FEM Modelling of Electric Field and Potential Distributions of MV XLPE Cables Containing Void Defect

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Abstract: Cross-linked polyethylene (XLPE) medium voltage (MV) underground cables are widely used today. This paper studies the electric field and potential distributions within an XLPE insulted cable containing void-defect. The finite element model of the performance of an armoured XLPE MV underground cable is presented. The variation of the electric field stress within the cable using the finite element method (FEM) is concentrated. The effects of the void-defect within the insulation are given. Outcomes will lead to deeper understanding of the modeling of armoured XLPE insulated cable and electric field response of XLPE insulted cable containing void defect.

Keywords: MV XLPE cables, Finite Element Method /COMSOL Multiphysics, electric field stress.

1. Introduction

XLPE insulation cable was developed in the early 1960s for 3-6 kV [1]. In the 1980s, XLPE insulations were used for 11-33 kV [2] and in the last few years have been applied up to 275-500 kV [3, 4]. Today MV XLPE cables are widely used to replace the MV Paper insulated lead covered (PILC) cable. That is because XLPE insulation has much better electrical, thermal, and mechanical performances than that of oilpaper insulation. Figure 1 shows the common construction of single-phase armoured XLPE cable type 11 kV. The cable dimensions and characteristics are taken from data sheets of a common single-phase 11 kV armoured XLPE cable. The conductor is made of copper and each is 95 mm^2, the overall diameter of the cable is 20.5 mm.

Failure in cable insulation is generally preceded by a degradation phase that may last several years. A significant cause of cable system failures is the breakdown of electrical insulation between the electrodes. The operational stresses that occur in cable insulation which include thermal, mechanical and electrical effects will vary with time and can cause degradation due to the resulting physical and chemical changes in cable properties.

It is widely recognized, irrespective of the causative mechanism, that degradation results in partial discharges (PDs) being generated at the degradation site(s). PDs are small electrical discharges produced by local enhancement of the electrical stress due to conditions around the fault. The internal discharge in insulation material and/or at its interface is caused by the strong and inhomogeneous electrical fields that are usually caused by voids, bubbles, or defects. Treeing discharge is also associated with internal discharge, and it starts from conducting particles or a void in solid insulation.

This paper investigates the electric stress within an armoured XLPE insulated cable containing a void-defect. The finite element model of the performance of an armoured XLPE MV underground cable containing void-defect is developed using the COMSOL multiphysics.

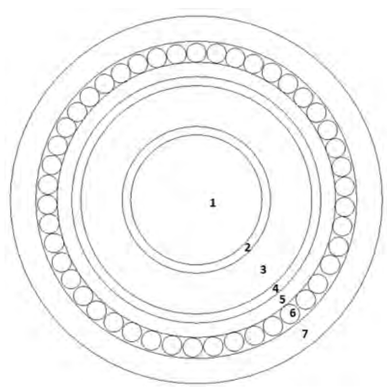

Figure 1. Typical layout of single-core 95 mm^2 XLPE cable, (1) copper conductor, (2) semiconducting material, (3) XLPE insulation, (4) semiconducting insulation, (5) bedding, (6) aluminium wire armour (AWA), and (7) PVC ground sheath.

2. Electrostatic Model

The electrical field distribution in a typical cable construction, is described by two-dimensional field models. The model is solved for a non-degraded system configuration as a base for further analysis. In addition, air-filled void is introduced into the model cable insulation to investigate the effect of void presence on the XLPE electrical field insulation system. The mathematical field model for electrical field distribution in the air-filled voids is created in respect of the single-phase XLPE cable field model. The electric field intensity is obtained from the negative gradient scalar potential. The relationship equation of E and V is as follows:

$$E = -\nabla V \quad (1)$$

The equation of the constitutive relationship between the electric field E and electric displacement D for the insulation material, in terms of the relative permittivity of the insulation and free space, are given in equation 2. The relationship between the electric field E and electric displacement D in the void or free space is given in equation 3.

$$D = \varepsilon E \ \ 3.10 \quad (2)$$

where ε is the relative permittivity, $\varepsilon = \varepsilon_0 \varepsilon_r$

ε_r is the relative permittivity of insulation martial

ε_0 is the permittivity of free space

D is the electric displacement of the conductor which is directly proportional to the applied voltage to the conductor.

$$D = \varepsilon_0 E \quad (3)$$

The forms of Gauss' law which involves the free charge and the equation of electric displacement will be represented as;

$$\nabla . \ D = \rho_f \quad (4)$$

where ρ_f is free charge density

By substituting equations 2 and 4 in 1 and introducing the free charge as charge density Poisson's scalar equation is obtained as:

$$-\nabla \cdot (\varepsilon \nabla V) = -\nabla \cdot \left(\varepsilon_0 \varepsilon_r \nabla V \right) = \rho \quad (5)$$

where ρ is the charge density

Due to the application of cable material which has a constant permittivity, ε applied, equation 5 becomes:

$$\nabla^2 V = - \frac{\rho}{\varepsilon} \quad (6)$$

The charge density in insulation is neglected due to its small amount as well as in the void due to its small size in comparison to size of the cable insulation. Therefore, the electric field is expressed by Laplace's equation as:

$$\nabla^2 V = 0 \quad (7)$$

The problem is solved regarding the solution of two-dimensional Laplace's equation:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 \quad (8)$$

Equation 8 will be used to calculate the electric field in the cable insulation and in the air-filled void-defect by using finite element method in COMSOL software in terms of boundary conditions.

Boundary conditions:

The boundary condition of the relationship of interfaces between two different medium for electrostatic model is mathematically express as [5]:

$$n. \ (D_1 - D_2) = \rho_s \quad (9)$$

ρ_s is the surface charge

n. D_1 and n. D_2 are the normal component of electric displacement of any two different medium in the model.

where the surface charges of the same insulation materials in the model are neglected, the boundary condition is continuity and surface charge is zero as:

$$n. (D_1 - D_2) = 0 \qquad (10)$$

At boundary between two different mediums, the normal component of electric displacement does not equal zero. It is infinite due to change in the permittivity.

$$n. D = \rho_s , \qquad n. (D_1 - D_2) = \rho_s \qquad (11)$$

The conditions of V and E are applied continuously.

The electric-potential boundary condition:

Due to the cable application, the applied voltage is sinusoidal. The single-phase potential of XLPE cable is the following:

$$V_{ph1} = V_0 \sin(\omega \ . t) \qquad (12)$$

The ground boundary condition: The sheath boundary potential is equal to zero.

$$V = 0 \qquad (13)$$

The continuity boundary condition: The normal component of the electric displacement is applied continuously across the sheath boundary.

$$n . (D_1 - D_2) = 0 \qquad (14)$$

3. Electric field response

Figure 2 shows the electric field and equipotential distribution within the cable at the point in the AC cycle where the conductor potential is at its maximum value. The field strength is strong on the conductor's surface and the weakness at the end of the cable insulation. It can be shown that due to the cable concentric construction, the electric field strength is high around the conductor and less at a distance from the conductor. The equipotential lines are close to each other where the electric field intensity is high and vice versa. The equipotential field lines are parallel to the ground sheath. The figure shows the rotational symmetry of electric field around the conductor, which is expected due to the symmetry of the cable.

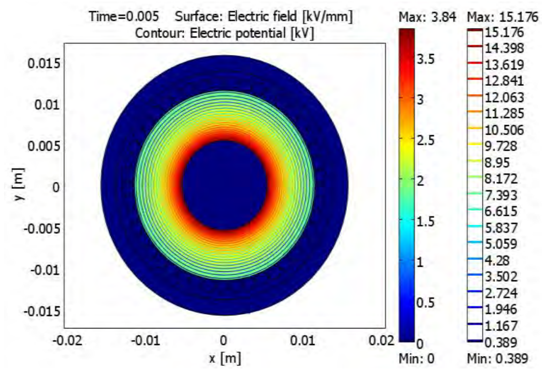

Figure 2. The electric field and equipotential distribution through the XLPE cable cross-section at the time 0.005 second.

Figures 3 and 4 show the results of inserting a void-defect of size 1 mm on the left to the conductor at a particular instant where the conductor is at its maximum value. Figure 3 shows the distortion of the electric field distribution caused by the void-defect. The void electric stress is higher than the electric stress of XLPE insulation material. The radial electric stress of XLPE insulation material around the void is higher than an axial electric stress.

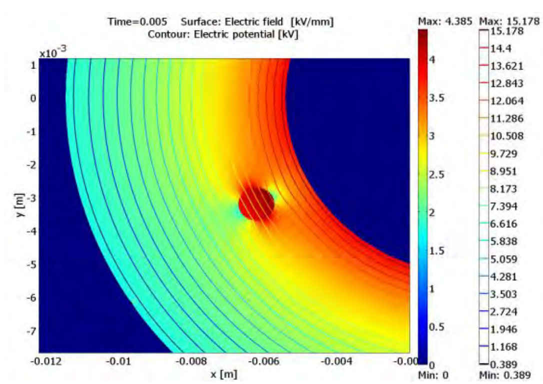

Figure 3. Effect of void-defect on electric field distribution.

Figure 4 shows the electric field distribution over the void-defect due to the conditions around the fault where the cable conductor is at its maximum potential value. The electric field lines are bridging between the surfaces of void that are parallel to the left side of the conductor. The highest amount of electric field intensity is in the void-defect where electric potential in a conductor is at its maximum value ≈15.55 kV peak.

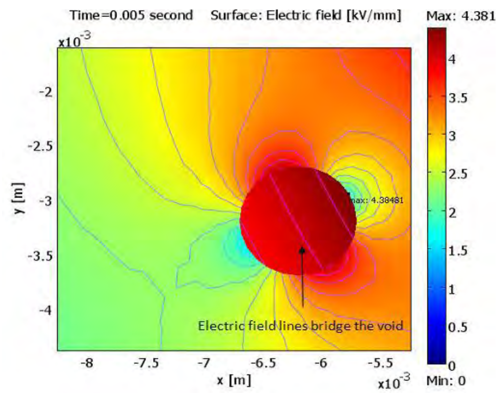

Figure 4. Electric field distributions over the void-defect in XLPE insulation with the highest magnitude of 4.38 kV/mm.

Conclusion

A two-dimensional FE model is developed to study the electric field for 11 kV armoured XLPE cable insulation continuing air-filled void-defect in COMSOL Multiphysics. The electric field modelling of MV armoured XLPE cable containing void-defect under single-phase voltage condition in service is presented. The electrostatic simulation showed a map of the electric field strength within the XLPE cable insulation. The void-defect strongly affect the electrostatic field distribution of 11 kV armoured XLPE cable insulation and will affect the electric field stress over that void-defect.

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