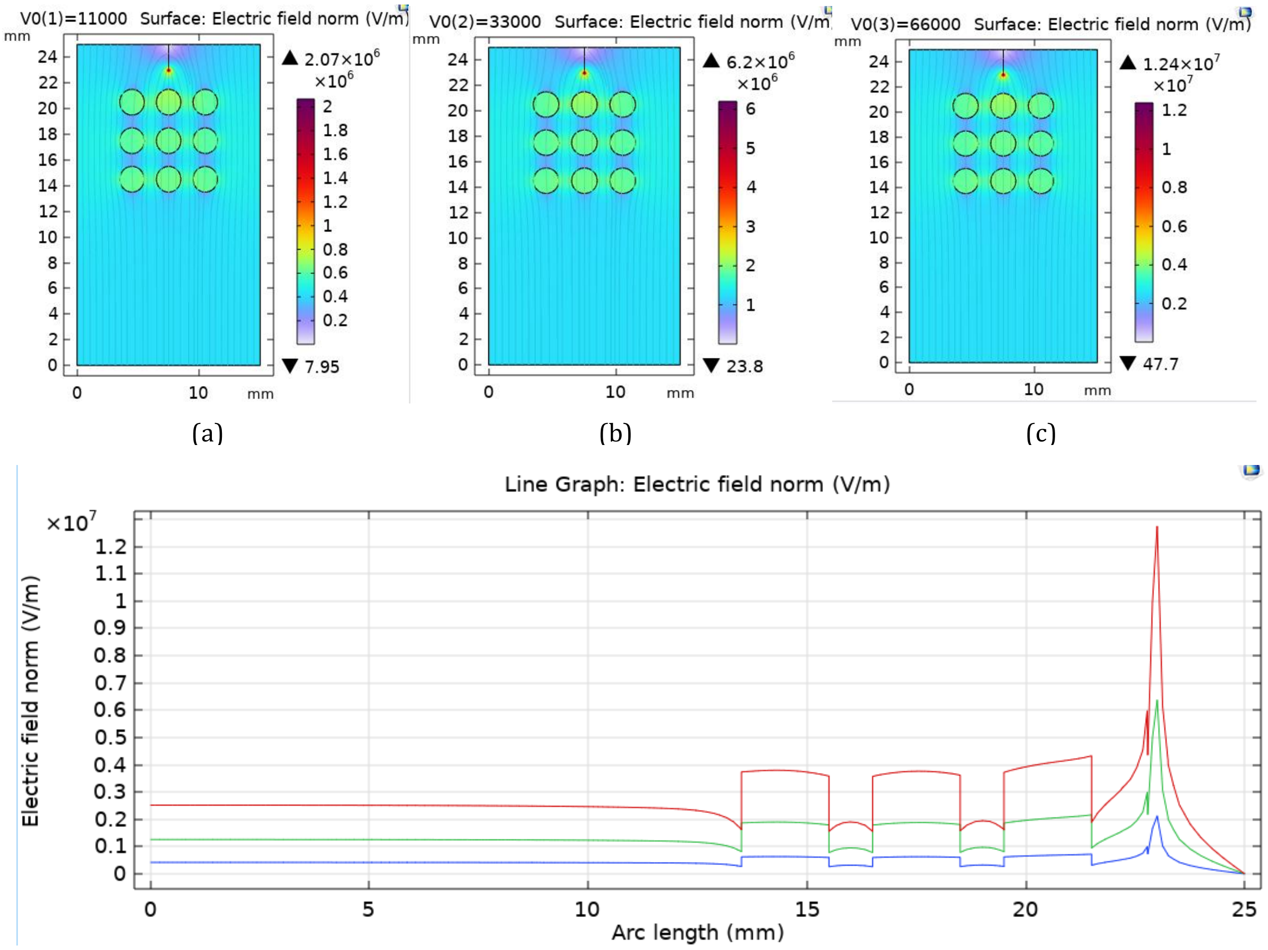
(a) (b) (c)

(d)

Fig. 4 *Electric field in COMSOL Multiphysics for polyethylene with air void: (a) 11kV; (b) 33kV; (c) 66kV; Line Graph for electric field in COMSOL Multiphysics (Air voids)*

3.3 Modeling the electric field in polyethylene influenced by titanium dioxide

The maximum electric field measured adjacent to the needle area is approximately 0.305 x 10^7V/m for 11 kV, 0.914 x 10^7V/m for 33 kV, and 1.83 x 10^7 V/m for 66 kV, respectively. These values exceed the maximum electric field observed in pure polyethylene. As a result, the likelihood of tree initiation is significantly reduced when nanoparticles are incorporated into the base matrix, leading to a decrease in the overall electric field intensity. The electric field within titanium dioxide shows a high degree of uniformity and reduced intensity. Consequently, breakdown is delayed, potentially enhancing dielectric performance. The electric field distribution and line graph across the 2D sample can be seen in Fig. 5.



(a) (b) (c)

(d)

Fig. 5 *Electric field in COMSOL Multiphysics for Nano filler: (a) 11kV; (b) 33kV; (c) 66kV; Line Graph for electric field in COMSOL Multiphysics (Nanofiller)*

The numerical analysis shows a notable decrease in the electric field within the nanofiller. Moreover, modifying the permittivity of the nanoparticle material can affect the electric field intensity inside the nanoparticles. This study examines the effects of nanofillers and void defects on the electric field distribution in polyethylene dielectric. COMSOL Multiphysics is employed to simulate the electric field distribution in the needle area configuration and to analyze the initiation of electrical treeing in solid dielectrics. Void defects enhance the electric field, leading to significant non-uniformity and exceeding the breakdown strength of the base material, thereby increasing the likelihood of electrical treeing. In contrast, nanofillers improve resistance to treeing, resulting in a more uniform electric field with a magnitude below the breakdown threshold of the base material. The study concludes that choosing suitable nanofillers can boost resistance to treeing and delay dielectric breakdown, such as electrical treeing. Polyethylene with nanofillers shows greater resistance to treeing, thus enhancing dielectric strength and electrical properties compared to untreated polyethylene and polyethylene with air-filled voids.

4. Conclusion

Creating a computational model in COMSOL Multiphysics 6.1 to simulate polyethylene dielectric tree formation is crucial for understanding and predicting these complex structures. This model enables researchers and engineers to explore the processes underlying tree-like patterns in polyethylene, gaining insights into their development mechanisms, structural properties, and potential failure locations. It supports optimizing material design, enhancing insulation performance, and mitigating dielectric breakdown risks through computational analysis capabilities. The study successfully achieved its objectives: accurately modeling geometry and material properties to simulate electric field distribution in XLPE, demonstrating the significant role of voltage stress in accelerating tree growth, and comprehensively analyzing tree development under conditions such as raw polyethylene, polyethylene with air voids, and polyethylene with titanium dioxide. This research significantly advances our understanding of dielectric materials under high electrical stress, facilitating the development of more reliable high-voltage insulation technologies.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The author attests to having sole responsibility for the following: planning and designing the study, data collection, analysis and interpretation of the outcomes, and paper writing.

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