Faculty of Electrical Engineering

MODELLING OF LEAKAGE CURRENT ON CONDUCTIVE SURFACE FOR OUTDOOR INSULATORS

Noor Afiqah binti Abd Rahim

Master of Science in Electrical Engineering

2021

MODELLING OF LEAKAGE CURRENT ON CONDUCTIVE SURFACE FOR OUTDOOR INSULATORS

NOOR AFIQAH BINTI ABD RAHIM

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Electrical Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

DECLARATION

I declare that this thesis entitled "Modelling of Leakage Current on Conductive Surface for Outdoor Insulators" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	....
Name	:	Noor Afiqah binti Abd Rahim
Date	:	3 December 2020

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature :………………………

Supervisor Name : Dr Rahifa binti Ranom

Date : 3 November 2020

DEDICATION

This thesis is dedicated to,

my beloved mother and father

Abd Rahim bin Md Dom and Rosmah Azizah binti Adimon,

all of my siblings

Noor Hidayah binti Abd Rahim and Muhammad Imran bin Abd Rahim,

and all my lecturers and friends.

Thank you for supporting me during ups and downs in finishing the master study.

ABSTRACT

The insulation system is the most important part in the high voltage applications to prevent the flow of leakage current to undesired path. Solid outdoor insulators are one of the basic elements in a power system such as in the transmission and distribution system. The outdoor insulator commonly exposed to environmental pollution. The presence of water like raindrops and dew on the contaminant surface can lead to the insulator surface degradation. The contaminant particles may be dissolved into water. Thus, this condition can caused the formation of the conductive path that can lead to the flow of the current due to the surface discharge event. However, the physical process of this phenomenon is not well understood. In order to understand the propagation of the surface discharge on the insulator, the mechanism for the charge carrier generation and transportation must be known. Hence, in this study, the mathematical model of leakage current on the outdoor insulator surface using the Nernst Planck theory that accounts for the charge transport between the electrodes (negative and positive electrode) and charge generation mechanism is developed. Meanwhile, the electric field obeys Poisson's equation. In this model, one-dimensional (1-D) model is studied. The charge continuity equations and Poisson's equation solved using a non-dimensional framework to reduce the difficulty while doing the simulation. Then, this model is solved numerically using the method of lines (MOL) technique which converts the partial differential equations (PDEs) into a set of ordinary differential equations (ODEs). The ODEs then solved using an appropriate time integration method '*ode15s*' in MATLAB. In order to validate the simulation result, experimental work is done according to inclined plane test (IPT) complying with BS EN 60587-2007. Then, the result from both simulation and experimental work is compared for the validation of this model. The findings from the simulation shows that the density of net space charge distribution gives the good correlation to the electric field. Besides, the conduction current also varies depending on the electric field distribution and charge concentration. In addition, The simulation result appears to have good correlation with the experimental result in terms of leakage current rising. Hence, from the simulation, it can, be seen that this mathematical model can be used in order to investigate the leakage current on the outdoor insulator due to the presence of surface discharge. In addition, the permittivity gives the effect to the number of charge produced on the outdoor insulator due to the present of wet contaminant. Thus, the charge will produce more flux in a medium with a lower permittivity than a medium with high permittivity.

MODEL PENGALIRAN ARUS BOCOR DI ATAS PERMUKAAN BERALIRAN UNTUK PENEBAT LUAR

ABSTRAK

Sistem penebat adalah salah satu bahagian penting di dalam aplikasi voltan tinggi untuk menghalang pengaliran arus bocor ke tempat yang tidak diingini. Penebatan luar pepejal adalah salah satu elemen asas di dalam sistem kuasa seperti untuk sistem penghantaran dan pengagihan. Penebatan luar kebiasaannya terdedah kepada pencemaran alam sekitar. Kehadiran air seperti hujan dan embun di atas permukaan yang tercemar boleh membawa kepada kerosakan permukaan penebatan itu. Zarah pencemaran akan melarut ke dalam air. Oleh itu, keadaan ini akan menyebabkan pembentukan jalan konduktif yang membawa kepada pengaliran arus disebabkan nyahcas permukaan. Walaubagaimanapun, proses fizikal untuk fenomena ini tidak difahami dengan baik. Untuk memahami penyebaran nyahcas permukaan di atas penebatan, mekanisma penjanaan dan pengangkutan caj mestilah diketahui. Oleh itu, matematik model untuk arus bocor di atas permukaan penebetan luar menggunakan teori Nernst Planck dengan mengambil kira pengangkutan caj di antara elektrod (negatif dan positif elektrod) dan mekanisma penjanaan caj dibangunkan. Sementara itu, medan elektrik pula mengikut persamaan Poisson. Model ini dijalankan dalam satu dimensi (1-D). Persamaan caj dan persamaan Poisson diselesaikan dengan menjalankan kaedah tiada dimensi untuk mengurangkan kesukaran dalam melakukan simulasi. Kemudian, model ini diselesaikan secara numerik menggunakan teknik kaedah garis (MOL) dimana ianya menukar persamaan perbezaan separa (PDEs) kepada persamaan perbezaan biasa (ODEs). Kemudiannya, ODEs diselesaikan menggunakan teknik pencantuman masa yang sesuai 'ode15s' di MATLAB. Untuk mengesahkan hasil simulasi, kerja eksperimen dijalankan mengikut inclined plane test (IPT) mematuhi BS EN 60587-2007. Kemudian, hasil daripada kedua-dua simulasi dan kerja eksperimen dibandingkan untuk mengesahkan model ini. Dapatan daripada simulasi menunjukkan ketumpatan caj memberikan kolerasi yang betul terhadap medan elektrik. Selain itu, arus juga berubah bergantung kepada medan elektrik dan kepekatan kaj. Tambahan, hasil simulasi didapati mempunyai kolerasi terhadap hasil eksperimen dalam bentuk peningkatan arus bocor. Oleh itu, daripada keputusan simulasi, ianya menunjukkan bahawa matematik model ini dapat digunakan untuk mengkaji arus bocor di atas permukaan penebatan luar disebabkan kehadiran nyahcas permukaan. Tambahan pula, permittiviti memberi kesan kepada bilangan cas yang terhasil di atas penebat luar disebabkan kehadiran kontaminan yang basah. Oleh itu, cas ini akan menghasilkan lebih banyak fluks di dalam media yang rendah permittiviti berbanding permittiviti yang tinggi.

ACKNOWLEDGEMENTS

First and foremost, I would like to express the deepest gratitude to ALLAH S.W.T the Almighty for giving me the blessing, the chance and the endurance to finish this study. Without His blessing and permission, I cannot stand alone to complete my research work successfully.

I would like to take this opportunity to express my sincere acknowledgement to my supervisor Dr. Rahifa binti Ranom from the Faculty of Electrical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for her essential supervision, support and encouragement towards the completion of this thesis.

I would also like to express my greatest gratitude to Associate Professor Dr Hidayat bin Zainuddin from Faculty of Electrical Engineering, co-supervisor of this project. Special thanks to UTeM short term grant funding for the financial support throughout this project.

I would like to thank the Universiti Teknikal Malaysia Melaka and Ministry of Higher Education, Malaysia for the giving an opportunity to pursue my master study and also the financial support.

Special thanks to all the technical supports provided by High Voltage Engineering (HVE) Research Laboratory and the technician of the laboratory, Encik Mohd Wahyudi bin Md Hussain for assisting me for the experimental setup and sharing the valuable knowledge and information during my years study.

Last but not least, special dedication for my beloved families for all their endless prayer, financial and support which have given me the strength to complete the master study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS/SYMBOLS

1-D	-	One-dimensional
δ	-	tan
ε	-	Permittivity
μ_i	-	Mobility of ion
Δ	-	Molecular ionization energy
AC	-	Alternating Current
D_i	-	Diffusion coefficient of ion
dA	-	Differential cross-sectional area of the insulator
DAQ	-	Data acquisition system
DBA	-	Dry-band arcing
DC	-	Direct Current
$\vec{E}$	-	Electric field vector
F	-	Faraday’s constant
FDM	-	Finite difference method
FEM		Finite element method
G_i	-	Generation rate
h	-	Planck’s constant
HV	-	High voltage
J_i	-	Conduction current density
k	-	Boltzmann constant
LC	-	Leakage Current
LLDPE	-	Low-density polyethylene
MOL	-	Method of line technique
MV/cm	-	Mega Volt/centimeter

m^*	-	Effective electron mass
N_A	-	Avogadro’s number
N_i	-	Ion concentration
ODE	-	Ordinary differential equation
q	-	Elementary charge
PDE	-	Partial differential equation
R	-	Universal gas constant
R_{pn}	-	Recombination rate
SIR	-	Silicone rubber
T	-	Absolute temperature
UV	-	Ultraviolet
V	-	Electric potential
V.m	-	Volt meter

LIST OF PUBLICATIONS

Conference Paper:

1. Rahim N.A., Ranom, R., Zainuddin, H., 2018. Mechanism of the Free Charge Carrier Generation in the Dielectric Breakdown. *Journal of Physics: Conference Series*, 708.

Journal Paper:

2. Rahim N.A., Ranom, R., Zainuddin, H., 2018. Mathematical Modelling of Surface Discharge on the Contaminated Surface of Insulator Using Nernst's Planck Equation. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, 10(2-2), pp. 5-10.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The insulation system is the most important part in the high voltage applications to prevent the flow of leakage current (LC) to undesired path. The insulation is commonly exposed to several stresses such as mechanical stress, thermal stress, electrical stress and environmental stress. However, the insulator has been suffering from more pronounced ageing under the action of multifactor stresses (Rusu-Zagar et al., 2007). In the case of the outdoor insulation system, their long-life performance is subjected to the surface degradation due to the continuous electrical and environmental stress (Douar et al., 2010).

Solid outdoor insulators are one of the basic elements in a power system such as in the transmission and distribution system. The overhead conductors for the transmission and distribution system are generally supported by the supporting towers or poles (Basappa et al., 2008). Hence, good insulator must be provided to prevent the flow of current from high voltage electrode to the ground electrode through the grounded supporting towers or poles. In addition, interruptions or failures within the power systems may result in the damage of the high voltage equipment and can cause danger to both human or animal.

Since their introduction in the early 1970s, solid polymeric insulators have been increasingly accepted by utilities as suitable replacements for porcelain and glass insulators (Bernstorf et al., 2000). A polymer is composed of very large molecules where each molecule contains atoms arranged one after another in a chain-like manner. There are many advantages of using polymeric insulator compared to the conventional insulator. Polymers are often the best and most economic electrically insulating construction material. They generally exhibit very high breakdown strengths (typically up to 10^9 V.m^{-1}), have low dielectric losses (typically tan $\delta<10^{-3}$) and high DC resistivity (typically > 10^{16} Ω.m) [3]. These polymeric insulators also have strong hydrophobic property compared to the conventional insulators (Mavrikakis et al., 2016).

The hydrophobic property of the polymeric insulator can be defined as its ability to resist the flow of water drops on its surface. The hydrophobic surface is a contrast to the hydrophilic surface that can be wetted by the water flow (Amin et al., 2007). Hence, due to its hydrophobic property, the polymeric insulator is used to avoid the LC flow which can cause tracking and erosion on the surface of the insulators during wet conditions.

However, the performance of polymeric outdoor insulator can be affected by the continuous electrical and environmental stress (Reynders et al., 1999). Contamination particles such as dirt or salt can build up on the surface of the outdoor insulator. In addition, with the presence of wet atmospheric conditions, the contaminant particles may be dissolved into water. Thus, this condition can cause the formation of a conductive path which can lead to the flow of the current due to the surface discharge event (Shakhashiri, 2011). This conductive surface generates more heat and increase the probability of tracking and erosion on the insulator surface (Ahmed et al., 1998). Therefore, this phenomenon reduces the hydrophobic property of the polymeric insulator.

Hence, LC measurement and analysis on the surface of the outdoor solid insulator has become an important tool to evaluate the performance of the insulation systems (El-Hag, 2007). Some researchers used various equivalent circuit models to investigate current leakage phenomenon of the insulator under different conditions (Waluyo et al., 2006; Suwarno et al., 2009). On the other hand, some researchers developed experimental set-up to investigate the performance of these insulators (Sarkar et al., 2010; Syakur et al., 2013). However, the drawbacks of experimental set-up tests are that they are very time-consuming and costly. In addition, the physical process of LC flow involves charge transport and generation mechanism that is still yet to be fully understood. Research on the fundamental physical process of LC is important to assist in the design consideration associated with the materials that are being used for the high voltage insulators.

The exact mechanism behind the surface discharge activities still needs to be studied. In order to understand the propagation of the surface discharge on the insulator, the mechanism for the charge carrier generation and transportation must be made known. There are several factors that can lead to the breakdown of the insulators due to charge generation and transport mechanisms. Among the mechanisms that are involved in the charge carrier generation are the impact ionization (Solomon and Klein, 1975), field emission (Sullivan, 2007), secondary electron emission (Niessen, 1998), ionic dissociation (Onsager, 1934) and molecular ionization (Zener, 1926). Besides that, recombination of free charge carriers like electrons, positive ions, and negative ions with each other and the surrounding media can also contribute in the charge carrier generation of the insulation (Sullivan, 2007). In addition to the recombination, electrons also combine with neutral molecules to form negative ions in the process of electron attachment (Sullivan, 2007).

Therefore, studies on the mechanisms that can lead to the breakdown of the insulators are very important to prevent failure in the high voltage system. For the transportation mechanism of the charge carrier, charge transport continuity equation accounted by the Nernst Planck theory can be used to understand the charge carrier behavior on the insulator (Zainuddin and Lewin, 2015) and this equation is coupled with Poisson's equation for the field distribution due the discharge propagation. This model is validated through the comparison between the simulation results and experimental data.

1.2 Problem statement

The long-life performance of an outdoor insulator is exposed to the electrical stresses and environmental pollution (Abd-Rahman et al., 2012a) especially for the insulator at the coastal area and industrial area that are exposed to heavy pollution. Contaminant particles such as dust or salt particle might accumulate on the insulator surface. In dry condition, the insulator surface is capacitive and the current amplitude is small. However, in the condition where humidity is high with rain or dew, these particles may be dissolved into water and generate free charge carriers (Belkheiri et al., 2009). Thus, the generation of the free charge carriers can lead to the formation of a conductive path on the insulator surface (Shakhashiri, 2011). The formation of the conductive path caused by the surface discharge activities allows the current to flow through it.

The long term of LC flow due to the discharge activities may lead to the insulator surface degradation. The increasing of the LC magnitude can cause the formation of dry-band and evaluation of arc (Narmadhai and Jeyakumar, 2011). Then the arc will lead to the occurrence of flashover on the insulator surface and causing breakdown. The LC flow increases the energy of which will cause tracking on the insulator surface (Salthouse, 1968). This phenomenon then changes the hydrophobicity behavior of the insulator into the hydrophilicity behavior. Heat from the current flow causes the breaking of the contaminant films, causing the carbonization and evaporation on the insulator surface. As a result, this condition can lead to the formation of a permanent tracking path, usually carbon, on the surface of the insulator (Wadhwa, 2013).

Therefore, the analysis of LC is very importance to investigate the performance of the outdoor insulator and can be beneficial to high voltage application. Thus, there are some studies had been done regarding the effect of LC on the outdoor insulator. There are several researchers (Sarkar et al., 2010; Syakur et al., 2013) focused on the experimental test set-up to investigate the condition of the outdoor insulator. This method shows the different amplitude and shape of the LC and provided the information of the outdoor insulator condition. However, this approach does not consider the physical process behind the surface degradation due to the LC flow. Therefore, it should be emphasized the physical process that effect the surface degradation of the outdoor insulator due to the presence of wet contaminant. In addition, experimental-test set-up are time consuming and costly due to the equipment installation. Therefore, to reduce the time consumption and installation cost, previous researchers (Moreno and Gorur, 1999; Bruce et al., 2010; Aman, 2013) have studied on the modeling of various equivalent circuit to investigate the insulator performance. Unfortunately, the modeling of various equivalent circuit is just focusing on predicting the LC patterns and flashover voltage without considering the physical theories behind the formation of the LC and the breakdown of the solid outdoor insulator. There are researchers (Ahmed et al., 1998) used the method based on the surface charge simulation that considered the surface conductivity. Based on this method, the calculation of electric field and leakage current on polluted insulator surface is done. This method also not considered the physical process that involved due to the presence of wet contaminant on the outdoor insulator due to the presence of high voltage.

It should emphasize the effect of wet contaminant on the outdoor insulator that can caused surface degradation and system failure. Therefore, in this research project, the physical process occurred on the insulator surface due to the presence of wet contaminant considering the charge transportation and generation mechanism is considered. Hence, a model of LC on the contaminated outdoor insulator had been developed by considering its physical process from the perspective of charge transportation and generation mechanism. It is very importance study that can provide beneficial knowledge to the industries in the designing requirements and monitoring condition. Thus, this research project may help in predicting the probability of the system failure due to the presence of contaminant on the outdoor insulator.

1.3 Objectives of the research

The following are the objectives of this research:

1. To develop a corresponding mathematical model of LC on contaminated surface of outdoor insulators based on the physical process occurred.
2. To solve the LC mathematical model on contaminated surface of outdoor insulators using finite difference method base on method of line technique (MOL). The mathematical model is validated using experimental results.
3. To develop the behavior of charge concentration, electric field distribution and LC behavior in order to study the physical process occurred on the outdoor insulator surface due to presence of wet contaminant.

1.4 Scope of research

This research work focuses on the modeling of LC on the conductive surface of the outdoor insulator. One-dimensional (1-D) model of LC for direct current (DC) voltage on the contaminated surface of artificially polluted insulation is used. In this work, the physical process of surface discharge activities on the insulator surface including free charge transport and generation mechanism are considered. In order to model the behavior of the charge carriers, Nernst-Planck theory is used. Then, Poisson's equation is used to determine the electric field distribution. The method of line technique (MOL) which discretize the spatial variable using finite difference method (FDM) is used to solve the mathematical model. The comparison between the LC of the simulation results and the experiment data (only the current signal can tell the macroscopic information of the surface discharge (Sima et al., 2013) is done to validate the results obtained from the mathematical simulation. The experimental data is collected from the Inclined Plane Test (IPT) complying with BS EN 60587-2007 standard. The graph of charge concentration, electric field distribution and LC behavior is plotted and analyzed. All the parameters used for this model is assumed to be dominated by the parameters of water because water is a polar liquid that is responsible in the solvation of the contaminant particles on the insulator surface.

1.5 Contribution of the research

In the presence of wet contaminant and high electric field on the outdoor insulator surface it can caused the generation of free charge carrier. Thus, with the presence of these free charge carriers, it can cause the conducting path between the electrodes and allow the flow of LC. This condition can cause outdoor insulator surface deterioration and lead to system failure. Hence, the development of physical and mathematical model of the LC with the presence of surface discharge is beneficial to the design consideration and in-depth knowledge on the faulty condition on insulation surface. Therefore, the following contributions have been identified:

1. The effect of wet contaminant from pollution on the insulator surface can cause the generation of free charge carriers which then, can cause the flowing of LC. Hence, the physical model in this research is explaining about the charge generation and transportation on the insulator surface. The description of the physical model has been discussed in Chapter 2. The model is able to describe the mechanisms of some physical processes that can cause surface degradation on the insulator surface due to the surface discharge activities.

2. A mathematical model has been developed to study the mechanism of surface discharge on the insulator surface due to the presence of wet contaminant. This model is developed by considering the wet contaminant that is dominant on the insulator surface. The mathematical model is solved by using ODE15s that can solve the model in fast period of time. This mathematical model has been discussed further in Chapter 3 that showed the summarization of the mathematical model of governing equations on the insulator surface.

3. In order to solve the mathematical model discussed, a numerical method known as method of line (MOL) technique is used. This technique converts the system of PDEs into the system of ODEs by approximating spatial derivatives using finite difference approximations. The experimental set-up is done by using DC voltage complying with BS EN 60587-2007 IPT test. The experimental data about LC pattern is collected for the validation purposed. The numerical method and experimental set-up have been discussed in Chapter 3.

4. The graph of electric field, charge behavior and current profile are plotted based on the mathematical model. Thus, the analysis of the physical process during the surface discharge activities is done from the electric field, charge behavior and current profile graph. The analysis of the electric field behavior, current profiles and charge behavior have been discussed in Chapter 4. This research project is very beneficial study that can give significant knowledge to the industry in terms of condition monitoring and designing of outdoor insulator. In addition, this work can assist in predict and reducing the system failure.

1.6 Thesis layout

In general, this thesis is divided into five chapters, which are: