INCLINED-PLANE TRACKING PARAMETERS VARIABILITY IN IDENTIFYING LEAKAGE CURRENT AND CARBON TRACK OF POLYMER NANOCOMPOSITES

FATIN LIYANA BINTI MUHAMEDIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2017

Specially dedicated to *Mak* and *Abah*

Family and friends

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful. Alhamdulillah, all praises to Allah for the lights, hopes and strengths and His blessing in my life.

I would like to give special appreciation to my supervisor, Assoc. Prof. Dr. Mohamed Afendi Bin Mohamed Piah for his guidance, encouragement, ideas, comments and patience throughout finishing the project. Not forgotten special gratitude to Dr. Nordiana Azlin Binti Othman, Mr. Nor Faizal Bin Kasri, Dr. Nor Akmal Binti Mohd Jamail, Mr. Suhi Tan and Mr. Mohamed for their knowledge, guidance and cooperation regarding this project.

Special thanks to all my friends in IVAT especially, Ms. Fatin Nabilah Binti Musa for her friendship, support, and loves during my thick and thin in completing my master project. Thanks for everything.

Last but not least, my deepest gratitude goes to my beloved parents; Mr. Muhamedin Bin Marsidin and Mrs. Faridah Binti Abd. Jalil and also to my siblings for their infinite love, prayers and encouragement. Also not forgetting to those who indirectly contributed in finish this project, may Allah (S.W.T) pay your kindness and prosperity. Thank you very much.

ABSTRACT

Surface discharge is a phenomenon of insulating surface failure due to intensive leakage current (LC) flow. The existence of LC on the wet contaminated material surfaces causes a permanent conducting path to the insulating material due to surface erosion, which is due to high-voltage stress. Conventionally, the standard experimental test requires the inclined plane tracking (IPT) test hardware arrangement and sample material preparation. This experiment is also time consuming and costly. Hence, this thesis proposes field simulation using finite element analysis software to investigate the LC and electric field during surface discharge activity. Different compounds of linear low-density polyethylene (LLDPE) and natural rubber (NR) blended with different percentage of silicone oxide (SiO_2) and alumina hydroxide ($Al(OH)_3$) nanofillers were tested using the IPT test and field simulation at 4.5 kV with a contaminant flow rate of 0.60 ml/min. The controlled parameters of applied voltage, conductivity and permittivity of material as well as contaminant solution were also tested in the IPT test and field simulation. Due to the limitation in the field simulation, the LC obtained displays similar impression though not explicit. Thus, correction factors (*f*) were determined to achieve absolute value of LC. LLDPE-NR/SiO_2 at 1wt% (A1) was found to be the lowest LC for both experimental and simulation results. In the experiment, the consequence of LC with the carbon track rate, hydrophobicity loss, and morphological analysis was investigated to obtain the tracking and erosion performance of the insulator materials. The high distribution of LC causes severe carbon track rate and larger hydrophobicity loss on the composition as demonstrated on LLDPE-NR samples. Morphological analysis on the surface also showed greater deterioration of the surface structure. The field simulation approach can be used as another option in investigating surface tracking resistance as the results due to LC could be forecasted.

ABSTRAK

Discas permukaan adalah satu fenomena kegagalan permukaan penebatan yang disebabkan oleh aliran intensif arus kebocoran (LC). Kewujudan LC pada permukaan bahan tercemar yang basah menyebabkan laluan tetap konduktor untuk bahan penebat akibat hakisan permukaan tekanan voltan tinggi. Sebelum ini, ujian eksperimen standard memerlukan susunan perkakasan ujian IPT dan persediaan bahan sampel. Eksperimen ini memerlukan masa dan kos. Oleh itu, tesis ini mencadangkan simulasi medan dengan menggunakan perisian analisis unsur terhingga (FEA) untuk menyiasat LC dan medan elektrik semasa aktiviti discas permukaan. Sebatian linear polietilena berketumpatan rendah (LLDPE) dan getah asli (NR) dicampur dengan pengisi nano yang berbeza iaitu silikon dioksida (SiO_2) dan alumina hidroksida (Al $(OH)_3$) telah diuji menggunakan ujian IPT dan simulasi medan pada 4.5 kV dengan kadar aliran bahan cemar 0.60 ml/min. Parameter terkawal voltan gunaan, kekonduksian dan ketelusan bahan serta penyelesaian bahan cemar juga telah diuji di ujian IPT dan simulasi medan. Oleh kerana batasan dalam simulasi medan, LC yang diperolehi memaparkan gambaran yang sama tetapi tidak jelas. Oleh itu, faktor-faktor pembetulan (*f*) telah ditentukan untuk mencapai nilai mutlak LC. LLDPE-NR / SiO_2 pada 1wt% (A1) menunjukkan LC yang paling rendah untuk kedua-dua keputusan eksperimen dan simulasi. Dalam eksperimen, akibat LC dengan kadar trek karbon, kehilangan hidrofobik, dan analisis morfologi telah diselidiki dalam mendapatkan pengesanan dan hakisan prestasi bahan penebat. Taburan LC yang tinggi menyebabkan kadar trek karbon yang teruk dan kehilangan hidrofobik lebih besar pada komposisi seperti yang ditunjukkan dalam sampel LLDPE-NR. Analisis morfologi di permukaan juga menunjukkan kemerosotan yang lebih besar pada struktur permukaan. Kerja-kerja simulasi medan boleh digunakan sebagai satu lagi pilihan dalam menyelidiki rintangan pengesanan permukaan kerana keputusan LC boleh diramalkan.

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LIST OF ABBREVIATION

AC	-	Alternate current
ACF	-	Auto correlation factor
ATH	-	Alumina hydroxide
ANN	-	Artificial network neural
A1	-	Linear low density polyethene + Natural Rubber + 1% wt silicone oxide (SiO_2)
A3	-	Linear low density polyethene + Natural Rubber + 3% wt silicone oxide (SiO_2)
A5	-	Linear low density polyethene + Natural Rubber + 5% wt silicone oxide (SiO_2)
A7	-	Linear low density polyethene + Natural Rubber + 7% wt silicone oxide (SiO_2)
B1	-	Linear low density polyethene + Natural Rubber + 1% wt aluminium hydroxide ($Al(OH)_3$)
B3	-	Linear low density polyethene + Natural Rubber + 3% wt aluminium hydroxide ($Al(OH)_3$)
B5	-	Linear low density polyethene + Natural Rubber + 5% wt aluminium hydroxide ($Al(OH)_3$)
B7	-	Linear low density polyethene + Natural Rubber + 7% wt aluminium hydroxide ($Al(OH)_3$)

CT	-	Carbon track rate
DBA	-	Dry band arcing
DC	-	Direct current
EAP	-	Early aging period
EDBA	-	Eroding dry band arcing
ESDD	-	Equivalent salt deposit density
FEA	-	Finite element analysis
FEM	-	Finite element method
FFT	-	Fast fourier transform
GRFB	-	Gaussian radial basic function
HTV	-	High temperature vulcanized
HVDC	-	High voltage direct current
IEC 60587	-	International electrotechnical commission standard test
IPT	-	Inclined plane tracking test
ITV	-	Initial track voltage
LABView	-	Laboratory Virtual Instrument Engineering Workbench
LC	-	Leakage current
LCR	-	Natural rubber
LLDPE	-	Linear low density polyethylene
N	-	Newton
NDI	-	Normalized degradation index
NR	-	Natural rubber

NSDD	-	Non-soluble deposit density
PC	-	Personal computer
Pc	-	Picocoloumb
PD	-	Partial discharge
PDC	-	Polarization and depolarization current
P0	-	Linear low density polyethene (80%) + Natural Rubber (20%)
RWDT	-	Rotating wheel dip test
Rpm	-	Revolutions per minute
SEM	-	Scanning electron microscopy
SiR	-	Silicone rubber
SMR	-	Standard Malaysia rubber
TE	-	Time to eroding
THD	-	Total harmonic distortion
UV	-	Ultra violet
WA	-	Sample P0 with applied voltage of 2.5 kV and contaminant flow rate of 0.15 ml/min
WB	-	Sample P0 with applied voltage of 2.5 kV and contaminant flow rate of 0.30 ml/min
WC	-	Sample P0 with applied voltage of 2.5 kV and contaminant flow rate of 0.60 ml/min
WD	-	Sample P0 with applied voltage of 2.5 kV and contaminant flow rate of 0.90 ml/min
XA	-	Sample P0 with applied voltage of 3.5 kV and contaminant flow rate of 0.15 ml/min

XB - Sample P0 with applied voltage of 3.5 kV and contaminant flow rate of 0.30 ml/min

XC - Sample P0 with applied voltage of 3.5 kV and contaminant flow rate of 0.60 ml/min

XD - Sample P0 with applied voltage of 3.5 kV and contaminant flow rate of 0.90 ml/min

YA - Sample P0 with applied voltage of 4.5 kV and contaminant flow rate of 0.15 ml/min

YB - Sample P0 with applied voltage of 4.5 kV and contaminant flow rate of 0.30 ml/min

YC - Sample P0 with applied voltage of 4.5 kV and contaminant flow rate of 0.60 ml/min

YD - Sample P0 with applied voltage of 4.5 kV and contaminant flow rate of 0.90 ml/min

ZA - Sample P0 with applied voltage of 6.0 kV and contaminant flow rate of 0.15 ml/min

ZB - Sample P0 with applied voltage of 6.0kV and contaminant flow rate of 0.30 ml/min

ZC - Sample P0 with applied voltage of 6.0 kV and contaminant flow rate of 0.60 ml/min

ZD - Sample P0 with applied voltage of 6.0 kV and contaminant flow rate of 0.90 ml/min

LIST OF SYMBOLS

I_n	-	Average leakage current
C_n	-	Rate of carbon track
I_c	-	Critical leakage current
C_c	-	Critical rate of carbon track
Λ	-	Thermal conductivity of composite
λ_m	-	Thermal conductivity of polymer
λ_f	-	Thermal conductivity of filler
v_f	-	Volume of fraction of filler particles
Θ	-	Contact angle
I	-	Leakage current
A	-	Area of cross section
J	-	Current density
ε_o	-	Free space dielectric constant (8.854 x 10^{-12} F.m)
C_o	-	Geometric capacitance
U_o	-	Voltage applied
$i_p(t)$	-	Polarization current
$i_{dp}(t)$	-	Depolarization current
V	-	Volume

L	-	Length
A	-	Area
Σ	-	Electric conductivity
P	-	Resistivity
R	-	Resistance
D	-	Separation between plate
ε_r	-	Relative permittivity
C_r	-	Carbon track rate
T	-	Time
Z_o	-	Peak value of z
Z	-	Electric field vary with time
$Ø_m$	-	Phase angle
ω	-	Angular frequency
E	-	Electric field
f	-	Correction factor
$LC_{ref(ipt)}$	-	Leakage current from IPT test result
LC_{si}	-	Leakage current from field simulation

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CHAPTER 1

INTRODUCTION

1.1 Background

Vast utilization of the polymer in the field of electrical insulation has developed a lot of investigation into their performance in terms of its electrical, mechanical and chemical properties. Previously, microfillers are added to the polymer-based in order to improve the characteristics of materials, but large amounts of up to 65 wt % are required [1]. The advances of nanotechnology in recent decades had attracted the researcher to apply nanofillers in the nanocomposite polymer to enhance the structure's properties. The major benefits of nanofiller implementation are the high availability of surface areas and the small quantity of nanofillers which are sufficient at typically less than 10 wt%. In the interaction zone, the interaction between the polymer matrix and filler increases as the surface area of the nano-scale filler is enhanced.

The application of polymer nanocomposite materials in the bushing and power cables of outdoor insulation systems has exposed the insulator to deterioration. Insulating surfaces is exposed to environmental stresses such as contaminants, UV rays, pollution, and severe fog conditions, causing the aging of the insulation. The aging of the polymer due to environmental stresses can cause the degradation of the insulator polymer through surface tracking phenomena. During wet contaminant conditions, leakage current (LC) exists on the insulator surface when it achieves certain voltage gradients. The temperature of the insulator surface increases with continuous flows of LC and accumulated heat dissipation leads to dry conditions in the insulator surface, eventually forming an arcing spark. Dry band arcing spark occurs to the lowest surface resistance when a non-uniform water layer is formed due to hydrophobicity loss. The hydrophobicity feature in the materials can reduce the onset of LC by increasing the failure time. Degradation occurs when the insulator's resistance diminished as the consequence of an increase in LC magnitude due to hydrophobicity loss in the materials. Meanwhile, surface discharges occur when the air gap reaches a critical flashover voltage across the dry band. Carbonized track and erosion will be formed when an arc burns the insulator material due to surface discharges. The carbonized track that develops a pathway between the two electrodes will eventually cause failure of insulation to the system. All degradation processes that contribute to the growth of carbon tracks such as hydrophobicity loss, weight loss, LC and erosion are called surface tracking [2-4].

The monitoring and prevention of insulation failure at the early stages is crucial to avoid any interruptions of the functions of the high voltage apparatus. Measurement of LC in the areas of surface discharges was implemented by previous researchers using a standard inclined plane tracking (IPT) test [4]. In this test, the LC was recorded for six hours or until the sample failed to investigate the electrical performances of polymeric insulating materials. The LC measurement is used as a tool to indicate the deterioration of materials, as the LC is reported to be proportional to the degree of material degradation [5].

One of the objectives in this research is to establish field simulation analysis which can develop the IPT test characteristics in studying surface discharge in terms of LC. The correlation of results in the simulation and experiment in terms of LC has demonstrated a new non-destructive test for surface discharge. In the field simulation, portrayals of different nanofiller loadings in the materials were constituted with its electrical conductivity and relative permittivity properties. The physical parameters in the IPT test such as applied voltage and contaminant flow rate are correspondingly changed in the field simulation to the voltage supply and electrical conductivity of contaminants. The study of surface discharge in the insulator materials is important to estimate the capability of the dielectric material, particularly in tracking and erosion resistance.

1.2 Problem Statement

The IPT test was used as the standard test to evaluate tracking and erosion resistance. In this test, the level of material degradation can be analyzed using the result of LC waveform in time domains, and harmonics in frequency domains with the consequence of surface conditions of the materials [6, 7]. The outcome shows that the LC is proportional to the degree of deterioration in insulator materials [8]. The establishment of the IPT test required preparation of the experimental equipment and tested sample material. However, the construction of hardware set-up and samples in the experimental works consuming time and cost. Therefore, a new non-destructive simulation works in prediction the LC due to the electrical tracking of the polymer materials was proposed.

A two-dimensional plane parallel model was built in accordance with the IPT test configuration of IEC 60587 standard tracking and erosion test are studied using the Finite Element software. The simulation model to estimate the results in the numerical solution of the electric field and current density problems by considering the physical parameters that may contribute to the electrical tracking results was carried out. By applying the voltage, electric conductivity, and permittivities of insulating sample and contaminant solutions as the controlled parameters, the investigation of the electric field, current density and LC distribution of insulator surface were achieved. The practice of model simulation in the new material of insulating sample can estimate the performance of the materials in the electrical tracking and erosion resistance. Thus, the conventional approach to the experimental test of the tracking and erosion can be replaced by working on the simulation test that much faster and economical.

1.3 Research Objectives

The purpose of this research is to establish a simulation analysis that can produce similar practices as the experimental standard. To fulfill this purpose, the study was separated into three objectives. The objectives of this research are:

1. To conduct simulation analysis using Finite Element Software to study the characteristics of IPT test results due to the variation in physical parameters characteristics

2. To conduct experimental works of IPT on different types of polymer nanocomposite.

3. To compare the result of simulation works and experimental work with references of IPT test.

1.4 Scope of the Research

This research was conducted in the Institute of High Voltage and High Current (IVAT), Universiti Teknologi Malaysia (UTM) and the research focuses on using

a) IEC 60587 standard was used as references to both Inclined-Plane Tracking test and field simulation using Finite Element Analysis (FEA).

b) Linear Low Density Polyethylene(LLDPE) and Natural Rubber(NR) grade SMR 20 as base materials with the ratio composition of 80:20.

c) Nanofiller chosen which are Silicone Oxide (SiO2) and Aluminium hydroxide ($Al(OH)_3$) with 1wt %, 3wt %, 5wt % and 7wt % percentage content.

d) The finite element software of Quickfield in field simulation analysis.

1.5 Significance of the Research

The implementation of polymer nanocomposites in high voltage insulation stimulates the study on material properties. Solid dielectric materials during a breakdown will cause permanent alteration of its structure. There are various mechanisms that cause a breakdown to occur under high electrical stresses. Some of them are the intrinsic or ionic breakdown, electromechanical breakdown, treeing, tracking, thermal breakdown, electromechanical breakdown, and internal discharges [9]. The focus on this research is the breakdown as a result of electrical tracking due to surface discharge on insulator surfaces. The investigation into the tracking effect using experimental test was conducted the most by researchers in this field [10, 11]. From the experimental test, the factors that contribute to the tracking formation have been examined closely to be implemented into field simulation study.

In this study, the characteristics of IPT test results of a variation in physical parameters have been applied for simulation analysis using the Finite Element Software. The different nanofiller loadings in the LLPE-NR compounding in the field simulation are set according to their values of electrical conductivity and relative permittivity. Meanwhile, applied voltage and conductivity of the contaminant flow rate was used as the variable parameters in the field simulation due to the respect of changing applied voltage and contaminant flow rate in the IPT test. The results of the experimental work on the IPT and simulation analysis in terms of LC has been studied under various conditions in finding the correlation.

The field simulation is a non-destructive test and successful demonstration of the analysis and could act as another option to investigate surface discharge in the materials under the tracking effect. Thus, the field simulation analysis can be practice as mean to study the material in an indication of tracking and erosion resistance by studying the LC as from the experimental study the relationship of LC effect with the physical visuals such as tracking marks, erosion depth and erosion mass can be used to evaluate the tracking phase.

1.6 Thesis Organisation

The thesis is divided into five chapters. In chapter two, elaboration of literature review on topics of surface discharge, dry band arcing (DBA), inclined plane tracking (IPT), other tests to evaluate surface discharges, and field simulation consisting of finite element method (FEM) in high voltage test method application are explained.

Chapter three outlines the test methods used in the inclined plane tracking (IPT) test, hydrophobicity test and field simulation. The experimental setup, procedure and method of the experimental work and simulation work are expanded in detail in this chapter.

Chapter four presents the results from experiment and simulation works. The discussion of the result has been done in this chapter.

Lastly, chapter five concludes the research and gives some recommendations of future exploration.

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