DETERMINATION OF SPACE CHARGE CHARACTERISTICS ON CONTAMINATED XLPE INSULATOR

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A special thankfully dedicated for,

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ABSTRACT

XLPE insulator cable has been widely used underground due to urbanization and this has exposed cable to many pollutants. Existence of pollutant on cable layer may mitigate performance of cable especially on XLPE insulator. Many studies had been done to identify effects of pollutant towards XLPE insulator performance and has showed various results on it. However, effect of mineral layer on space charge on underground XLPE insulator remain unanswered. These minerals Silicone Dioxide, Titanium Dioxide and Aluminium Oxide exist due to its content in underground soil. The purpose of this study is to determine space charge effects towards contaminated XLPE insulator with these contaminants forming a uniform layer on cable. Space charge density gives a view on performance of XLPE as insulator as its existence may shorten life span of cable. Result has shown that these uniform mineral layer reduce space charge density effects in XLPE insulator and this has improved its performance. Besides than taking study for different contaminant, each contaminant is being tested on its different thickness on cable at 1mm, 2mm and 3mm. Consequently, relationship of thickness contamination layer with space charge density is established such that it is random. Al_2O_3 has shown the least space charge density presence when it contaminates the cable. Decrement of space charge gives a view that these minerals can be used as nanofillers at optimum sizes.

ABSTRAK

Kabel penebat XLPE telah digunakan secara meluas di bawah tanah disebabkan oleh pembandaran dan ini telah mendedahkan kabel kepada banyak bahan pencemar. Kewujudan pencemar pada lapisan kabel boleh mengurangkan prestasi kabel terutama pada penebat XLPE. Banyak kajian telah dilakukan untuk mengenal pasti kesan pencemaran terhadap prestasi penebat XLPE dan telah menunjukkan pelbagai hasil mengenainya. Walau bagaimanapun, kesan lapisan mineral pada cas ruang pada penebat XLPE bawah tanah kekal tidak dijawab. Mineral ini termasuk Silikon Dioksida, Titanium Dioksida dan Aluminum Oksida wujud kerana kandungannya di dalam bawah tanah. Tujuan kajian ini adalah untuk menentukan kesan cas ruang kepada penebat XLPE yang tercemar dengan bahan pencemar ini membentuk lapisan seragam pada kabel. Ketumpatan cas ruang memberikan pandangan mengenai prestasi XLPE sebagai penebat kerana kewujudannya dapat memendekkan jangka hayat kabel. Keputusan telah menunjukkan bahawa lapisan mineral seragam ini mengurangkan kesan ketumpatan cas ruang dalam penebat XLPE dan ini telah meningkatkan prestasinya. Selain daripada mengambil kajian untuk bahan pencemar yang berbeza, setiap bahan pencemar sudah diuji pada ketebalannya yang berlainan pada kabel iaitu 1mm, 2mm dan 3mm. Akibatnya, hubungan lapisan pencemaran ketebalan dengan ketumpatan cas ruang ditentukan sedemikian rupa seperti rawak. Al_2O_3 telah menunjukkan kehadiran ketumpatan pengecasan ruang paling sedikit berbanding minerals yang lain apabila ia mencemarkan kabel. Pengurangan caj ruang memberi pandangan bahawa mineral ini boleh digunakan sebagai nanofiller pada saiz yang optimum.

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ε_r	-	Permittivity value
σ	-	Conductivity in Sm^{-1}
SiO_2	-	Silicone Dioxide
TiO_2	-	Titanium Dioxide
Al_2O_3	-	Aluminum Oxide
TNB	-	Tenaga Nasional Berhad

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CHAPTER 1

INTRODUCTION

1.1 Project Overview

High voltage transmission and distribution has been growing in technology to ensure its efficiency and benefits both producers and consumers. Due to its low in losses for high voltage transmission, high voltage direct current (HVDC) is preferably being used in long distance for underground transmission. There are few factors affecting the performance of transmission including high voltage cable performance. High voltage cable performances are affected by varieties of internal and external factors which includes the performance of insulators. Insulators are used in cable to avoid the flowing current through it by separating the electrical conductors in order to support it. XLPE insulators has been widely used due to its advantages in cost efficiency, environment and maintenance [1].

However, underground cables are exposed to various pollutants including minerals and this will mitigate the behavior of cable as these contaminants will form layers on XLPE insulators. Therefore, performance of cable has to be investigated due to contaminants layer using COMSOL to model and simulate the problem. COMSOL has the ability to be used in modelling the standard cable with layers consists of conducting and insulating components. Besides, conducting components used is copper with insulation materials as XLPE and mineral contaminants of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and titanium oxide (TiO_2). The cable performance will be simulated using COMSOL in standard operated temperature and due to reliability of simulation result, space charge performance on cable will be observed.

Therefore, it is vital to study the effect of minerals contaminants towards XLPE by observing space charge. Accumulation of charges at a particular region and the

charges are being counted as continuum in a region rather than as one distinct point charge is called space charge. Space charge are affected by conductivity and permittivity of different layers as accumulation of it occurs at interfaces [2]. Due to permittivity value of each contaminants and XLPE insulator is different, contaminants will be layered on XLPE insulators at different thickness and space charge is being observed through it. Contaminants layer will be uniformed throughout XLPE insulator. Thus, thickness and permittivity value of layers will be used to determine space charge value.

Essentially, this study consists of modelling HVDC cable in COMSOL and simulation of space charge is being applied. In order to distinguish on the performance, non-contaminated XLPE insulator is first being observed and next, it will be layered with different contaminants. Each contaminant will be layered at different thickness in noticing the amount that will give significant impact on space charge. Simulated space charge result will then be obtained and compared.

1.2 Problem Statement

HVDC cable has been widely used for renewable energy transmission line and due to urbanization scape factors, these transmission line cable is being built underground. As known, underground consist compositions such that it is composed of 45% minerals, 25% water, 25% air and 5% organic matters [3] and these may contribute to contamination of XLPE insulator. Contamination is naturally occur underground on XLPE insulator which causes electrical stresses [4]. Contamination of water have causes water treeing and chemically contaminated water has cause insulator to degrade physically such as cracking [5, 6].

Underground also contained minerals and organic matters in the form of oxide that will also contribute to the performance of XLPE insulator. Silicon dioxide which abundantly found in sand and silt, titanium oxide which also can be found underground and aluminum oxide that can be found in clay may contaminate XLPE insulator. Due to this contamination, XLPE performance may degrade or otherwise. Space charge has been focused in analyzing insulator performance, thus, space charge effect on contaminated is being studied here. Due to uncertain effect of contaminated XLPE insulator, design of insulator cable and analysis of the

contaminated insulator will be done to investigate its performance on space charge effect.

1.3 Objectives of the Study

The main purpose of this project is to simulate HVDC XLPE insulator cable with contaminants of natural minerals and its effect on space charge. The simulation is being done in COMSOL Multiphysics software from modelling to simulating. Therefore, quantified objectives for this project are:

(i) To determine and analyse space charge density value at clean and contaminated XLPE insulator cable.

(ii) To determine and analyse current density value at clean and contaminated XLPE insulator cable.

(iii) To determine the relationship of space charge and current density towards HVDC XLPE insulator cable.

1.4 Project Scopes

The focus of this project primarily to investigate and analyse space charge effect towards contaminated HVDC XLPE insulator. Thereby, to achieve project objectives, several limitations in certain aspects knows as scopes for this project is being pointed out. The focused research scopes are as follows:

(i) Cable

The conducting material is Copper, Cu while the insulator used is cross-linked polyethylene, XLPE and outer sheath is PVC.

(ii) Contaminants

The natural minerals selected in underground to be layered on XLPE insulator are silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and titanium oxide (TiO_2).

(iii) Simulation software

COMSOL had been used to design and simulate space charge on XLPE cable insulator with several allocated parameters value.

(iv) Variable analysis

Space charge characteristics are being determined through different types and thickness of contaminants.

1.5 Thesis Organisation

Thesis being composed with five chapters. First chapter brief through the introduction to cover project background that leads to problem statements and provide objectives and scopes of this project and the significances of this project. Next, it is highlighted in chapter two on literature review encompasses on cross-linked polyethylene (XLPE), the contaminants presence underground chosen which are silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and titanium oxide (TiO_2). Besides that, space charge and its relation towards cable performance on electric field with COMSOL Multiphysics software is being described in this chapter.

Chapter three define the methodology of this project in describing the simulation software used to investigate space charge effect towards contaminated XLPE cable with different selected contaminants. The outline is to describe the method from the beginning of modelling until the obtained and analysed result is being produced.

Chapter four focus on result and discussion is being made in this chapter to obtain objectives and scopes of project. This chapter will highlight on results for each contamination along with its effect on different thickness level of contamination. A complete model and study of space charge density, current density is being presented in this chapter.

Last but not least, Chapter five highlights on summary of the project and recommendations on future study.

CHAPTER 2

LITERATURE REVIEW

High voltage transmission has developed through various aspects to increase its efficiency and that includes increased in sustainable energy and its transmission mostly are in direct current or known as HVDC due to its transmission in high voltage. Since urbanization scape has been a factor, most transmission line is builds underground. Other than that, cross-linked polyethylene (XLPE) is used as insulator rather than using polyethylene insulator. This is due to its benefits from mechanical to electrical advantages.

Underground HVDC cable has been exposed to various pollution or other external substances and this will eventually contaminate insulator. It is known that contaminated insulator will affect performance of cable itself. Contamination of insulator has been a topic as different contamination affects differently. Since insulator is exposed to various minerals underground, SiO_2, TiO_2 and Al_2O_3 has been undiscovered on its effect towards insulator performance. Insulator performance greatly affected by space charge that will eventually lead to breakdown, therefore, space charge study is being conducted to identify contamination effect.

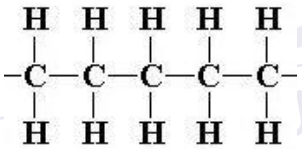
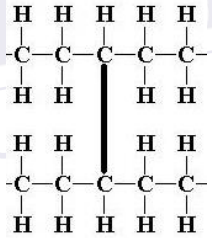
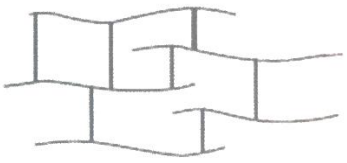
It is known that COMSOL Multiphysics has its efficiency and precision in handling electric currents problem. Therefore, investigation for space charge on contaminated insulator is done using COMSOL with different type of contamination and at different thicknesses.

2.1 XLPE Insulator Cable

XLPE is known as cross-linked polyethylene that has become the most preferred insulation power cable due to its mechanical stability compared to paper insulator [7]. Plus, XLPE shows a good electrical performance under humidity for a long

period of time compared to PVC [3]. Thus, it has been widely used in distribution and transmission system for its performance and efficient in cost [1]. Temperature perspective is important in high voltage condition due to its presence during transmission and thermoset materials will be suitable for the condition as it will not deformed in operating temperature or higher. Therefore, crosslinked solutions are preferred to endure the foreseeable future [1]. XLPE insulator is derived through cross-bonding processes that includes linking polyethylene in cross manner. Polyethylene has the characteristics to easily deform and become brittle at high temperature and due to oxidation as it is chemically unboned as shown in Table 2.1. XLPE as the name implies, it cross the polyethylene by having the molecules to be chemically bonded in three dimensional network which results in higher resistance towards deformation at high temperature [1, 8].

Table 2.1: Properties of Polyethylene and Cross-linked Polyethylene (XLPE)

Properties		Polyethylene	XLPE
Chemical [9]	Molecule Structure		
	Molecule bonding		

XLPE is being produced through compounding of Low Density Polyethylene (LDPE) and crosslinked it with peroxide as its agent such as dicumyl peroxide (DCP). Free radicals is being formed by having DCP which then extract hydrogen molecules from polyethylene and form cross-link at reactive site for combination of it [1]. The cross-link has substituted the thermoplastic properties of PE into thermoset of XLPE which is an elastic material.

Besides than its ability to perform at high temperature, XPLE also shows that comparing with paper and polyvinyl chloride (PVC), it has lower dielectric losses. Paper insulated cable has one decimal power higher while PVC insulated has two decimal higher factor losses compared to XLPE insulated cable. Dielectric losses will lower mutual capacitance and reducing charging and earth-leaking currents [6].

2.1.1 Previous Related Research of XLPE

Due to preferences in using XLPE in distribution and transmission system, many researched has been done to identify its characteristics and performance in various conditions. These conditions are being set up to test on its mechanical strength, lifespan and space charge effect. Research on the aging of XLPE has widely being done in different conditions and aspects to identify the limit performance and suggest improvement.

G. C. Montanari et al. has made a comparison of performance on LDPE and XLPE by investigating its change on electrical properties including space charge, conduction and lifetime by considering thermal treatment effects on it [10]. Xia Wang et al [11] has made a study on space charge behavior in long-term aging under temperature gradient and DC stress on XLPE insulator while [12] has studied on thickness dependence of space charge under the same condition. This has shown that thermal study in XLPE insulator has been widely made to identify its performance for space charge and other factors.

Study has been done to determine performance of XLPE cable for underground condition through measuring tan delta and capacitance value [13] for cables in service. It shows that tan delta has been a reliable measurement to identify ageing of the cable. The presence of contaminations on XLPE insulator has been studied for its electrical stress enhancement as quality control criteria [6]. Reviewed has shown that performance studies on XLPE insulator has been made in various conditions and aspects from clean XLPE to contaminated XLPE along with identifying ageing factor of XLPE insulator.

2.2 Contamination

It is mentioned that due to environment factors, undergrounding cable has increased in demand [14] that leads to many studies being done on underground cable performance. Direct-buried cable has been used in between transformation point and consumers due to aerial cable limitation. Thus, soil physical properties and its content has been the influenced for performance of insulators. Contaminations for underground condition have different sources either due to pollution or naturally occurred presence in the soil. Contaminants of naturally occurs for example are due to rain or soil composition and pollution contaminants are by human factors such as from fertilizers that produce acid and alkali that will react in soil. Soil composed of 45% minerals, 25% water, 25% air and 5% organic matters and these compositions may be contaminants to XLPE underground cable. Degradation of principal resins in electrical insulation are due to presence of humidity, heavy metals, external and internal composition factors [3, 14].

Aging of insulators are divided into three categories which are; electrical aging, physical aging and chemical aging. These aging are affected due to contamination and existence of contaminations may also cause “extreme oxidative degradation”. In addition, metallic contaminants will also initiate sites for electrical treeing [3]. Temperature of cable will increase with the presence of fungus and bacteria, it will affect temperature and causing unseen overloads [14].

Therefore, it has shown that with occurring contaminations on insulators, will affect the performance of it either the contaminations is due to pollution or natural occurring in underground itself. Among contaminations studies, a focus on natural composition of soil or Earth’s crust is being adopted such as Silicon dioxide (SiO_2), Titanium Oxide (TiO_2) and Aluminum dioxide (Al_3O_2) due to its abundant quantity and function.

2.2.1 Silicone Dioxide

Silicon dioxide or also known as silica is being used for glass and quartz. Silicon is the second abundant element found on Earth’s crust after oxygen as it composed of 28% by mass found on earth. Silicon is unreactive but has chemical affinity for

oxygen. Thus, pure element of silicon is rarely found in the Earth's crust and mostly found as silicon dioxide and exist in various conditions such as dust, sands and planetoids. A silicon atom when oxidized with two oxygen atoms will produce silicon dioxide due to bind of atoms which has chemical formula of SiO_2 [15].

Primary and secondary crystalline silicates are the only form that is found previously that are developed from rocks and sediments and found abundantly in mineral soils [16, 17]. Silicon are found in soil in three different phase which includes adsorbed phase, liquid phase and solid phase [18, 19]. However, silicon dioxide is mainly found in solid phase which also has several forms which are poor crystalline and microcrystalline forms, amorphous forms and crystalline forms. Crystalline forms occur mainly as primary and secondary silicates and silica materials. Sand and silt particles are the primary mineral-bearing silicates found in soil that is found in crystalline forms and mainly consist of silicon dioxide [20].

Therefore, it is seen that silicon dioxide is one of contaminants that may contribute to performance factors of XLPE cable insulators due to its abundant occurrences that is found in sand and silt.

2.2.2 Titanium Dioxide

Titanium is the 9th most abundant element in Earth's crust and mainly found in rocks and sediments. The isolated Titanium is being produced in 1910 before it is commercially produced in 1948. Thus, it shows that Titanium can only be found in nature and Titanium has the same characteristic as silicon in having a strong interaction with oxygen which made them found in the form of Titanium Dioxide. Titanium dioxide is a form such that one Titanium atom is combined with two oxygen atom and become TiO_2 in chemical molecular form [21].

Ilmenite and rutile are the form of titanium dioxide where ilmenite consists of 35% to 65% of Titanium dioxide. Rutile which is less abundant than ilmenite consists of 98% of Titanium dioxide [22]. Both minerals are composed of abundant of Titanium dioxide but are rare to be found. However, the content of Titanium dioxide in soil has increased due to its application in manmade product such as sunscreen, paint and textiles. Along the way from production to disposal, Titanium

dioxide will be released to environment especially soil through different pathways [23].

2.2.3 Aluminium Oxide

Now, aluminum oxide is found naturally in bauxite and corundum. Its physical characteristics are white odorless crystalline powder and is water insoluble. Aluminum is the pure metal that will react with oxygen naturally and form aluminum oxide Al_2O_3 which consists of two aluminum atoms and three oxygen atoms.

Aluminum oxide has the function to stabilize soil structure due to its aggregate stability and clay dispersion. Thus, this has made the content of aluminum oxide to be increased in soil either naturally or through human applications. Aluminum oxide consist of positive charge that help to coagulate clay particles. Therefore it decreased critical coagulation concentrations, clay dispersion and clay swelling which the interactions dependent on PH value [24]. Aluminum oxide also has the function as electrical insulator due to its benefits in handling high thermal conductivity and corrosion resistance [25].

Since aluminum oxide is a good insulator, properties of aluminum oxide as contamination has not yet being searched. Due to this research gap, this contamination is being look through for its effect towards insulator.

2.2.4 Previous Related Research of Contamination

It has been acknowledged that electrical stress due to contamination on insulator does occur either it will degrade the insulator or it will affect the performance of it by introducing fault. Therefore, several studies had been made regarding effect of contamination on insulator either due to nature or pollution.

Table 2.2 shows summary of studies done on contaminated XLPE insulator. Studies done for various variables and various results from physical outcome to electrical outcome. Anwar et al. find that crack will presence on insulator if it is being exposed to chemically contaminated water and cable will only last for four years of operation [5]. Metallic contaminant will add on electrical stresses towards the cable and these metal were found using tape approach such that tape is being

used to take sample from insulator in identifying its content and thickness [4]. XLPE insulator is being used in high voltage has water treeing, reduced in conductivity, degradation of materials has appeared and change in permittivity occurred when expose to organic contaminants [26].

Generally, contaminated XLPE will affect the performance of cable either electrically or physically. However, there are still lack of studies on content of soil specifically on SiO_2, TiO_2 and Al_2O_3 and its effect towards XLPE insulator space charge.

Table 2.2: Summary of previous research on contaminated insulator

Author	Type of insulator	Type of contamination	Procedure	Result
Anwar Ul-Hamid et al. [5]	XLPE (Low voltage)	Chemically contaminated water	Visual inspection and photography	Physical effect and functionality
Jan-Ove et al. [4]	XLPE	Metallic contaminants	Tape approach for sample taking	Increase in electrical stress
Espen H. [26]	XLPE (High voltage)	Organic contaminants (Methylene)	Produced samples of contaminated XLPE cable and series of tests are conducted on samples. COMSOL is used to test on electric field.	Water treeing, conductivity, degradation in materials, change in permittivity

2.3 Space Charge

Space charge is a region containing free charges in between short distance of two different type of materials when an external field is applied. It is also a collection of

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