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doi:10.15199/48.2024.02.58

Study of DC Voltage Effects on the Electrical Treeing Phenomenon in XLPE Insulating Materials

Abstract. *In this study, we present the propagation of electrical tree in solid insulation via dynamical simulation with cellular automata. Taking a specimen of XLPE dielectric situated between two electrodes under DC voltage. Electrical tree emanates from the end of the needle where the electric stress reaches the dielectric strength of the dielectric material. The potential distribution is determined at every step due to the boundary changes according to tree advancement by resolving Laplace's equation. The effect of the applied voltage levels on the formation of the electrical tree is investigated. The obtained results are in agreement with the available experimental data and published technical literature.*

Streszczenie. *W tym badaniu przedstawiamy propagację drzewa elektrycznego w izolacji stałej poprzez dynamiczną symulację z automatami komórkowymi. Pobranie próbki dielektryka XLPE umieszczonego między dwiema elektrodami pod napięciem stałym. Drzewo elektryczne emanuje z końca igły, gdzie naprężenie elektryczne osiąga wytrzymałość dielektryczną materiału dielektrycznego. Rozkład potencjału jest określany na każdym kroku ze względu na zmiany granic w zależności od postępu drzewa poprzez rozwiązanie równania Laplace'a. Zbadano wpływ przyłożonych poziomów napięcia na tworzenie się drzewa elektrycznego. Uzyskane wyniki są zgodne z dostępnymi danymi eksperymentalnymi i opublikowaną literaturą techniczną.* (***Badanie wpływu napięcia stałego na zjawisko drzewa elektrycznego w materiałach izolacyjnych XLPE***)

Keywords: Electrical Tree, Cellular Automata, XLPE, Laplace.
Słowa kluczowe: Drzewo elektryczne, automaty komórkowe, XLPE, Laplace.

Introduction

XLPE are considered as the preferred in high and medium-voltage cables due to their longevity, breakdown strength, low dielectric permittivity and resistance to current load [1-4].

Electrical tree is type of the principle causes to degradation of the XLPE dielectric. Trees can be inception in many sites where electric stress is enhancement like as: gas-filled cavities, presence of the conducting particles, contamination with impurities and material inhomogeneity due to manufacturing defects. Consequently, the initiation and propagation of the electrical tree branches is followed with partial discharge activity inside the channels. The phenomenon of treeing is started by the formation of branches and finalised by electrical tree that deteriorates the dielectric, i.e. damaging the cable [4-8].

Impact of the electrical trees on the insulation of power cables is very critical which achieved damages and economics losses.

More researches were presented for understand, analysed and limited this effect experimentally and by simulation from one side, in another side for optimization the reliability of these dielectrics. In this area, are examined the impact of the impurities, gap between electrodes, temperature on the behaviour of the treeing phenomenon in XLPE cable samples using experimental technics [1-3, 9].

Other authors have analysed the mechanism of electrical tree initiated and propagated from experiment to theory [6-8; 10].

Numerous models are proposed for clarify the mechanism's formation and growth of tree branches in solid dielectrics. Niemeyer et al. [11] are analysed the failure phenomenon based on the fractal dimension. A model of three-dimensional is created to present the treeing phenomenon propagation and partial discharge activity within the increasing tree channels by Noskov et al. [12]. Dissado et al. [13] are proposed the model that called “Deterministic Discharge- Avalanche”; it is deterministic in concept and associates the channels with local field variations produced by itself mechanism.

G. E. Vardakis et al. is simulated the phenomenon of treeing in solid dielectrics via Cellular Automata in various cases: existence of voids, the of particles (conducting and insulating) [14, 15, 16] in addition, investigated the impact of spaces charges density on the growth of branches [17], but not focused on the effect of the level of the applied voltage.

In this paper, we investigate on the effect of the applied voltage on the behaviour of electrical tree inside cross-linked polyethylene by cellular automata based on inherent inhomogeneity of the dielectric.

Cellular automata model

The physics system behaviour is not determined only by macroscopic parameters. The significant aspects of the microscopic laws of physics are a great trial for anyone who tries to simulate physical system. CA method is an idealization of dynamical method where time, space, and variables are separate and interactions are only local [18, 19]. CA are first announced by John Von Neumann in the late 1940s [20, 21]. It has been used extensively to the modelling of ordinary phenomena and complex systems [22].

Due to their ability to describe the behaviour of the complex physical phenomena, despite the simplicity of their structure. Jon Conway in the 1970, and Stephen Wolfram in the start of the 80's are developed architecture of CA, the first had proposed what is termed Game of Life and the last has studied in much detail a family of simple “one-dimensional CA rules”, acknowledged as: Wolfram rules [23].

CA contains of a n-dimensional regular uniform i.e. matrix. At individually cell of the matrix, a physical number takes values. This number is the global state of the CA, and the value of this number at each cell is the local state of this cell. Each cell is restricted only to local neighbourhood interaction, and as a result, it is unable of immediate global communication [18].

The neighbourhood of the cell which is taken to be the cell itself and some or all the immediately neighbouring cells. The state of each cell is updated concurrently at discrete time steps, based on the states in its neighbourhood at the previous time step. The programme is used to compute its successor state is mentioned as the local rule of CA.

Generally, the similar local rule is applied to all cells of the CA matrix. The state of a cell at step (t+1) is affected by the states of all neighbourhood eight cells at time step t and by its particular state at time step t.

Model simulation

Laplace's equation (1) is solved at each time step by PDE Toolbox of Matlab for calculated potential distribution inside the dielectric:

$$\nabla^2 V = 0 \tag{1}$$

For the correct calculation of the potential distribution as we shown in Figure 1, the definition of the appropriate boundary conditions is crucial:

- Dirichlet boundary conditions at the border between the needle electrode and dielectric, plane electrode and XLPE.
- Neumann boundary conditions between the dielectric sample and surrounding air.

The potential values obtained from PDE Toolbox of Matlab are classified with the aid of a Matlab algorithm in a matrix of 10000 elements at every time step.

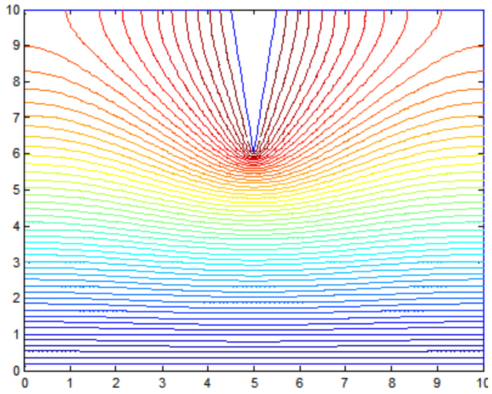


Fig.1. Potential distribution at step t=0

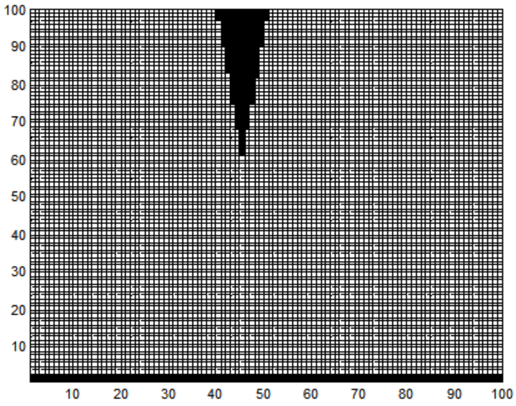


Fig.2. Cellular automata representation of an XLPE dielectric

From the Figure 2, the physical system with needle/plane electrodes is alienated into a matrix of square cells (100×100), in which every cell has dimensions (0.1×0.1) mm; thus, dimensions of XLPE sample are (10×10) mm. In this model, the internal state of each cell is defined by two parameters: the potential value V and a value of dielectric inhomogeneity factor g which is generated randomly between two values.

Before simulation, we assume the value of the electric stress E_{max} at the end of the needle tip by the formula [24]:

$$E_{\max} = \frac{2V}{r(\ln(1+\frac{4s}{r}))} \tag{2}$$

If the E_{max} attains a dielectric strength $E_c=40$ *kV/mm* [24], the electrical tree emanate from the end of the needle tip because the value of the electric stress is transferred into this latter [25, 26], and consequently the state of the cell at the end of the needle tip at time *t+1* is *1*.

At every time step the common local rule illustrated in the Table 1 which is applied to all cells to simulate electrical tree growth is:

Table 1. Common rule applied to simulate electrical tree evolution

	Time step		Conditions
	t	t+1	
State of the (i, j) cell	1	1	/
	0	0	• None of its neighbor's tree flags is 1.
	0	1	• One or more of its neighbor's state are 1 and E/Ec>1.

The potential distribution obtained from solving Laplace's equation with PDE of Matlab at every time step is used to calculate electric field E between every cell of the electrical tree and the surrounding eight cells by the following equation [14, 27]:

$$E \rightarrow g\frac{\Delta V}{\Delta x} \tag{3}$$

Where *g* is the dielectric inhomogeneity factor (D.I.F) of a cell is generated randomly, $\Delta V = 0$ is the potential distance between centres of cells.

The algorithm checks in every step cells that can belong to an electrical tree by applying cellular automata rule illustrated in the Table 2. If the tr ee progresses, then its structure will modification, which means new boundary conditions are applied in the next step, and Laplace's equation is solved again to gain the new potential distribution.

The tree stops growing if:

- Electric stress is less than dielectric strength $E/E_c<1$.
- Branches reach the plane electrode.

Details of three simulations are included in the Table 2:

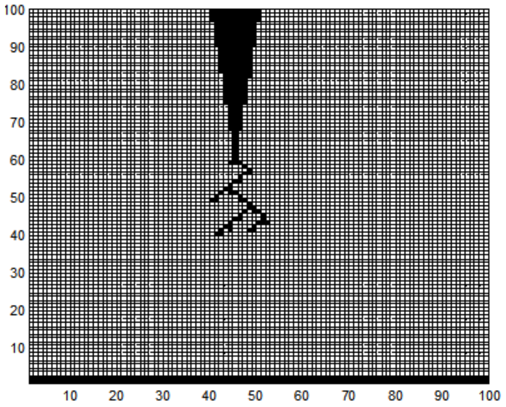
Table 2. Parameters of three simulations for tree growth

	Simul. 1	Simul.2	Simul. 3
Matrix dimensions	100×100	100×100	100×100
Site dimensions (mm)	0.1×0.1	0.1×0.1	0.1×0.1
XLPE permittivity ε	2.3	2.3	2.3
Dielectric strength (kV/mm)	40	40	40
g	0.95-1.04	0.95-1.04	0.95-1.04
Applied voltage (kV)	50	80	110

Results and discussion

The influence of the applied voltage level, i.e. electric stress Emax on the behaviour of the electrical tree inside XLPE dielectric is simulated in three different cases as shown in Figure 3, Figure 4 and Figure 5. Distance between electrodes was taken to be equal to 6 mm and the dielectric inhomogeneity factor is fluctuating between 0.95-1.04.

a)



b)

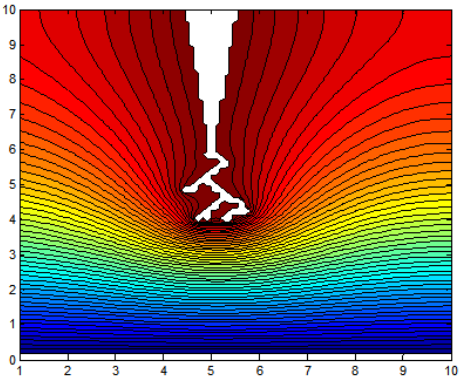
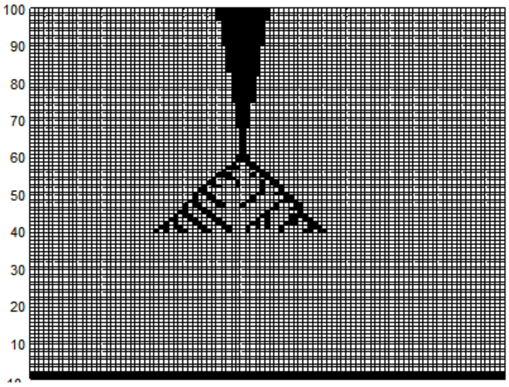


Fig.3. Results of simulation: *t= 20* when the V_{ap}= *50 kV* (a) electrical tree shape (b) equipotential distribution

The electrical tree initiates from the end of the electrode tip and spreads toward the plane electrode by activities of discharges within the gas-filled channels following the paths where the homogeneity of XLPE is the weakest. Tree channels consist as conducting material, (i.e. are played the same role of the point electrode), so the potential value at every tree cell is considered to be equal the value of the potential applied at the end of the needle tip. In every time step, Laplace's equation is solved to compute a new distribution of the potential due to the propagation of branches which means a modification of boundary conditions.

The CA model presented in this paper is sensitive to changes in the applied voltage at point electrode. In the case of Figure 3, the voltage applied to be equal to 50 kV. The cases of Figure 4 and Figure 5 are the similar as the case of figure 3 concerning to the geometry, the electrode arrangement, same time step and range of g but in these study the applied voltage is taken to be equal 80 kV case of Figure 4 and 110 kV case of Figure 5.

a)



b)

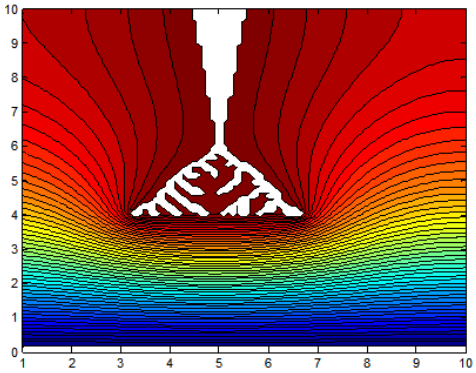
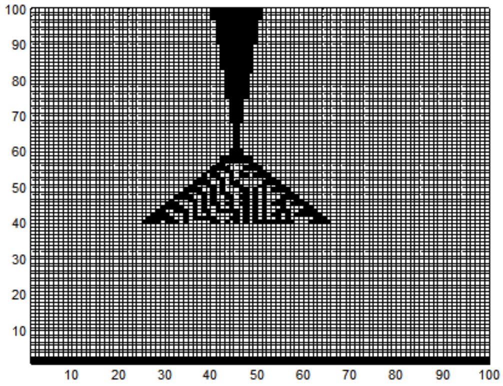


Fig.4. Results of simulation: *t= 20* when the V_{ap}= *80 kV* (a) electrical tree shape (b) equipotential distribution

a)



b)

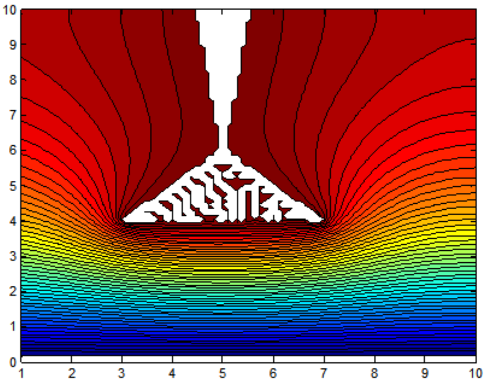


Fig.4. Results of simulation: *t= 20* when the V_{ap}= *110 kV* (a) electrical tree shape (b) equipotential distribution
(b)

Conclusion

Electrical tree propagation in the cross-linked polyethylene (XLPE) dielectric with point/plane electrodes via CA is successfully simulated. The effect of the electric stress (voltage level) on the process and shape of the electrical tree formation is evident.

There are various trees formed under different voltages applied; at higher applied voltage bush-tree is dominated, whereas at lower voltage different types of trees can be formed.

The cellular automata technique is powerful to simulate the inhomogeneity systems.

Finally, a qualitative agreement between simulation results and experimental data is observed.

Acknowledgement

This work was supported by Laboratory Research & Development Materials Semiconductors and Dielectrics, Faculty of Technology, University Amar Telidji, Laghouat – Algeria.

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