ISSN:1687-1006

The Egyptian International Journal of Engineering Sciences and Technology

Vol. 30 (2020) 90–99

https://eijest.journals.ekb.eg/

Voltage Variations and Composite Solid Insulation Effects on Electrical Tree Propagation Based on Finite Element Method

A. El-Zein[a], M. Tayseer[a,*] , M. Talaat[a,b]

[a]*Electrical Power & Machines Department, Faculty of Engineering, Zagazig University, Egypt.*
[b]*Electrical Department, College of Engineering, Shaqra University, Dawadmi, Ar Riyadh, Saudi Arabia.*

ARTICLE INFO

Keywords:

Electrical Tree
Voltage Variations
Change of Solid insulation
Finite Element Method
Composite Solid Insulation

ABSTRACT

This paper investigates the effect of the voltage variations and the change of solid insulation material on the initiation and propagation of Electrical Tree (ET) through solid dielectrics based on the application of Finite Element Method (FEM) approach using the environmental domain of [COMSOL Multiphysics $5.3a$] program as an innovative way to be used in the complicated study of Electrical Treeing Phenomenon (ETP). This research provides an innovative solution to suppress the initiation point of ET and suppress its growth rates using a composite solid insulation material of Poly – Vinyl Chloride (PVC) and Cross – Linked Polyethylene (XLPE) regardless to the mechanical features of this composition. In this research, the study cases are conducted for High Voltage (HV) and Extra High Voltage (EHV) power system networks as the effect of ETP is to be observed clearly. The simulation model is used in this research to imitate the proposed hyperbolic needle – plane system. Case studies are compared between each others to validate the results

1. Introduction

The complete study of High Voltage (HV) and Extra High Voltage (EHV) complicated dangerous issues or phenomena in the generation, transmission and distribution systems is nowadays considered as an open challenge for researchers to either discover more hidden secrets or improve the methodologies to enhance the features of the power system networks in the presence of these harmful phenomena [1-7]. One of the most effective and common studies that are related to these HV and EHV phenomena is the accurate distribution of electric and magnetic fields and their calculation methodologies that affect and control directly the severity degree of these issues on the quality and service continuity of the different power system networks [8].

Regarding the importance level, the structure and operation of stranded conductors are categorised as the most effective parts that are affected by the distribution of electric fields in the power system networks. Talking about stranded conductor, it is always exposed to the presence of different harmful defects in its manufactured structure due to the heating and cooling treatments that may cause direct damages to the operational efficiency of the utilized conductors leading to the decrease in the quality of HV and EHV systems for repeated abnormal modes such as switching process [9].

For repeated abnormal operations on the power system networks, These conductor defects that are shaped in the form of conducting protrusions become the ignition spark of the excessive formation of non – uniform electric fields that are considered as the most harmful factor to strongly

---

* Corresponding author. Tel.:+2 – 01284900094
E-mail address: mohamedtayseer357@gmail.com

contribute in the initiation of dangerous phenomena like Electrical Corona Discharge (ECD) and Electrical Treeing Phenomenon (ETP) [10]. In this research, ETP issue is to be discussed under the influence of different affecting factors and improvements. Due to the heat treatments and sudden cooling processes, The solid insulation is extremely exposed to the formation of air voids in the manufacturing. The presence of both air voids of the solid dielectric around the conducting wire and the initiated conducting protrusions through the conductor under abnormal operational modes will lead to the excessive generation of the non – uniform electric fields and the initiation or propagation of Electrical Tree (ET) [1-4]. It is necessary to show that the term "Electrical Treeing" is associated with the theoretical concept of ETP unlike the term "Electrical Tree" that is associated with the actual configurable representation of ETP so, it is commonly said that "ET is the realistic embodiment of ETP".

ETP effect in solid insulations is categorised as a pre-breakdown phenomenon that is associated with the influence of electrical Partial Discharges (PDs) and the distribution of electric fields along the protrusions and the particles of the solid insulation in initiating a conducting or semi – conducting channels (cracks) with a path extended from the protrusion tip to the ionized air voids that may lead in worst cases to the failure of the solid insulations affecting conductor operation and the quality of the whole power network. Reaching to the excessive growth rates of ET in solid insulations, the stages; Inception, propagation and completion are the sequential steps to be followed and these stages enable the operators to take a fast effective actions at early stages using optical – sensation measurements of PDs emissions to avoid the exacerbation of danger [11-16].

As ETP issue affects the insulation levels and the lifetime of both conductor and its solid insulation, the analysis of ETP issue is considered nowadays as a fertile domain for researchers to study the behavior of ET in different solid insulations, predict the shape of ET in initiation and propagation modes under different affecting factors and provide some practical solutions to improve the quality assessment of solid insulation level, conductor operation and the whole electrical power networks [15, 17].

To mimic the ET inception and propagation steps, a hyperbolic needle – plane system is used as it is the most common configuration to generate excessive non – uniform electric fields with a high concentration of electric stress around the needle tip that is enough to initiate cracks and simulate the ET propagation in the proposed solid insulation [2].

Due to the complexity of calculating the non – uniform electric fields arisen that arisen from the needle electrode tip that mimics the protrusion tip, the accurate distribution of these fields is an urgent process to be calculated using the powerful effective numerical methods not the traditional physical – analytical approaches [18-21]. Numerical methods are classified as the magic tools to deal with the complicated mathematical and physical problems like the scope of this research. These methods are categorised into two major branches according to the computational domain and operational equations; open domain methods with the solution of integral equations without any restrictions in calculations but with less accuracy to be used alone without the application of artificial intelligence methods such as the Charge Simulation Method (CSM) approach and the constrained domain methods with the solution of differential equations to treat with any random non – uniform shapes such as Monte Carlo Method (MCM) and Finite Element Method (FEM) approaches [22].

In this research, to avoid the complexity of high cost, practical HV potential errors, and the assembly of experimental components, the simulation models are the best way to enrich the study of complicated issues such as this research scope. In this work, a needle – plane system with bounded considerations is used to imitate the ET initiation and propagation in the proposed solid insulation. As the proposed model in this work is bounded area and associated with a complicated random shape of ET, FEM is the most effective numerical method to be used in this case study. Regarding to mesh generation approach, FEM analysis can simplify the complicated problems into small elements to facilitate the analysis under the satisfaction of the applied constraints [20-23].

In this work, the FEM analysis for calculating non – uniform electric fields for ET initiation and growth is conducted using the environmental domain of [COMSOL Multiphysics 5.3a] program [20]. This research tries to study the behavior and shape of ET initiation and growth under the variation of the applied abnormal over – voltages in HV and EHV systems. Furthermore, this work focuses on the effect of using different solid insulation materials on the ET initiation and propagation. Finally, the master scene of this study is the usage of composite materials as a vital solution for suppressing the ET growth rates or in best cases suppressing its initiation point.

The results of the proposed simulation model at each case study are highlighted to be compared each others to validate their significance. All proposed figures and results in this research explain the mechanism of ET initiation and growth in solid insulations that may cause its failure, shorten the cable lifetime and push the electrical power system to incur heavy losses; financial and technical [18].

Briefly, this research concentrates on the methodologies of reducing the ET growth rates in solid insulation materials. These methodologies can be divided according to this research into two types. One of them is studying the effects of some factors that are commonly applied to assess the behavior of ET propagation or controlling its inception point such as voltage variations and the type of solid insulation material. The other one is finding new solutions to reduce or suppress the ET growth rates such as using a composite solid insulation material. The motivated aim of this work is to control or inhibit the ET progression in solid insulation material to increase the reliability of the power system network.

2. Overview of Electrical Tree Structure

In this research, the scope is to study the effect, methodology, and suppression of ET initiation and propagation through the proposed solid insulation. First of all, the simulated needle tip that mimics the tip of the conductor's protrusion must reach to a critical value of electric field strength equal to $4MV/cm$ in case of solid inslations[23-25]. This stress value is very convenient for ionizing the air voids and the solid insulation particles deterioration around the needle tip to form a suitable conductive area to initiate at least one crack in the proposed insulation material after exceeding the mechanical tensile and compression strengths of the utilized insulation material and regardless to the effect of temperature. Taking about the HV and EHV systems, the repeated switching operations are one of the common abnormal modes that provide values of potentials reach to 1.5 and 2.5 times of the operating potential. These abnormal potentials are enough to ionize the dielectric surface particles to start the ET shape. With successive operations and highly electric field strengths, more cracks are formed and spread out with large size and long conducting paths that through the solid insulation medium. The sequential progression of cracks increases the ET growth rates with respect to the calculated electric field strengths at each point through the insulation material using the numerical methods and regarding to the influence of the affecting factors [26-29].

3. Finite Element Method Approach

3.1. General Overview

FEM is one of the most important powerful numerical software methods to be used in such a complicated irregular topics and issues such as the scope of this research. FEM is considered as a Two – Dimensional (2 – D) software. This provided approach is very suitable to be utilized in the field of this research as the non – uniform electric fields are the main reason for the ET initiation and propagation through solid insulation. The great importance of this software comes from its unique behavior to be used in solving different problems that are associated with the two common field study theories; electrostatics study and electromagnetics study. This unique behavior is based directly on the automatic usage of the mesh generation approaches. Mesh generation approach depends directly on the simplification criterion and the division of the calculation domain of the complicated problems into small elements to facilitate the study of these problems accurately under without neglecting the importance of applying the desired constraints. FEM provides the calculation of both electric field strength and electric potential at any desired boundaries. Another important feature of FEM technique is its availability to estimate the charge at any boundary by integrating the electric field values. With the field and equipotential lines distributions over the mesh regions, FEM is the most effective numerical method to deal with the complex, random and non – uniform shaped configurations such as the initiation and propagation shapes of ET [30, 31].

3.2. Mathematical and Computational Domains

As the nature of this thesis is concerned with an electrical problem that is included in electrostatics studies, it is necessary to describe the features of the theory of electrostatics, the application of electrostatic studies on the solid insulation and how to be simulated using FEM analysis [32, 33].

Electrostatics is considerd as an effective branch that is forked from the tree of electromagnetics and is specialized in studying the generated electric field strength that is generated from the static charges or. Electrostatics studies are applicable for both free space and solid dielectric medium. To focus on the operational analysis of the theory of electrostatics, the following formula will describe the relation between charges and generated electric field strengths in the free space medium according to electrostatics studies and the application of divergence theorem:

$$\nabla \cdot E = \rho_v / \varepsilon_o \tag{1}$$

where,
ρ_v is the density of space volume charges and ε_o is the permittivity of free space that is equal to $(10^{-9}/36\pi)\ F/m$

In the presence of electric field strength, the electric potential must be expressed in terms of electric field strength or vice versa under the gradient theorem as the following equations:

$$V = -\int E \cdot dl \tag{2}$$

Finally, the theory of electrostatics can be expressed in only one equation that is called Poisson's equation without the application of any dielectric medium except free space as follows:

$$-\nabla \cdot \nabla V = -\nabla^2 V = \rho_v / \varepsilon_o \tag{3}$$

Due to the excessive presence of bonded charges in solid dielectrics, the polarization effect can not be neglected. Polarization effect and its relation to the generated electric field strengths can be expressed in the terms of following modified Poisson's equation:

$$\nabla \cdot (\varepsilon_o \mathrm{E} - P) = -\nabla \cdot (\varepsilon_o \nabla \mathrm{V} - P) = \rho_v \tag{4}$$

where,
P is the polarization vector field

The relation between polarization effect and the electric field strength can be expressed according to the following equation:

$$P = \mathcal{X}_e \varepsilon_o E = (\varepsilon_r - 1)\varepsilon_o E \tag{5}$$

where,
$\mathcal{X}_e$ is the electric susceptibility which is considered as a unique property for each solid dielectric material and is directly related to its relative permittivity ε_r

All the previous equations are embedded in the form of a study case in the environmental domain of [COMSOL Multiphysics 5.3a] program as shown in Fig. 1. Talking about FEM, there is no way to neglect the boundary conditions of solid dielectric materials that are related to the problems of electrostatics.

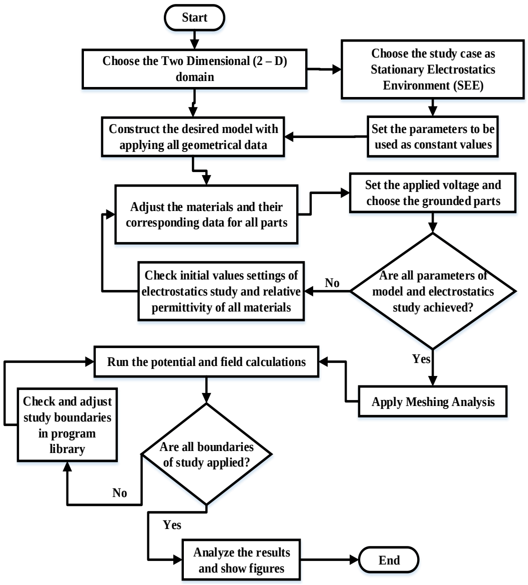

Fig. 1. Methodology of [COMSOL Multiphysics 5.3a] program in field calculation in electrostatics domain based on FEM technique

4. Proposed Model

4.1. Needle – Plane Configuration System

As illustrated before that to mimic the processes of ET initiation and propagation in the proposed solid insulation, a hyperbolic needle – plane system with a breaking force to penetrate the cohesion of the solid insulation molecules is to be utilized [32, 34, 35]. Taking about the structure of this model, it consists of two different shaped electrodes. One of these two electrodes is shaped as a needle to mimic the actual protrusion in the real life with a tip radius R and the applied voltage (V_n) is to be applied along it. The other electrode is shaped as an earthed plane with $(V = 0)$. The separation distance between the two adjacent electrodes (D) must be adjusted according to the model considerations regarding to the applied case study. The medium between the two adjacent electrodes is to be filled with the proposed solid insulation material with taking into account the penetrated distance by the needle tip through the proposed solid insulation. The simple construction of the proposed practical model in this research study for FEM analysis is represented with the help of a Two Dimensional (2 – D) coordinations in both $r - axis$ and $z - axis$ as shown in Fig. 2 [2, 33]. As illustrated before, the mathematical formulation of the equation that describes the hyperbolic shape of the needle electrode is expressed as the following [36]:

$$\frac{z^2}{D^2} = 1 + \frac{r^2}{DR} \tag{6}$$

It is necessary to illustrate that the parameters of this configuration model will be mentioned later according to the data of the proposed simulation model for this configuration regarding to the applied case study.

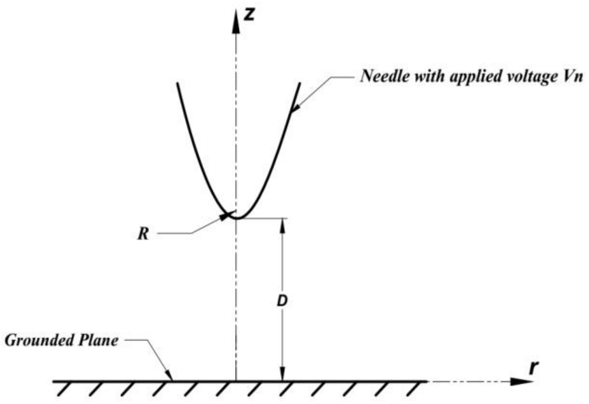

Fig. 2. A hyperbolic needle – plane system structure

4.2. Proposed Simulation Model Parameters

In this portion, The corresponding data to be adjusted for the proposed simulation model that mimics the practical model of the needle – plane system for ET initiation and propagation is illustrated in Table 1. This proposed simulation model for FEM analysis is constructed and imitated depending on the environmental domain of [COMSOL Multiphysics $5.3a$] program with inserting a random distributed four air voids (each one of radius $1\ \mu m$) for the applied previous studies as shown in Fig. 3 [37]. To start the applied case studies with the electric field strength calculations depending on the FEM analysis, a mesh generation approach should be conducted as shown in Fig. 4.

Table 1. Data of The Proposed Simulation Model

Component	Parameters
Needle Electrode	Its material type is chosen to be copper with a radius to be $R = 300\ \mu m$ for HV systems
Plane Electrode	Its material type is chosen to be copper with adjusted dimensions of $1\ cm$ width and $0.2\ cm$ thickness
Dielectric Material	• Its material type is chosen to be XLPE with a relative Permitivity of $\varepsilon_r = 2.1$ • The adjusted dimensions of this solid insulation are $1\ cm$ width and $2\ cm$ height
Extra specifications	The material of voids if added is chosen to be air with $\varepsilon_r = 1$ The radii of voids or if added is chosen to be $r_n = 1\ \mu m$ The penetrated distance inside dielectric material from the needle is adjusted at $1\ cm$ height The distance between needle and plane is adjusted at $D = 1\ cm$ height

From the previous table, it is important to illustrate that all adjusted parameters are chosen according to the allowable common features and considerations that are used repeatedly as base values, the previous contributions that are achieved in this case study be researchers and the help of trial – error criterion that is applied sequentially until reaching to the most precise values for all parameters to achieve the best results without affecting the calculation analysis.

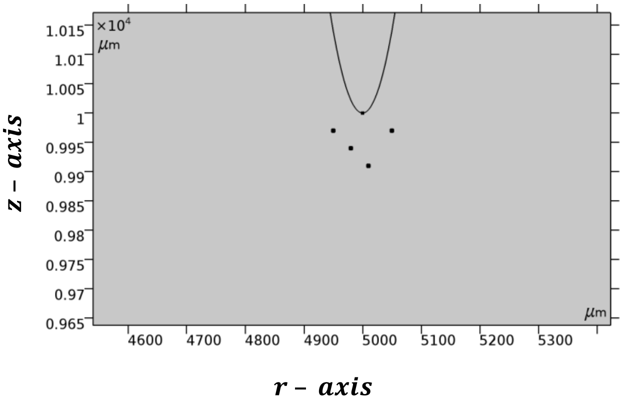

Fig. 3. Constructed simulation model for the study with FEM analysis with random distributed voids

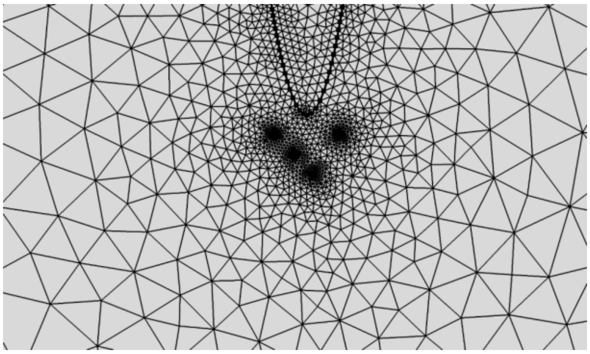

Fig. 4. Mesh generation analysis of constructed simulation model for the applied study

5. Results and Discussion

5.1. Effect of Voltage Variation on ET with FEM

There is a direct relation between the applied voltage and the calculated electric field strength according to the formula of $(E = V/d)$. According to the previous consideration, the increase in the applied voltage on the needle tip of the proposed needle – plane system or the tip of any initiated crack through the solid insulation will lead to the increase in the calculated values of electric field strengths leading to the increase in the process of ionization. Due to the increase in the ionized molecules, the propagation process will be accelerated leading to the increase in ET growth rates and vice – versa.

The study will be conducted in the environmental domain of [COMSOL Multiphysics 5.3a] program depending on varying the value of the applied voltage on the needle tip with the application of three different values of voltages of $V_n = 294\ kV$ which is the critical value to be applied in order to provide an electric field strength of value $4\ MV/cm$ along the needle tip according to the specifications that are illustrated in Table 1 and the following equation:

$$E = \frac{2V_n}{R\ ln(4D/R)} \qquad (7)$$

The other applied voltages are 1.5 times of the critical value and 2.5 times of the critical value respectively, the variation effect of voltage on ET growth rates can be easily illustrated in the obtained results in Table 2 and the concluded figures from Fig. 5 to Fig. 7 at each applied voltage value.

Table 2. Voltage Variation results on ET growth rates for FEM analysis

Only XLPE solid insulation is used		
Applied Voltage	Maximum Calculated Stress	Number of Cracks
$294\ kV$	$E = 4.65\ MV/cm$	0
$441\ kV$	$E = 7.05\ MV/cm$	1
$735\ kV$	$E = 11.8\ MV/cm$	2

From the previous table, it is obvious that for the increase in the applied voltage at the needle tip, the maximum calculated electric field strength increases, and the number of cracked of voids increases sequentially. The closer to the needle tip, the increase in the probability of cracking.

For $294\ kV$, the total calculated field strengths along all voids are less than $4\ MV/cm$, so there is no formation of ET. For $441\ kV$, only one void with a total field strength of $4.05\ MV/cm$ is cracked to initiate the ET formation. For $735\ kV$, two voids with a total field strengths of $4.6\ MV/cm$ and $4.25\ MV/cm$ are cracked to increase the ET growth rates. By controlling the voltage, ET propagation and growth rates can be reduced.

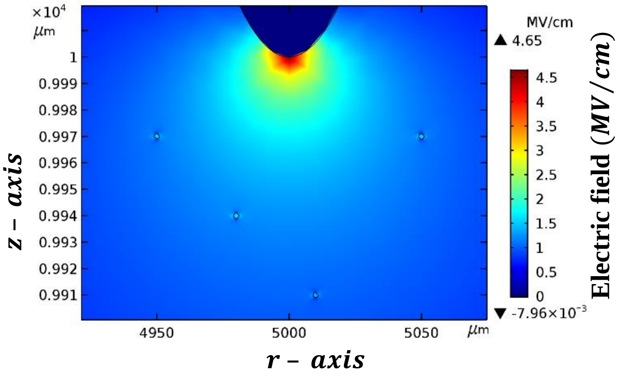

Fig. 5. Field calculation at $294\ kV$ critical voltage for FEM analysis with no cracked voids

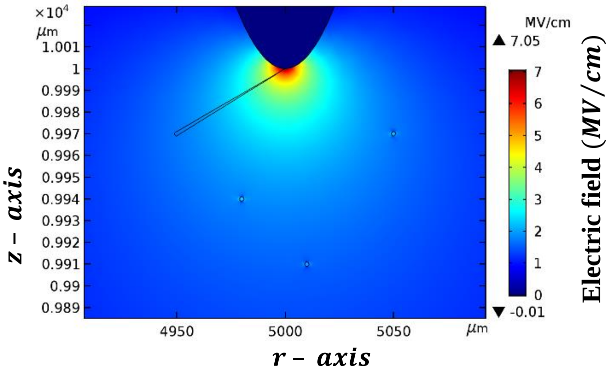

Fig. 6. Field calculation at 1.5 times of 294 kV critical voltage ($441\ kV$) for FEM analysis with one cracked void

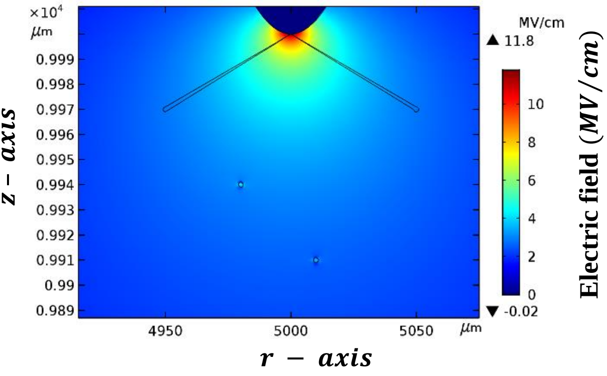

Fig. 7. Field calculation at 2.5 times of 294 kV critical voltage ($735\ kV$) for FEM analysis with two cracked voids

5.2. Effect of Solid Dielectric Type on ET with FEM

To express the effect of solid insulation type on ET growth rates, the constructed proposed model for FEM analysis of adjusted parameters as illustrated in Table 1 with the model that is illustrated in Fig. 3. The study will be conducted in the environmental domain of [COMSOL Multiphysics $5.3a$] program depending on varying the type or the relative permitivity value of the utilized solid insulation at each iteration. To study the field calculation with FEM analysis, a mesh generation approach should be conducted as shown in Fig. 4. with the application of a voltage value of $294\,kV$ (the critical value to be applied according to Eqn. 7) and different materials of Poly – Vinyl Chloride (PVC) and XLPE as illustrated in Table 3, the variation effect of solid insulation type on ET growth rates can be easily illustrated in the obtained results in Table 3.

Table 3. Dielectric changed type results on ET growth rates for FEM analysis

Insulation Type	Maximum Calculated stress	No. of Cracks
PVC ($\varepsilon_r = 2.9$)	$E = 4.65\ MV/cm$	0
XLPE ($\varepsilon_r = 2.1$)	$E = 4.65\ MV/cm$	0
XLPE ($\varepsilon_r = 2.3$)	$E = 4.65\ MV/cm$	0

From the previous table, it is obvious that using any type of insulation material with any value of relative permitivity not affects the ET growth rates. It is important to illustrate that dielectric size and thickness affects directly the ET initiation and growth rates as they increase its insulation level. Changing the solid insulation type or relative permitivity can not suppress the ET propagation ever for the deadly damage increase of its growth rates.

5.3. Effect of Composite Dielectric Materials on ET

To express the effect of using composite dielectric materials on ET growth rates, the constructed proposed model for FEM analysis of adjusted parameters as illustrated in Table 1 with a needle tip radius of $300\ \mu m$ and a random distributed four air voids (each one of radius $1\ \mu m$) utilizing two solid insulations is illustrated in Fig. 8 [37]. The study will be conducted in the environmental domain of [COMSOL Multiphysics $5.3a$] program depending on dividing the utilized dielectric material into two equal portions; one of PVC material with ($\varepsilon_r = 2.9$) and the other of XLPE material with ($\varepsilon_r = 2.1$) as shown in Fig. 8. To study the field calculation with FEM analysis, a mesh generation approach should be conducted as shown in Fig. 9. with the application of three different values of voltages of $294\,kV$ (the critical value to be applied according to Eqn. 7), 1.5 times of the critical value and 2.5 times of the critical value respectively besides the composition process, the effect of composite materials with voltage variation on ET growth rates can be easily illustrated in the obtained results in Table 4 and the concluded figures from Fig. 10 to Fig. 12 at each applied voltage. The results of this case will be compared to the results and shapes of Section 5.1.

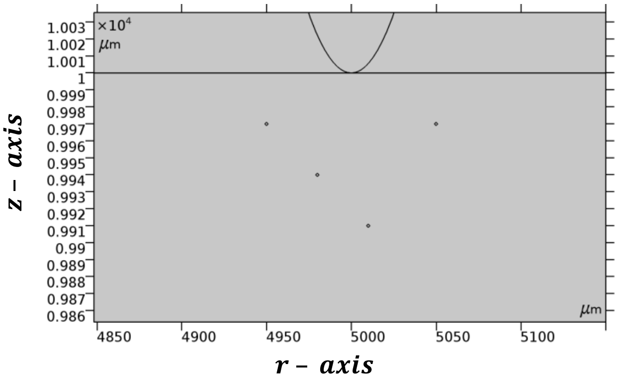

Fig. 8. Constructed simulation model for using composite insulation material with FEM analysis with respect to random distributed voids

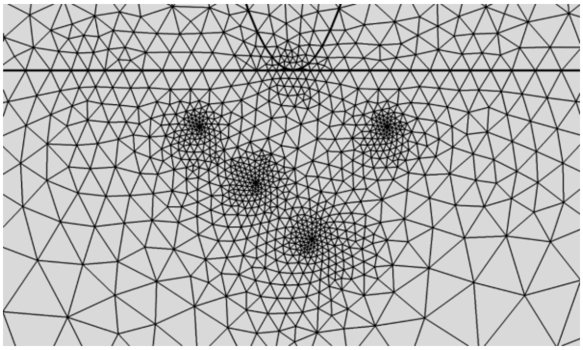

Fig. 9. Mesh generation analysis of the constructed simulation model for utilizing composite dielectric material with voltage variation study

Table 4. Voltage Variation results on ET growth rates for FEM analysis

Composite solid insulation material of PVC and XLPE is used		
Applied Voltage	Maximum Calculated Stress	Number of Cracks
$294\ kV$	$E = 3.06\ MV/cm$	0
$441\ kV$	$E = 4.59\ MV/cm$	0
$735\ kV$	$E = 7.66\ MV/cm$	0

From the previous table, it is obvious that for using the composite solid insulation material, the maximum calculated electric field strength decreases with a great effect of suppressing the initiation and propagation of ET up to voltages of 2.5 times the critical value of $294\,kV$ without any void to be cracked compared to the obtained results in Table 4. This study provides an effective solution for manufactures to increase the insulation level of the solid dielectrics, increase the lifetime of stranded conductors and improve the quality of HV and EHV systems regarding to the financial approach besides the technical and protective manners.

It is necessary to show that the mechanical features of the solid dielectrics may be affected by this composition process so, there are more considerations to be studied in this field in order to enhance the ET problems without weakening any features in the structure of the solid insulation material.

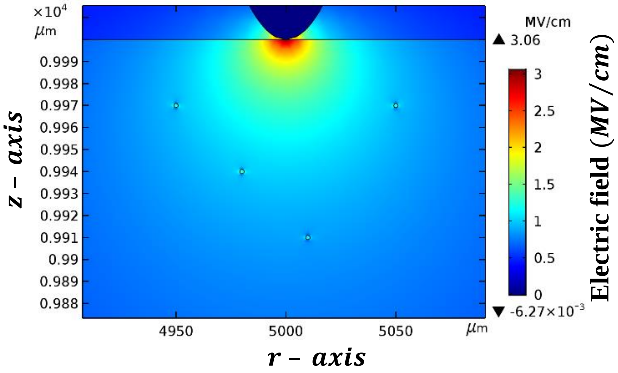

Fig. 10. Field calculation at $294\,kV$ critical voltage for FEM analysis with no cracked voids using composite dielectric material

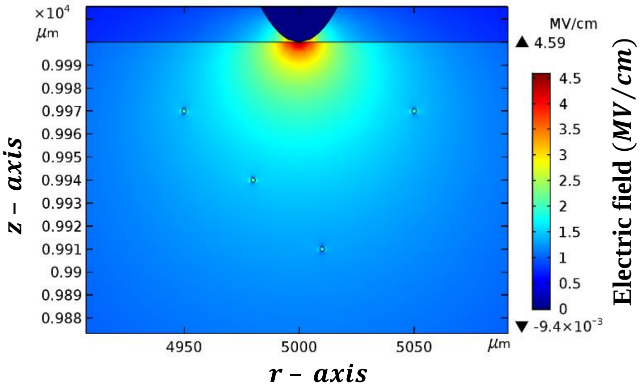

Fig. 11. Field calculation at 1.5 times of $294\,kV$ critical voltage $(441\,kV)$ for FEM analysis with no cracked voids using composite dielectric material

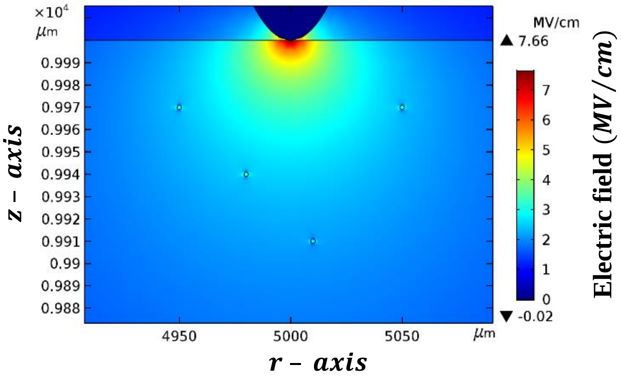

Fig. 12. Field calculation at 2.5 times of $294\,kV$ critical voltage $(735\,kV)$ for FEM analysis with no cracked voids using composite dielectric material

6. Conclusions

Reaching to the final destination of this work, it is important to summarize the achieved goals of this research. This work as previously mentioned deals with the study of the ETP issue and the methodologies to suppress its growth rates or control the factors that have a direct effect on its initiation and growth through solid insulations.

The importance of this work is related to the stability of the power system networks, their overall efficiency and the provided service quality regarding to the size and effectiveness of the networks such as HV and EHV ones. Talking about this phenomenon, solid insulations are exposed to complete damage due to the excessive amount of non – uniform electric field strengths and as a result, the damage will be inflicted to conductors and sequentially the whole system causing not only financial damage but also human casualties.

With the obtained simulation results and the concluded figures, the following points are to be concluded:

- Voltage variations affect directly the electric field calculations and sequentially the ET growth rates.
- Changing the type or relative permitivity of the solid insulation material can not affect on the field calculations and sequentially can not suppress the ET propagation only if the size or thickness has been changed.
- Using composite solid insulation materials can suppress the ET growth rates and in best

cases can suppress its initiation that helps manufacturers to increase the insulation level, enhance the lifetime and improve the service continuity with respect to the financial aspect.

- enriching the importance of utilizing the environmental domain of the [COMSOL Multiphysics $5.3a$] as a powerful program for simulating complicated problems.
- Simulation studies are the powerful arm of latest researches and provide a great support for the experimental studies to explain complicated issues.

References

[1] M. Talaat, M. Tayseer, and A. El-Zein, "Efficiency of different optimization approaches for optimal parameters of the charge simulation method for investigating the onset field due to corona point," IET Generation, Transmission & Distribution, 2020.

[2] A. El-Zein, M. Talaat, and M. El Bahy, "A numerical model of electrical tree growth in solid insulation," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 16, pp. 1724-1734, 2009.

[3] S. Natarajan, M. Balasubramanian, S. M. Ghouse, and R. Rajesh, "Morphological studies of electrical tree due to high alternating electric fields in epoxy solid dielectrics," ARPN Journal of Engineering and Applied Sciences, vol. 13, pp. 512-516, 2018.

[4] D. Rabah, C. Abdelghani, and H. Abdelchafik, "Efficiency of some optimisation approaches with the charge simulation method for calculating the electric field under extra high voltage power lines," IET Generation, Transmission & Distribution, vol. 11, pp. 4167-4174, 2017.

[5] V. Chartier, L. Lee, L. Dickson, and K. Martin, "Effect of high altitude on high voltage AC transmission line corona phenomena," IEEE transactions on power delivery, vol. 2, pp. 225-237, 1987.

[6] Q. Shaozhen and S. Birlasekaran, "The study of PD propagation phenomenon in power network," IEEE Transactions on power delivery, vol. 21, pp. 1083-1091, 2006.

[7] N. Shimizu and C. Laurent, "Electrical tree initiation," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 5, pp. 651-659, 1998.

[8] R. Amiri, H. Hadi, and M. Marich, "The influence of sag in the electric field calculation around high voltage overhead transmission lines," in 2006 IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2006, pp. 206-209.

[9] M. Ramesh, L. Cui, and R. Gorur, "Impact of superficial and internal defects on electric field of composite insulators," International Journal of Electrical Power & Energy Systems, vol. 106, pp. 327-334, 2019.

[10] K. Adamiak and P. Atten, "Simulation of corona discharge in point–plane configuration," Journal of electrostatics, vol. 61, pp. 85-98, 2004.

[11] L. Cisse, G. Teyssedre, D. Mary, and C. Laurent, "Influence of frequency, electrode material and superimposed dc on ac electroluminescence in polymer films," IEEE transactions on dielectrics and electrical insulation, vol. 9, pp. 124-129, 2002.

[12] C. Laurent and C. Mayoux, "Analysis of the propagation of electrical treeing using optical and electrical methods," IEEE Transactions on Electrical Insulation, pp. 33-42, 1980.

[13] L. A. Dissado, "Understanding electrical trees in solids: from experiment to theory," IEEE Transactions on dielectrics and electrical insulation, vol. 9, pp. 483-497, 2002.

[14] B. Du, J. Xue, J. Su, and T. Han, "Effects of ambient temperature on electrical tree in epoxy resin under repetitive pulse voltage," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 24, pp. 1527-1536, 2017.

[15] R. Schurch, J. Ardila-Rey, J. Montana, A. Angulo, S. M. Rowland, I. Iddrissu, et al., "3D characterization of electrical tree structures," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 26, pp. 220-228, 2019.

[16] H. Zheng, G. Chen, and S. M. Rowland, "The influence of AC and DC voltages on electrical treeing in low density polyethylene," International Journal of Electrical Power & Energy Systems, vol. 114, p. 105386, 2020.

[17] J. Su, B. Du, J. Li, and Z. Li, "Electrical tree degradation in high-voltage cable insulation: progress and challenges," High Voltage, 2020.

[18] X. Chen, Y. Xu, X. Cao, S. Dodd, and L. Dissado, "Effect of tree channel conductivity on electrical tree shape and breakdown in XLPE cable insulation samples," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 18, pp. 847-860, 2011.

[19] S. M. Rowland, R. Schurch, M. Pattouras, and Q. Li, "Application of FEA to image-based models of electrical trees with uniform conductivity," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, pp. 1537-1546, 2015.

[20] R. Eichhorn, "Treeing in solid extruded electrical insulation," IEEE Transactions on Electrical Insulation, pp. 2-18, 1977.

[21] D. J. Jabha, K. Selvi, and R. Joselin, "A new approach for the failure prediction in XLPE power cables using acoustic emission technique," International Journal of Electrical Power & Energy Systems, vol. 81, pp. 336-345, 2016.

[22] W. H. Koh and I.-H. Park, "Numerical simulation of point-to-plane corona discharge using a Monte Carlo method," Vacuum, vol. 84, pp. 550-553, 2009.

[23] L. Dissado and R. Hill, "The statistics of electrical tree inception," IEEE transactions on electrical insulation, vol. 25, pp. 660-666, 1990.

[24] J. H. Mason, "Breakdown of solid dielectrics in divergent fields," Proceedings of the IEE-Part C: Monographs, vol. 102, pp. 254-263, 1955.

[25] J. Champion and S. Dodd, "The effect of voltage and material age on the electrical tree growth and breakdown characteristics of epoxy resins," Journal of Physics D: Applied Physics, vol. 28, p. 398, 1995.

[26] A. El Zein, "Electrically induced pressure under switching operation and mechanical tensile strength as a new measurement tool of cable aging," in Conference Record of the 1996 IEEE International Symposium on Electrical Insulation, 1996, pp. 155-158.

[27] A. El-Zein, M. El Bahy, and M. Talaat, "Types of electrical trees in solid insulation under electrical and mechanical energy basis," in 2008 12th International Middle-East Power System Conference, 2008, pp. 80-84.

[28] J. Fothergill, "Filamentary electromechanical breakdown," IEEE transactions on electrical insulation, vol. 26, pp. 1124-1129, 1991.

[29] E. J. McMahon, "The chemistry of corona degradation of organic insulating materials in high-voltage fields and under mechanical strain," IEEE Transactions on Electrical Insulation, pp. 3-10, 1968.

[30] J. S. Campbell, "Computer modelling in electrostatics, D. McAllister, JR Smith and NJ Diserens (eds), Research Studies Press Ltd, Letchworth, 1985, Price:£ 19.75, ISBN 0

86380 035 1," Communications in Applied Numerical Methods, vol. 2, pp. 543-543, 1986.

[31] H. Elayyan and M. Abderrazzaq, "Electric field computation in wet cable insulation using finite element approach," IEEE transactions on dielectrics and electrical insulation, vol. 12, pp. 1125-1133, 2005.

[32] I. Radu, "Electric field calculation and the influence of water trees on insulation breakdown in needle–plane geometry," Journal of electrostatics, vol. 60, pp. 49-67, 2004.

[33] M. Talaat, A. El-Zein, and A. Samir, "Numerical and simulation model of the streamer inception at atmospheric pressure under the effect of a non-uniform electric field," Vacuum, vol. 160, pp. 197-204, 2019.

[34] R. Vogelsang, T. Farr, and K. Frohlich, "The effect of barriers on electrical tree propagation in composite insulation materials," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 13, pp. 373-382, 2006.

[35] Y. Cui, L. Zhu, S. Ji, P. Cao, and F. Zhang, "Partial discharge development in needle-plane configuration of oil-paper insulation under AC voltage," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 24, pp. 2469-2476, 2017.

[36] W. Lama and C. Gallo, "Systematic study of the electrical characteristics of the``Trichel"current pulses from negative needle- to- plane coronas," Journal of Applied Physics, vol. 45, pp. 103-113, 1974.

[37] H. Ding and B. Varlow, "Thermodynamic model for electrical tree propagation kinetics in combined electrical and mechanical stresses," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 12, pp. 81-89, 2005.