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Simulation of Electrical Trees Grow in Three-Core Submarine Cable

***Abstract**. The efficient insulation of electric power cables is assured by cross-linked polyethylene due the good performance and mechanical properties. Nevertheless, the presences of electrical trees in insulator can lead to the partial discharge; aging and breakdown of cable insulation. In order to assess the effect of electrical trees phenomena in cross-linked polyethylene cable. This paper aimed to study the partial discharge process by using finite element method, a several electrical trees with electrical discharge was designed to show the partial discharge process. So an electrostatics parameters measurement system was used to obtain the partial discharge characteristic patterns during treeing. Furthermore, four structures of electrical tree development of stages are considered in this study. These discharge types in the electric cable are in vacuum, insulation, and conductor. The electric field distribution and magnitude is affected by the discharge nature, shape, length, and electric tree origin. Finally, the study shows the parameters influence on the electric treeing phenomenon to improve the modelling approaches and their performance.*

***Streszczenie.** Skuteczną izolację przewodów elektroenergetycznych zapewnia polietylen usieciowany ze względu na dobre właściwości użytkowe i mechaniczne. Niemniej jednak obecność drzew elektrycznych w izolatorze może prowadzić do wyładowań niezupełnych; starzenie się i uszkodzenie izolacji kabla. W celu oceny wpływu zjawisk drzew elektrycznych na kabel z usieciowanego polietylenu. Niniejsza praca miała na celu zbadanie procesu wyładowań niezupełnych za pomocą metody elementów skończonych, zaprojektowano kilka drzew elektrycznych z wyładowaniami elektrycznymi, aby pokazać proces wyładowań niezupełnych. W celu uzyskania charakterystyki wyładowań niezupełnych podczas drzewkowania wykorzystano więc system pomiaru parametrów elektrostatycznych. Ponadto w niniejszym opracowaniu rozważono cztery struktury etapów rozwoju drzewa elektrycznego. Te typy wyładowań w kablu elektrycznym występują w próżni, izolacji i przewodzie. Na rozkład i wielkość pola elektrycznego ma wpływ charakter wyładowania, kształt, długość i pochodzenie drzewa elektrycznego. Na koniec badanie pokazuje wpływ parametrów na zjawisko drzewiastości elektrycznej w celu poprawy metod modelowania i ich wydajności. (**Symulacja drzew elektrycznych rosnących w trójżyłowym kablu podmorskim**)*

Keywords: Cables, Electric Field, electric tree, submarine.
Słowa kluczowe: Kable, pole elektryczne, drzewo elektryczne, łódź podwodna.

Introduction

Nowadays, submarine and underground line cables are widely used in the transport and distribution network to improve the stability, quality and security of electrical network against lightning and the incident[1, 2]. The majority of cables are manufactured by cross-linked polyethylene (XLPE) insulator with perfect properties and less cost has become the very important material insulator applied to underground and subsea electric cable [2-4].

However, there are several factors affecting cable insulation over time, interne or extern such as: thermal stresses, electrical, mechanical and finally environmental constraints [3-5, 6]. In addition, some inevitable failure and defects, including vacuum, cavities, moisture, and mechanical damages (deformation, pressure, constraint and forces) [5, 6].

In addition, the premature aging of the cables can come from contaminants (foreign particles), defects, protuberances or voids, which appear in the insulation during production, transport or installation of the cable. Initially, these imperfections are point or localized defects in the insulation. On the other hand, during over time, they can get worse and gradually spread through the insulation when the cable is in service. They may even involve the complete destruction of insulation [5, 6].

The propagation and orientation of diverse electrical trees possesses randomness characterized with high complexity, thus explaining the process of electrical tree phenomena via unified theory becomes even harder. Over the decades, several experts and scholars have studied the various factors affecting the presence and generation the growth process of electrical trees [5, 7].

The electrical trees were studied in polyethylene as a prelude to Breakdown by first searcher D.W. Kitchinin this area since 1958 [8].

Many researches show the factors affecting the tree's development is related to:

- The crystalline state of the material,
- The distance of discharge, The material of electrodes,
- The amplitude and frequency of the voltage,
- Residual mechanical stress and air gap, etc [7].

Similarly, other work investigates the growth process of electrical trees in XLPE has classified by four stages of partial discharge [9].

The particles contamination, cavities and voids present inside the insulated cable may cause the initiation of electrical tree inside the polymer if the applied voltage is large enough. Electrical trees are the prime cause of insulation part failure in polymeric power cable, a number of branch fine conductive channels growths in one direction as the electric field [5, 6]. Propagation rate of electrical tree depends upon of frequency and magnitude of applied electric field, environmental, mechanical stresses and temperature [7, 8].

There are four cases (stage during the growth) of electric discharge tree development restrained by insulation, categorized by:

Initial few electric trees (initiation growth)
Branch-like tree (slow growth)
Bush-like tree (rapid growth)
Final electric trees to finally breakdown (sustained growth stage) [9].

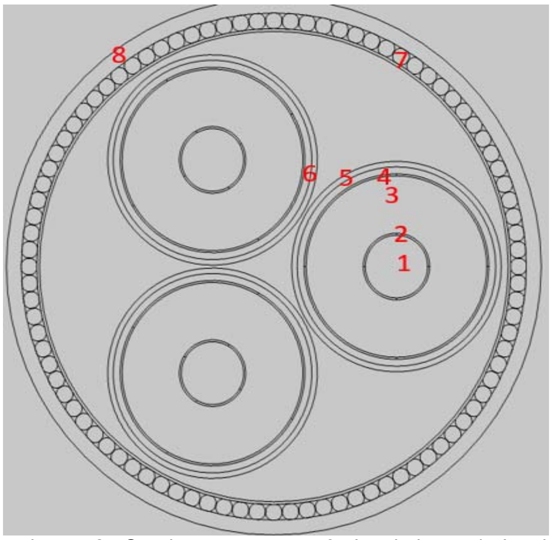
However, many other experimental studies show the new parameter impact as: temperature Gradient on Electrical Tree Growth, charge migration and Partial Discharge under AC Voltage [10].

The new double electrical tree structure and propagation of growing mechanism were analyzed by experiment works, based on improved treeing propagation by the three phases (initiation, stagnation, and rapid propagating phases) affected by two other coefficients are growth rate and dynamic fractal dimension of treeing [11]. The mechanical stress, high temperature charge transport and electric field, influential directly on electrical tree process impact and behaviors [12]. Finally, Recent work and research mainly focuses on theoretical models and approach by experiments and simulation development.

This paper studies the process and the effect of electrical trees and partial discharge in cross-linked polyethylene cable, by finite element method (fig.1). The aim of this paper is to simulate the four electrical trees and electrical discharge and measurement electrostatics parameters during treeing. The simulation results show the effect of different structures of electrical tree development for four stages on the electric field variation and form. The second part contains the different discharge types in the electric cable from: vacuum, insulation, and conductor. The electric field distribution and magnitude is affected directly by the discharge nature, shape, length, and electric tree origin.

Geometry data and parameters of simulation cable model

The three core cable shape is illustrated in fig 1.



1: Conductor 2: Conductor screen, 3: Insulation, 4: Insulation screening-semi conductive, 5: Screen, 6: Laminated sheath, 7: Armor-galvanized round steel wires, 8: cover sheath Fig.1. Three core cable shape [6,13].

Table 1 gives the structure sizes and characteristics of the cable. Table 2 presents the characteristics of different materials used in the model simulation, for both single-core and three-core submarine electrical cables.

Table 1. structure size of three core XLPE cables [6.13]

Description	Value [mm]
Diameter of the conductor (Phase)	26.2
Insulation thickness (Phase)	24
Semi-conductive compound thickness (Phase)	0.85
Lead sheath thickness (Phase)	2.9
Diameter of fiber optic cable core	2.5
Armor thickness	6.5
Outer diameter of the cable	219
Diameter over insulation (Phase)	77.6
Diameter over phase (Phase)	89.2
Diameter over fiber optic core	2.5

Table 2. Material characteristics of submarine power cables [6, 13].

Materials	Electrical conductivity [S/m]	Relative permeability (per unit)	Relative permittivity (per unit)
Air	1·10-14	1	1
Polyethylene	1·10-18	1	2.25
Polypropylene	1·10-18	1	2.36
XLPE	1·10-18	1	2.5
Lead	4.55·106	1	1
Copper	5.998·107	1	1
High-strength alloy steel	4.032·106	1	1
Semi-conductive compound	2	1	1
Silica glass	1·10-14	1	2.09
Sandy	1	1	28
Water	5.5·10-6	3	81

Numerical model methodology

The capacitive effects of the model

The Maxwell model is used to solve a 2D in-plane current conservation problem in the frequency domain. Using the electric scalar potential V as a dependent variable, this includes the following equations [6, 14]:

(1) $$\begin{cases} \vec{E} = -\vec{\nabla} V \\ \vec{D} = \varepsilon \vec{E} \\ \vec{\nabla}.\vec{D} = \rho \\ \vec{\nabla}.\vec{J} = -j\omega\rho \end{cases}$$)

where $\vec{D}$ is the electric field displacement, ρ is the free charge density and $\vec{J}$ is the free current density , $\vec{E}$ and the electric field displacement.

Where the relation between electric field and electric potential, Gauss law and current conservation law is used here when Faraday's law evaluated to be zero [6, 14].

(2) $$\vec{\nabla} \times \vec{E} = -j\omega\vec{B} = 0$$

In other words, the model assumes that the magnetic field is negligible (zero) and focuses solely on in-plane or directional electric fields. The displacement current is included in the current definition this give $\nabla.J' = 0$ and $J' = J + j\omega D$ for the current conservation law and the current definition, respectively.

(3) $$\vec{\nabla}.(\vec{J} + j\omega\vec{D}) = 0$$)

The constitutive relations $\vec{D} = \varepsilon\vec{E}$ and $\vec{J} = \sigma\vec{E}$ are adding to get:

(4) $$\vec{\nabla}.(\sigma\vec{E} + j\omega\varepsilon\vec{E}) = 0$$

When we piece $\vec{E} = -\nabla V$, in (4) we end up with the following 2D partial differential equations for the dependent variable V:

(5) $$-\vec{\nabla}.((\sigma + j\omega\varepsilon)\vec{\nabla}V) = 0$$

The electric current interface uses this equation in the domains to determine the value of *V* and consequently, the value of E, J and J_D. The electric voltage of the three phases in time variation is as follows [6, 14]:

(6) $V_a = V_0, V_b = V_0 e^{-j2\pi/3}, V_c = V_0 e^{j2\pi/3}$

3.2 The Finite Element Analysis (FEA) Model

The numerical method used to solve mathematical linear differential equation. The principle of the FEM lies in the division of the elementary domain of finite dimensions for each domain called finite element, the unknown function is approached by a tooth polynomial degree number can vary from one application to another. The main stages of a finite element method construction are the following [15, 16]:

●Discretization of the continuous environment, representing the field of study in sub-field (element);

● Construction of the nodal approximation by subdomain(different part of cable) ;

●Calculates elementary matrices (for each element) corresponding to the integral of the problem;

● Assembly of elementary matrices taking into account the boundary conditions [17, 18];

● Solve the equation system [19, 20].

In our case, the field of study, which is two-dimensional, we often meet with linear, quadratic or cubic elements. To lead to a better accuracy of the solution, one proceeds to refine the mesh see fig .2.

This engineering operation called discretization, nodes and elements is woven onto the design for the finite element method The physical interfaces determine meshing sequence according to the physics-controlled mesh section and coarse element size (fig 2) [21-25].

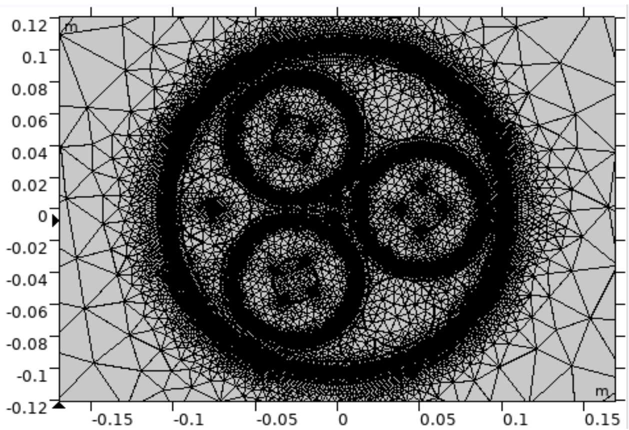


Fig.2. Mesh in 2D.

4.Simulation results

4.1 Electric tree:

The vacuum (or cavity) placed near the conductor or insulation and middle insulator, placed in the higher electric field and gas ionization process, will grow significantly in size until it forms branch and channels near the cavity. The pattern of channels formed determines the type of electric discharges from the superficial part of the vacuum or conductor and insulation.

Growth phases of electrical tree are divided into four phases: the first initial phase contains few tree limited by number of branches, the variation concentred in the first part of discharge. The two successive phases propagation phase (slow and rapid growth) characterized by appearing of multiple branch in the middle and near the end parts of discharge. The last phase is breakdown characterized by direct contact between the ground and conductor parts trough the electric tree.

From the previous four cases shown that trees size, form and position (a number of fine conductive channels) have significant impact on the progression of Electric Trees (ET) in XLPE cable. Polyethylene failure and trees increase when it is subjected to an AC voltage stress above a certain threshold voltage, due to the variation of positive and negative polarities injected inside the poly From fig. 3 we note that the magnitude of electric field (1.25107 V/m initiation growth) in the tree is much greater than the normal case (0.85 107 V/m), the waveform is affected by the shape of tree defect.

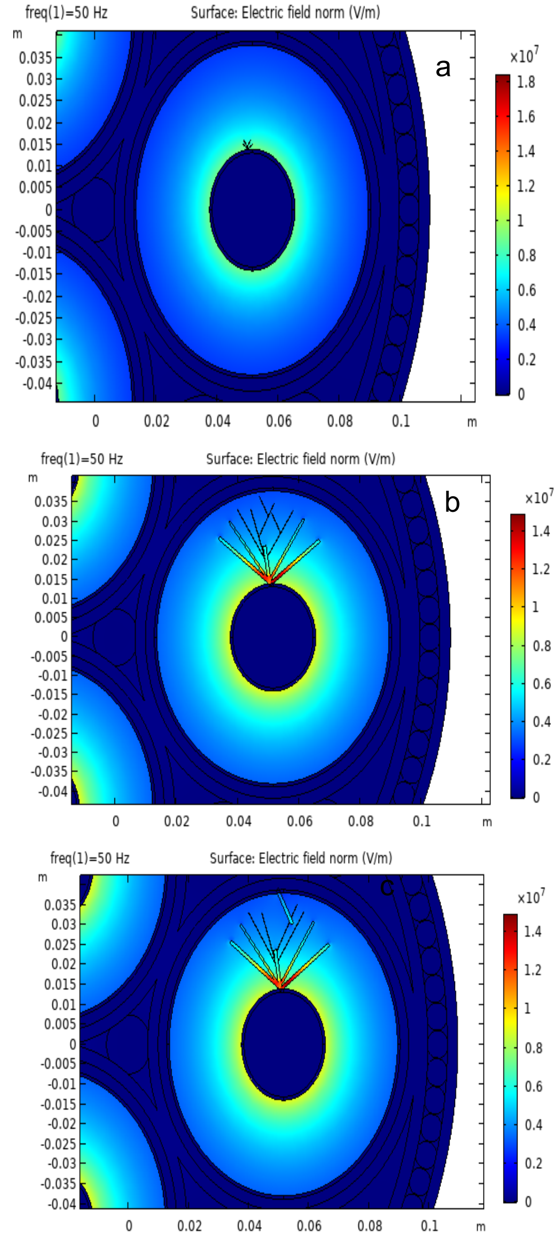
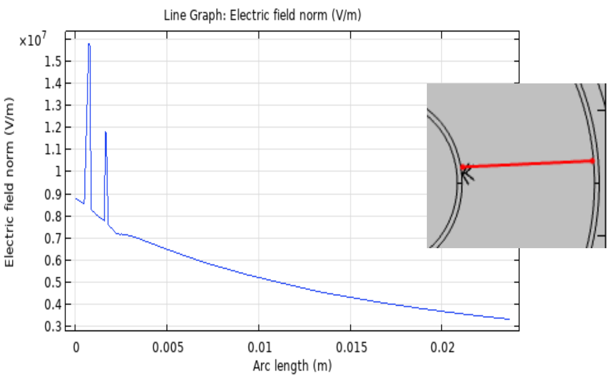


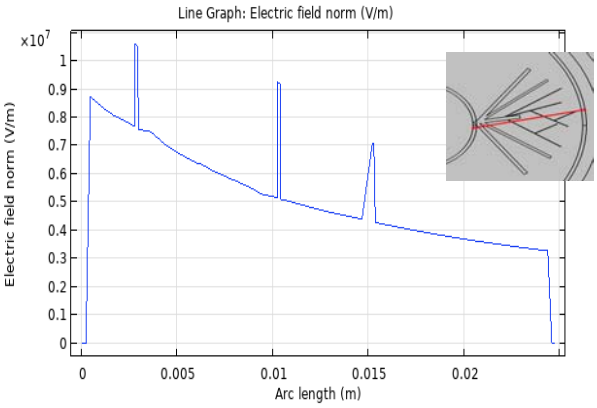
Fig.3. Typical process of the electrical trees growth

4.2 Electric field computation:

The electric field distribution analysis of four cases computation represents the important variation depending on the number and size of branch of each electric tree impact. The computation of magnitude changes due to the relationship between the form, position and length characteristics of electric trees and electric field. These branches affect the electric field by repetitive pulse magnitude with important amplification see fig.4.



(a)



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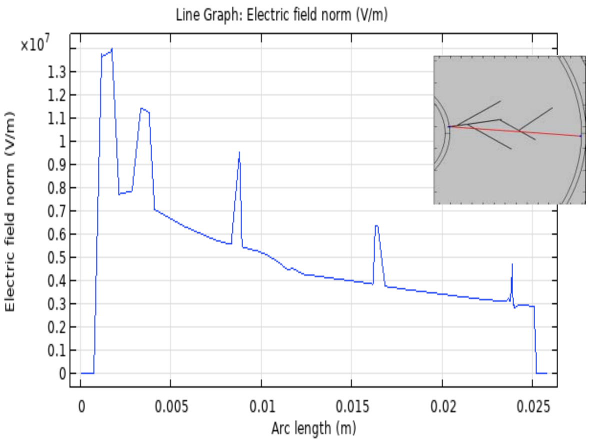

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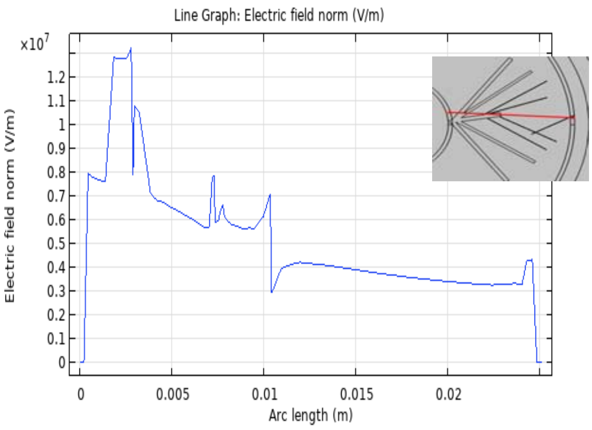


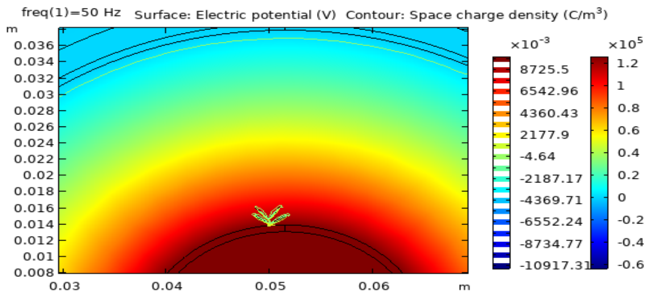
(d)

Fig.4. Computation of electric field variation with presence of electric trees for four steps.

4.3 Space charge density of four electric trees structures

Fig. 5 shows the pattern of space charge density in the cable insulation for different tree structures. In Fig. 5(a). The tree structure can influence the space charge density (i.e. accumulation of positive or negative charges) in power cables because the creation of high electric field strength region (the vicinity of the tree structure).

The magnitude of the electric field varies depending on the structure of the cable. In a normal cable, the electric field magnitude ranges from 8.5 106 V/m. However, in a defective cable, the electric field magnitude can reach 1.6 107 V/m, which is twice the intensity.



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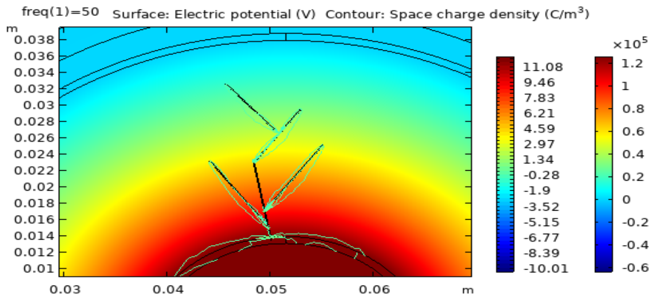

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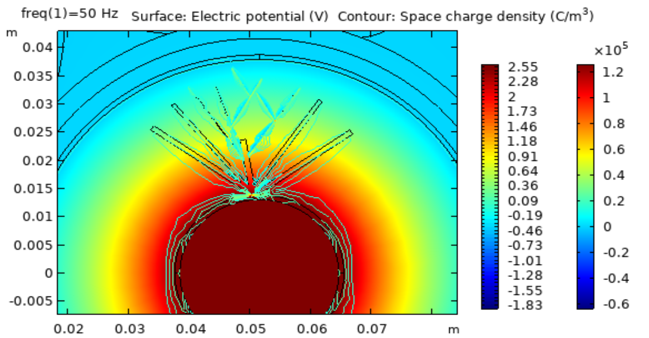

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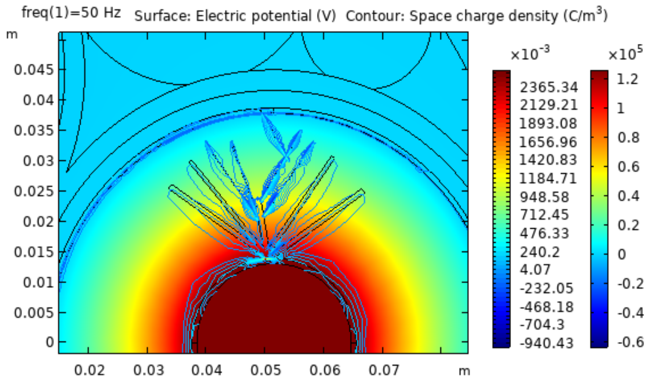


(d)

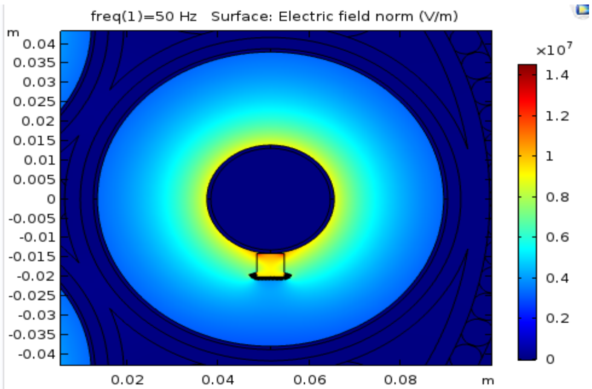
Fig.5. Space charge density and electric potential of four electric trees.

Electric trees are formed due to the accumulation of space charge density in a specific area. This accumulation leads to electric discharge from the conductor to the screening semi-conductive material, which passes through the insulating part and eventually reaches the ground electrode before causing final breakdown. (The propagating growth under conducting channels). The discharge partial mechanism is very complexity affected directly the lifetime or failure time of cable insulator degradation, see fig .5. On different spacers, the electric field distribution varies and affects the discharge flashover greatly, which facilitates the growth of trees.

4.4 Different discharge origin types:

- Discharge from vacuum:
- Discharge from insulation:
- Discharge from conductor:

The discharge characterized by several electrical bushes' branches with different orientations generated by electrical, mechanical and thermal factors. The space charge distribution depends on the shape and size of the tree structure, of the insulation material properties.



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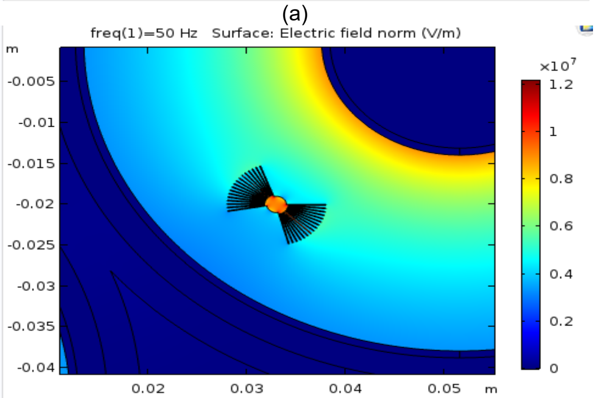

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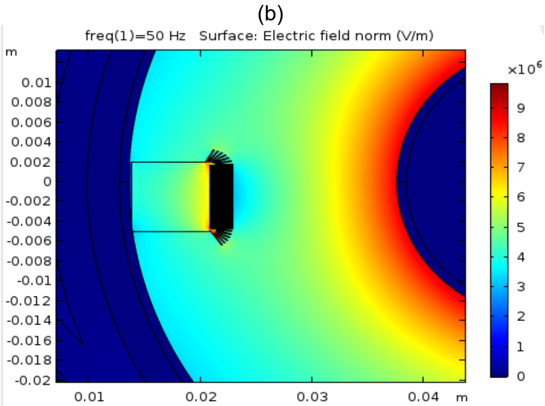
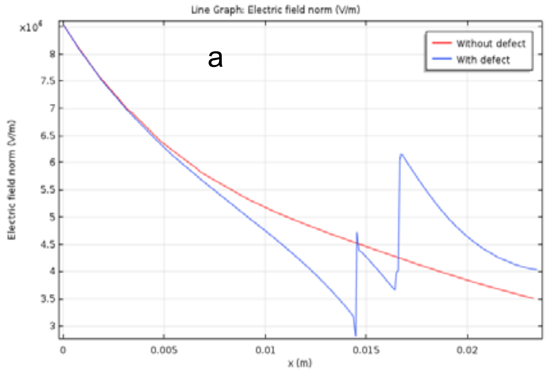


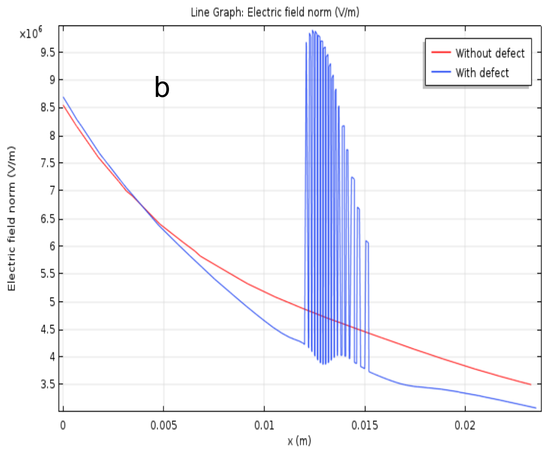
(c)

Fig.6. Several discharge from: a) Vacuum (b) near conductor (c) near the ground electrode.

The line field along and through the discharging domains and cable insulation respectively are shown in Fig. 7. In Fig. 7(a), it can be seen that.

Electric Field Computation:





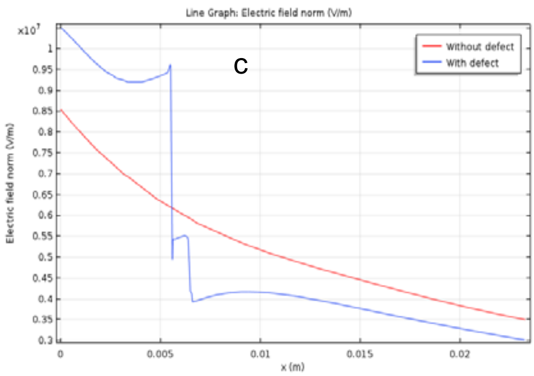


Fig.7. Line electric field plots on discharge (a) Middle of insulation (b) Near the insulator (c) Near the ground.

The simulation results show the multiple channels oriented from the end of conductor cable, where the discharge is based from insulator layer in semiconductor material (ground screen). The measurement shows the variation of electric field affected by the discharge form and distance. Fig. 6 illustrates the electric discharge characterized by special shape produced around the vacuum. The numerical measuring presents the importance of electric lines discharge with repetitive modulation and values. The position of discharge from conductor changes the electric field orientation and distribution compared by the last cases Fig 7. In three different previous cases, A, B, and C, the maximum ratio can vary between 1.47, 2, and 1.53 times, respectively.

6. Conclusion

This paper focused on the various electric trees simulation in the three-core submarine power cable with finite element analysis. For better understanding the different phase's electrical tree effects on inception discharge and the electric field distribution and magnitude analysis by finite element method. There are four stages during the growth of electrical trees, categorized by: initiation, slow growth, rapid growth, and sustained growth stage. Further, with growth of electric trees, it was found that the electrical charge impact and electric field increases linearly with increasing of brunch number and size on the either side. According to the electric trees forms and space charge density (electric field distribution) the partial discharge is produced, and the influence of electrical trees position, size and orientation tend to expand in the direction of the electric field they are exposed have also been studied. Besides, the electric field distribution and discharge origin structure are summarized into three from vacuum conductor insulation. The simulation results indicate that the important electric potential and trees length contributes to electric charges and gradually lowers the cable insulation.

Finally, these results indicate that the increase of electric tree growth and partial discharge in the electric power cable will affect the insulation directly and produce failure, the consequence is the acceleration the aging and heating, posing a threat to the safety of the cable system and electric network.

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