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Space charges analysis on insulator with uniform layer contamination effect

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Abstract

High voltage direct current (HVDC) transmission provides an attractive alternative for bulk power transfer. However, HVDC transmission may have loss about half per unit length of high voltage alternating current (HVAC) at the same amount of power carried. This is due to the space charge formation around the conductor in HVDC cables. It is known that the presence of space charge inside an insulator may distort the local electric field and surface energy. This paper investigates the effect of electrostatics for space charge, electric field and surface energy in the HVDC cable in clean and contaminated conditions. The effect of uniform layer contamination from oil, sandstone and fresh water was conducted on 11 kV XLPE cable using finite element software under electrostatics study. The contamination layer was created around the XLPE cable by multifarious the radius of layer contamination from the conductor. The simulation results show that enlargement of contamination layer radius by 1.0 mm (light), 1.5 mm (medium) and 2.0 mm (heavy) resulted in the reduction of surface energy by 20% and electric field by 22% but increase the space charge amplitude by 76%. The study also found that fresh water can be considered as the worst contamination compared to oil and sandstone.

Keywords: *contamination, electric field, space charge, surface energy, XLPE*

1. Introduction

Technology in HVDC transmission has managed many industrialists in the world to invest polymer in direct current (DC) on power cables. Polymeric insulation such XLPE is the most commonly used and best insulator in features [1-8], when used with DC operation may inconsistently lead to a problem. Space charge inside the insulated material increased due to the lowest carrier mobility and high trapped rate in certain states, increased the space charge through the body of the insulated material.

Understanding the concept of space charge is the most importance because the space charge accumulates on interfaces. Permittivity and conductivity also not same on the different layers [9] and an electric charge is treated over a region of space [10]. Through this concept, space charge can be determined by the thickness of insulator and various types of uniform layer contamination. While the voltage and electric field distribution can be calculated by finite element software.

Researcher [11] had explained molecular structure and chemically bonded of cross-linked polyethylene where it easy deform at extraordinary temperature. While linear molecular structure and chemical bonded strongly resist to deform even at extraordinary temperature.According to the parameter of HVDC cable, every model of HVDC can be designed by using Quickfield software and simulation have been shown the results of space charge, electric field and surface energy for various types of uniform later contamination. Various types of uniform layer contamination have been displayed different effect on space charge.

Cross-Linked Polyethylene (XLPE)

XLPE materials are derived through processes which cause a cross-bonding [12]. Polyethylene has a linear molecular structure as shown in Figure 1 (a) molecules of polyethylene not chemically bonded as shown in Figure 1 (b) are easily deformed at high

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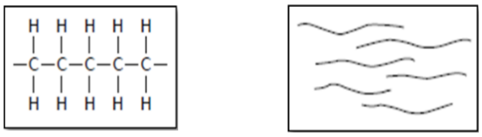
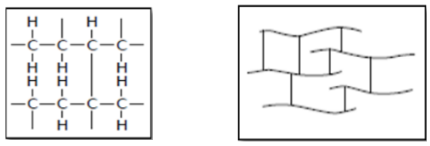
temperature, while XLPE molecules bonded in a three dimensional network as shown in Figures 2 (a) and 2 (b) have strong resistance to deformation even at high temperature [11, 13].



(a) (b)

Figure 1. Molecular structure and chemically bonded of polyethylene (a) molecular structure of polyethylene (molecular structure) (b) chemically bonded of polyethylene molecules (chemically bonded) [11, 13]



(a) (b)

Figure 2. Linear molecular structure and chemically bonded of polyethylene (a) structure of polyethylene (linear molecular structure) (b) polyethylene molecules (chemically bonded) [11, 13]

Cross-linked polyethylene is produced from polyethylene under high pressure with organic peroxides as additives. The application of heat and pressure is used to effect the cross linking. This causes the individual molecular chains to link with one another which in turn causes the material to change from a thermoplastic to an elastic material [11].

An important advantage of XLPE as insulation for medium and high voltage cables is their low dielectric loss. The dielectric loss factor is about one decimal power lower than that of paper insulated cables and about two decimal powers lower than that of Polyvinyl Chloride (PVC) insulated cables. Since the dielectric constant is also more favorable, the mutual capacitance of XLPE cables is also lower, thus reduced the charged currents and earth-leakage currents in networks without the rigid star point earthed [11].

2. Research Method

This part explained about research method to gain simulation results of space charge, surface energy and electric field of XLPE insulator by using Quickfield Software.

2.1. Space Charge Measurement Setting

Gauss's law states that the net electric flux through any closed surface is equal to the total charge enclosed by that surface. In a like manner, total electric charge, Q in particular volume can be calculated as a flux of electric displacement, D over its closed boundary and written as [14]:

$$Q = \int_{s} (D.n)dS \tag{1}$$

2.2. Electric Field Measurement Setting

High voltage cable almost always have a coaxial configuration with conductor of inner and outer radius of a and b, respectively. When a test voltage, V_T is applied across the cable, a charge q = CV_T is produced on the cable's conductor where ε_r, ε_0 and C are relative permitivitty, space permitivitty and capacitance value of the insulation. By application Gauss's Law, the electric stress, E in the coaxial cable insulation at a distance r from the cable center is given as [15]:

$$E_r = \frac{CV_T}{2\pi\varepsilon_r\varepsilon_0 r} = \frac{V_T}{r\, In\left(\frac{b}{a}\right)} \tag{2}$$

2.3. Surface Energy Measurement Setting

Electrostatic potential energy is a measure of the energy stored in the electric field where W_s, E and D are surface energy, electric field strength and electric displacement and is given by [14]:

$$W_s = ½\int_s (E.D)dS \quad (3)$$

2.4. Material Properties
The material properties and contamination layer thickness used in this simulation study is shown in Table 1 and Table 2, respectively.

Table 1. Materials Properties Used for Simulation Purpose [13, 16-23]

Material	Relative Permittivity, ε_r
XLPE	2.30
Oil	2.00 - 2.40
Sandstone	4.65
Fresh water at 75 ^oF	78.30

Table 2. Contamination Layers Thickness [24]

Contamination Level	Thickness
Light	1.0mm
Medium	1.5mm
Heavy	2.0mm
Clean	None

2.5. Design Model and Simulation Parameter
The insulator of XLPE cable was modelled and designed by using QuickField software. Cable model and parameter are shown in Figure 3. Figures 4 and 5 illustrate cable model after mesh setting for with and without contamination in 2D and 3D views. In this paper, the problem type of electrostatics has been chosen to analyse the space charge, electric fields and surface energy of the XLPE insulation. For parameter setting, the coordinate system is in Cartesian, the length of cable is 1000mm and the length units are in millimetre (mm). Plane parallel (model class) was chosen because length is on the z-axis.

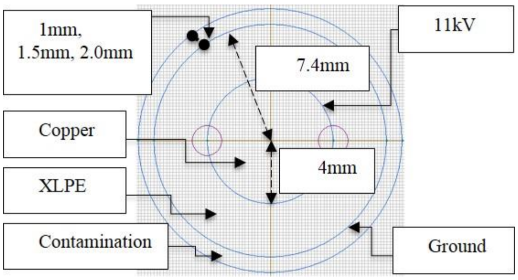
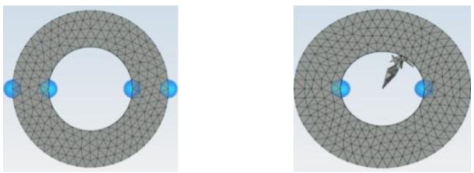
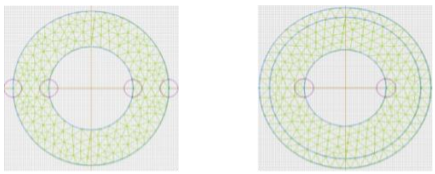


Figure 3. HVDC cable profile and dimensions



(a) (b)

Figure 4. 3D views (a) Normal HVDC cable without contamination (b) HVDC cable with contamination



(a) (b)

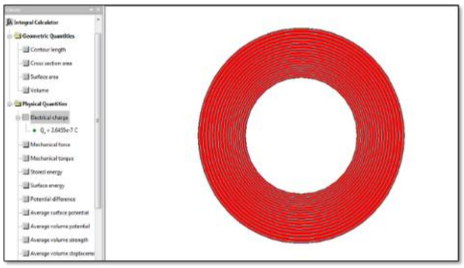
Figure 5. 2D views (a) Normal HVDC cable without contamination (b) HVDC cable with contamination

3. Results and Analysis
In this section, it is explained the simulation results of space charge, electric field and surface energy of XLPE insulator by using Quickfield Software.

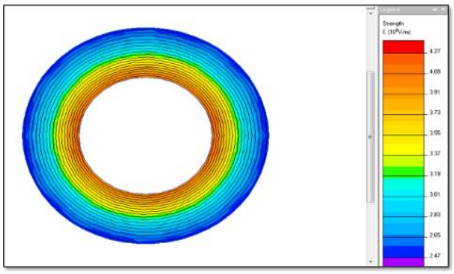
3.1. Simulation Results for Space Charge, Surface Energy and Electric Field on XLPE Insulation
The simulation and analysis results for the XLPE insulation is to find the space charge, surface energy and electric field strength in XLPE insulation without oil, sandstone and fresh water contamination. The space charge and the electric field result can be viewed from

the colour map shown in Figure 6 (a) and Figure 6 (b). It is apparent that red colour map because the highest and lowest value of space charge depends on cross sectional area. The value for space charge is 264.55nC. Nevertheless, electric field can be viewed from the colour map and the value referred to the legend. The diagram shows the value of the electric field fall off from the conductor to ground. For electric field, legend shown that red colour indicates as greater voltage while blue colour indicates as ground. The value for surface energy is 14.61J/m as shown in Figure 6(c) and cross sectional area influence highest and lowest value.

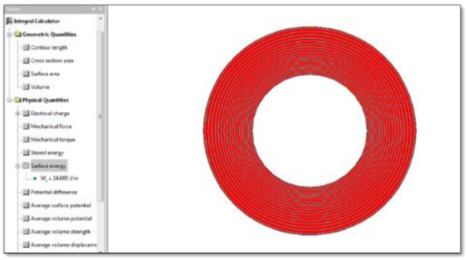
However, the contamination layer for space charge is bigger than without contamination layers which is 2362.00 nC compared to 2098.30 nC shown in Figure 7 (a). Prior to this, contamination layers contain more cross sectional area compared to the area without contamination layers. While the value for the electric field on contamination layer is zero based on the colour map in Figure 7 (b) because in ground mode.This factor contribute to surface energy where it is lower than without contamination layers which is 5.91J/m compared to 8.67 J/m in Figure 7 (c). Similarly, same concept for space charge was applied to surface energy.



(a)

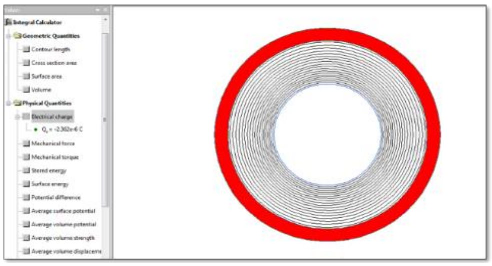


(b)

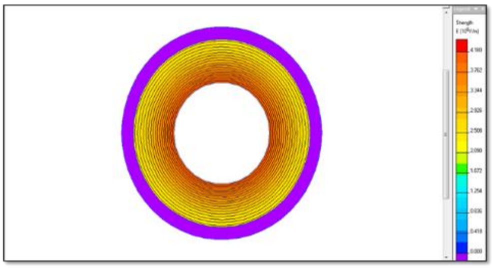


(c)

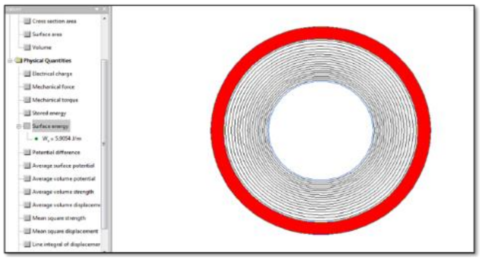
Figure 6. Colour map and integral calculator for HVDC cable without contamination (a) space charge (b) electric field (c) surface energy



(a)



(b)

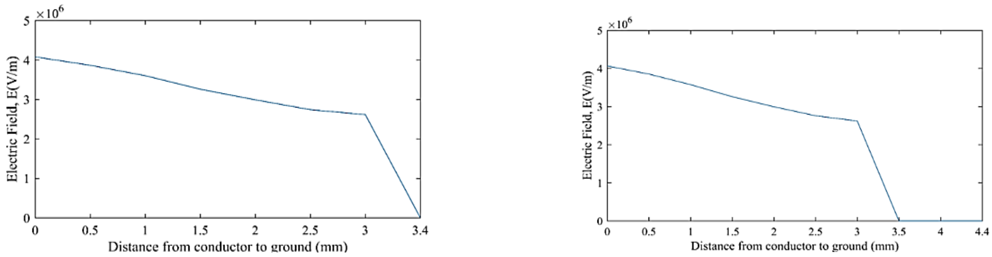


(c)

Figure 7. Colour map and integral calculator for HVDC cable with contamination (a) space charge (b) electric field (c) surface energy

Another essential point, the electric field strength for HVDC insulation cable without oil, sandstone and fresh water contamination are shown in Figure 8 (a). Based on the graph, the electric field declined from 0.0mm to 3.4 mm which start around the conductor until the ground. The electric field strength is enhancing at 4078220 V/m when close around the conductor and become weaker at 0V/m when near to ground. In comparison, Figure 8 (b) shows HVDC cable with oil contamination for electric field strength. The electric field also decayed from 0.0mm to

3.4 mm which is started from the conductor to the ground of the cable. Electric field strength is mark up at 4064460V/m around the conductor and become lessen at 0 V/m when near to ground. It has been shown that the electric field at the contamination layer is 0 V/m that starts from 3.4 mm to 4.4 mm.



(a) (b)

Figure 8. Electric field strength (a) without contamination (b) with contamination

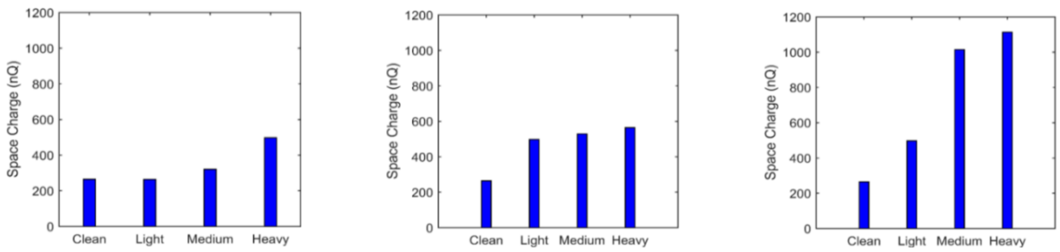
3.2. Simulation Results for Space Charge, Surface Energy and Electric Field on XLPE Insulation with Different Contamination Level and Source

Table 3 compares the simulation results of space charge in clean and contaminated conditions. The result shows that fresh water contamination has higher space charge compared to oil and sandstone in all conditions. As might be expected that high permittivity of fresh water produce much more space charge in the insulator [25].

Figure 9 shows the distribution of space charge in clean conditions is quite similar for all contamination sources; where the huge difference at heavy between fresh water and sandstone which approximately 49 percent. For contaminated conditions, there is a clear trend of the space charge distribution increases as the contamination levels is increase. J.W. (1998) disputed [25] that the presences of contamination can effect an uncontrolled increase in the generation rates of free charge.

Table 3. Space Charge and Surface Energy in Clean and Contaminated Conditions

Condition of HVDC cable		Space Charge, Q_s (nC)	Surface Energy, W_s (J/m)	Electric Field, E (10^6V/m) Simulation	
Contamination Level	Contamination Source	Simulation		Minimum (E_{min})	Maximum (E_{max})
Clean	Normal (Without Contamination)	264.55	14.61		4.27
Light	Oil	263.70	14.58		4.18
	Sandstone	497.40	13.75		4.00
	Fresh Water	497.40	13.75		4.00
Medium	Oil	320.40	14.43	0	4.14
	Sandstone	529.10	13.64		3.88
	Fresh Water	1015.00	12.43		3.64
Heavy	Oil	497.40	13.76		4.00
	Sandstone	564.20	13.00		3.76
	Fresh Water	1113.70	11.75		3.35

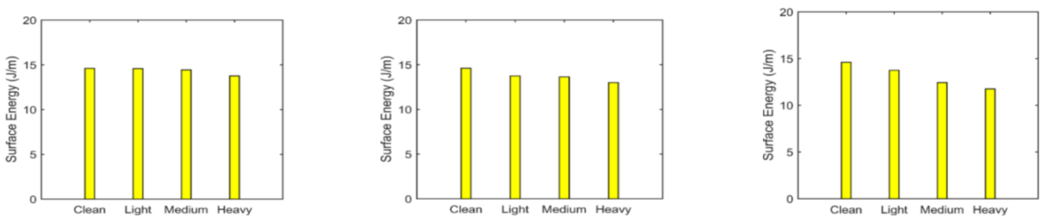


(a) (b) (c)

Figure 9. Space charge distribution for (a) oil contamination, (b) sandstone contamination, and (c) fresh water contamination

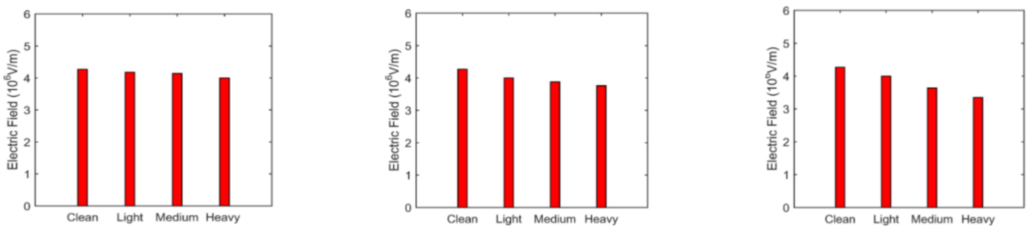
Table 3 and Figure 10 demonstrate the simulation of surface energy in clean and contaminated conditions for all contamination sources. Complementary to this it is analyzed from the tabulated results that the surface energy for fresh water at the heavy condition of HVDC cable insulation for simulation result is wither than the surface energy at normal HVDC cable insulation which is 11.75 J/m compared to 14.61 J/m. The surface energy at fresh water contamination is lower than the surface energy at the oil and sandstone contamination due to high permittivity of contaminant. Due to contaminant molecules change the balance of forces and reduce the net inward force. Since the net inward force is related to the surface energy, the surface energy is reduced by contaminant and was investigated in [26]. Thus, it can cause damage and poor performance of the cable.

When Gauss's law is applied, minimum electric field is zero as shown in Table 3 and Figure 11. Equally important, apply the Gauss's law and there is no charge inside that insulator that the electric field will be zero, so outside zero and here in the core also zero. Maximum electric field for normal at clean HVDC cable insulation for simulation result is 4.27x10 V/m strengthens than the electric field for fresh water at the heavy condition of HVDC cable insulation which is 3.35x10 V/m. In short, high permittivity of fresh water also shows the weaken electric field at contamination compared to the electric field at oil and sandstone contamination. Similarly, Malik et al. [15] stated that electric field is inversely proportional to the permittivity.



(a) (b) (c)

Figure 10. Surface energy for (a) oil contamination, (b) sandstone contamination, and (c) fresh water contamination



(a) (b) (c)

Figure 11. Electric field for (a) oil contamination, (b) sandstone contamination, and (c) fresh water contamination

4. Conclusion

In a nutshell, by using this software, XLPE cable with the effect of uniform layer contamination of oil, sandstone and fresh water have been analysed by multifarious the condition level and source of contamination. It was shown that the space charge became higher when the radius of contamination is greater while electric field and surface energy are depressed. In brief, fresh water can be justified as the worst among oil and sandstone due to high permittivity. To sum up, normal HVDC insulation cable without contamination can be highlighted as superior through performances and capabilities where it produce inferior space charge.

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