Effects of Ionic solutions in Water Treeing Propagation of XLPE Insulated HV Cable by Using ANSYS MAXWELL 2D

Narupon Promvichai^a, Kelvin Melckzedek Minja^a, Pius Victor Chombo^a, Tassanai Supanarapan^a,
Terapong Boonraksa^b and Boonruang Marungsri^{a,*}

^aSchool of Electrical Engineering, Suranaree University of Technology,
Nakhon Ratchasima 30000, Thailand.

^bSchool of Electrical Engineering, Rajamangala University of Technology Rattanakosin, Salaya Phutthamonthon,
Nakhon Pathom 73170, Thailand.

*Corresponding Author: bmshee@sut.ac.th

Abstract

Most of the distribution systems are nowadays upgraded to underground systems. Cross-linked polyethylene (XLPE) insulation has been employed as an insulator in underground power cables due to its excellence in electrical properties. The environmental issues in service have been the major studied problem that associated with the formation of water treeing and reduction of XLPE insulation performance. In the humid underground environment where XLPE power cables are laid, a number of ionic solutions can be found which in the presence of water treeing can lead the aging process. This paper studies the effects of electric fields in the presence of $\text{Cu}(\text{NO}_3)_2$, CuSO_4 , FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl solutions with water treeing radius of 0.1, 0.5, 1.0 and 1.5 mm in ANSYS MAXWELL 2D. Bush type water treeing resulted into 31 kV/mm in 1.5 mm radius with $\text{Cu}(\text{NO}_3)_2$, FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl solution. In vented type water treeing, 38 kV/mm in 1.5 mm radius with CuSO_4 , was observed. The observed field strengths were above the minimum acceptable breakdown voltage (30kV/mm) of XLPE insulation but CuSO_4 solutions showed great contribution in the intensification of electric fields.

Keywords: Water treeing, Electrical tree, Electric field, XLPE power cable, ANSYS MAXWELL 2D.

1. Introduction

Water treeing in underground power cable is described as an electrochemical treeing process in presence of ionic solutions which cause distortion due to partial discharge

and progressing through layers under electric stress in extremely non-uniform fields⁽¹⁾. It is a major source of causes ageing of polymeric cable insulation apart from thermal degradation, partial discharges, aggression by environment and losses⁽²⁾. Cross-linked polyethylene (XLPE) is widely used as insulation in underground high tension cables but a damaging phenomenon called treeing takes place inside the material with continued exposure to moisture and electrical stress⁽³⁻⁶⁾. The study of inception and extent of the growth of water treeing to electrical treeing have been examined and analyzed in Wang et al.⁽⁷⁾; Boggs et al.⁽⁸⁾; Assay⁽⁹⁾. They aimed to evaluate acceleration ageing and improve the high performance of insulation material by considering the dimensions of water treeing, ageing structural changes, the concentration of the electrolyte, type of applied voltage and temperature on inception voltage of electrical tree.

When XLPE cable is subjected to lightning or switching overvoltage, there is a high possibility for water treeing to become electrical treeing⁽⁷⁻⁸⁾. Ref.⁽¹⁰⁾ defined the applied voltage as a source of external forces (electric fields) that squeezes ionic solutions into small cracks and weak points of the XLPE cable. The presence of ionic solutions in small cracks and/or weak points causes the formation of water treeing. The tips of growing water treeing experience the different strength of electric fields. The theory about the concentration of strong electric field on sharp tips has been described in Wang et al.⁽⁷⁾. In the underground level, different ionic solutions can be occupied in small cracks or weak points of XLPE cable and hence water treeing which can cause different stressing in XLPE insulation. But the study of the electric field distribution

under different ionic solutions in the water treeing is not well known. This does not assure if the XLPE insulations can withstand electric fields under different ionic solutions in water treeing.

This paper has studied the effect of electric field distribution in water treed XLPE insulation under different ionic solutions. The proposed ionic solutions to be used in the study were $\text{Cu}(\text{NO}_3)_2$, CuSO_4 , FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl . Due to the complexity of the effect, the study was done on bases on simulation. ANSYS MAXWELL 2D has been widely used to analyze electric fields by employing numerical techniques for finding approximate electric fields. ANSYS MAXWELL 2D is a high-performance interactive software package that applies finite element analysis (FEA) to solve electric field and magnetic field problems. Also, it uses meshing process as discretization to transfer continuous functions, models, and equations into discrete counterparts. The first part of the report shows materials and mathematical modeling of electric fields. The second part shows the study of electric fields in XLPE insulation under proposed ionic solutions.

2. Materials

2.1 Power Cable

A commercial HV power Cable 12/20(24) kV 1 core (XLPE) power cable was used in this study with a cross-section as shown in Fig. 1. Ref. ⁽¹¹⁾ showed more information about this XLPE power cable. This power cable is mostly used in distribution systems in Thailand.

In Fig. 2, circular compact stranded annealed copper conductors have 8.33 mm diameter, the inner semi-conductive layer has 0.785 mm thick, cross-linked polyethylene (XLPE) layer has 5.5 mm thick and outer semi-conductive layer has 0.8 mm thick. These were the most useful layers in this study.

Fig. 1. 22 kV XLPE HV power Cable

Fig. 2. 22 kV XLPE power Cable with XLPE, inner and outer semiconducting layers

2.2 Ionic Solutions

Six ionic solutions were used for the study of electric field i.e. $\text{Cu}(\text{NO}_3)_2$, CuSO_4 , FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl . The relative permittivity and bulk conductivity of the cross-linked polyethylene (XLPE), semiconductors, copper, and ionic solutions ($\text{Cu}(\text{NO}_3)_2$, CuSO_4 , FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl) are shown in Table 1.

Table 1. The relative permittivity and bulk conductivity of the materials.

Solution	Relative Permittivity	Bulk Conductivity (S/m)
$\text{Cu}(\text{NO}_3)_2$	77.66	1.391
CuSO_4	24.5	0.535
FeSO_4	46.19	1.036
K_2SO_4	80.97	1.609
Na_2SO_4	56.96	1.405
NaCl	30.23	1.049
Semiconductor	100.00	2×10^{-3}
XLPE	2.30	1×10^{-17}
Copper	1.00	5.8×10^7

2.3 Electric Field in an XLPE Power Cable

A mathematical model of electric fields (E) spreading around an XLPE power cable is presented by the wave equation (Helmholtz's equation) derived from a differential form of Maxwell equations which are Faraday's law and Ampere's law as defined in equations (1) to (9) as given in Chari and Salon⁽¹²⁾.

Faraday's law;

$$\nabla \times \vec{E} = -(\partial \vec{B} / \partial t) \quad (1)$$

Take the curl (∇) of both side, equation (1) become

$$\nabla \times (\nabla \times \vec{E}) = -\partial / \partial t (\nabla \times \vec{B}) \quad (2)$$

Since B and H are related by the constitutive equation

$$\vec{B} = \mu \vec{H} \quad (3)$$

Then

$$\nabla \times (\nabla \times \vec{E}) = -\mu \partial / \partial t (\nabla \times \vec{H}) \quad (4)$$

Use Ampere's law to replace $(\nabla \times \vec{H})$ since

$$\nabla \times \vec{H} = (\vec{J}) + (\partial \vec{D} / \partial t) \quad (5)$$

Then

$$\nabla \times (\nabla \times \vec{E}) = -\mu \partial / \partial t (\vec{J}) - \mu (\partial^2 \vec{D} / \partial t^2) \quad (6)$$

For isotropic materials, we can use the constitutive equation

Since

$$(\vec{J}) = \sigma \vec{E} \text{ and } \vec{D} = \epsilon \vec{E} \quad (7)$$

Then Equation (6) become

$$\nabla \times (\nabla \times \vec{E}) = -\mu \sigma \partial / \partial t \vec{E} - \mu \epsilon (\partial^2 \vec{E} / \partial t^2) \quad (8)$$

Using a vector identity for the curl-curl operator, equation (9) become

$$\nabla \times (\nabla \times \vec{E}) = \nabla (\nabla \cdot \vec{E}) - \nabla^2 \vec{E} \quad (9)$$

Because the divergence of the electric field is zero in homogeneous material then equation (9) become

$$\nabla^2 \vec{E} = -\mu \sigma \partial / \partial t \vec{E} - \mu \epsilon (\partial^2 \vec{E} / \partial t^2) = 0 \quad (10)$$

Where ϵ is the dielectric permittivity of media, μ and σ are the magnetic permeability and the conductivity of conductors, respectively.

The electric field in complex form, as in⁽¹³⁾ were considered in this paper as time harmonic system, and then,

$$\partial \vec{E} / \partial t = j\omega \vec{E} \text{ and } (\partial^2 \vec{E} / \partial t^2) = -\omega^2 \vec{E} \quad (11)$$

Where ω is the angular frequency then equation (10) becomes,

$$\nabla^2 \vec{E} - j\omega \sigma \mu \vec{E} + \omega^2 \epsilon \mu \vec{E} = 0 \quad (12)$$

Equation (12) in Cartesian coordinates (x, y) with the problem in two dimensions, it becomes

$$\partial / \partial x (1/\mu \partial \vec{E} / \partial x) + \partial / \partial y (1/\mu \partial \vec{E} / \partial y) - (j\omega \sigma - \omega^2 \epsilon) \vec{E} = 0 \quad (13)$$

It is not easy to analyze electric field by using equation (13) in analytical techniques. Equation (13) was used in ANSYS MAXWELL 2D to analyze electric fields.

2.4 Designing of water treed model in ANSYS Maxwell 2D.

The geometry of water treeing in XLPE cable was discretized automatically in ANSYS Maxwell 2D as indicated in Fig. 3. The desired field is approximated with a second order quadratic polynomial expressed as in equation (14).

$$A_z(x, y) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 \quad (14)$$

Field quantities inside the triangles were calculated by using second order quadratic interpolation scheme. The Poisson's equation as equation (15) is replaced with energy functional in equation (16). This function is minimized with respect to each node in every triangle.

$$\nabla^2 A = -\mu J \quad (15)$$

$$F(A) = 1/2 \int ((\nabla A \cdot \nabla A) / \mu + AJ) dV \quad (16)$$

Fig. 3. Discretized water treed XLPE Cable

3. Simulation Results

The results of electric fields distributions with Bush and Vented type water treeing of radius r_0 0.1 mm, 0.5 mm, 1.0 mm and 1.5 mm with $\text{Cu}(\text{NO}_3)_2$, CuSO_4 , FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl ionic solutions are shown in Fig. 4 and Fig. 5 respectively. In Fig 4 and 5, the thickness of layers from inner to outer semiconductor is represented in x-axes.

(a) bush water treeing 0.1 mm

(b) bush water treeing 0.5 mm

(c) bush water treeing 1.0 mm

(d) bush water treeing 1.5 mm

Fig. 4. Electric field distribution in bush type water treeing

(a) vented water treeing 0.1 mm

(b) vented water treeing 0.5 mm

(c) vented water treeing 1.0 mm

(d) vented water treeing 1.5 mm

Fig. 5. Electric field distribution in vented type water treeing

4. Discussion of Results

From Fig. 4, the maximum field strength of approximately 31 kV/mm was observed in a treeing radius of 1.5 mm with $\text{Cu}(\text{NO}_3)_2$, FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl . In Fig. 5, the maximum field strength of approximately 38 kV/mm was observed in a treeing radius of 1.5 mm with CuSO_4 . The maximum value of field strength in Fig 4 and 5 was seemed to exceed minimum field strength of XLPE insulation (30 kV/mm)⁽¹⁴⁾.

From the observation, vented water treeing was seen to exceed minimum field strength of XLPE insulation earlier than bush type water treeing. El-Zein et al⁽¹⁵⁾ presented the study of electrical trees in solid insulation and showed that vented water treeing may occur sooner compared to bush water treeing. Furthermore, the presence of CuSO_4 ionic solution showed the greatest influence in vented type water treeing. The disposition of CuSO_4 ionic solution in vented treeing and hence exalt considerably was also presented in Boonraksa⁽¹⁶⁾. Therefore, an environment with CuSO_4 ionic solutions may result in high service cost due to the performance of vented water treeing.

5. Conclusions

Effects of ionic solutions in the propagation of water treeing in HV XLPE cable have been presented. Bush and vented water treeing with treeing of radius r_0 of 0.1 mm, 0.5 mm, 1.0 mm and 1.5 mm under the effects of $\text{Cu}(\text{NO}_3)_2$, CuSO_4 , FeSO_4 , K_2SO_4 , Na_2SO_4 , and NaCl ionic solutions were clearly designed in ANSYS MAXWELL 2D software. Electric field strength of 38 kV/mm and 31 kV/mm in treeing radius of 1.5 mm were observed in vented and bush water treeing respectively. Observed maximum field strength was seen to exceed minimum field strength of XLPE insulation (30 kV/mm). Moreover, vented was investigated to occur in lower electric fields compared to bush water treeing. Therefore, CuSO_4 ionic solution revealed to exhibit much contribution in the advancement of water treeing.

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