# LEAKAGE CURRENT ANALYSIS OF SILICONE RUBBER FOR HIGH VOLTAGE INSULATION APPLICATION

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Faculty of Electrical Technology and Engineering

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**NORNAZURAH BINTI NAZIR ALI**

**A thesis submitted**
**in fulfilment of the requirements for the degree of**
**Doctor of Philosophy in Electrical Engineering**



**Faculty of Electrical Technology and Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2025**

# DECLARATION

I declare that this thesis entitled “Leakage Current Analysis of Silicone Rubber for High Voltage Insulation Application” 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

| | |
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## 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 Doctor of Philosophy in Electrical Engineering.

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# DEDICATION

To my beloved late father, *Nazir Ali Bin Shangkotti*. Though you are no longer with me in this life, your presence is still deeply felt in everything I do. Your strength, guidance, and wisdom continue to be my greatest inspiration. To my dearest mother, *Noor Begam Binti Mohd Said*. Thank you for always believing in me, even when the journey was uncertain. Your unconditional love, sacrifices, and steadfast encouragement have been the foundation of my perseverance. I am forever grateful.

## ABSTRACT

The study of Silicone Rubber (SiR) polymeric outdoor insulating materials primarily focuses on enhancing their performance against ageing, allowing these materials to achieve a longer lifespan. To develop an optimised outdoor insulating material, both the material composition and processing parameters are investigated using the Design of Experiment (DOE) approach via *Design Expert Software* of two-level full factorial analysis. This study consists of two stages: the first to identify the best SiR mix based on selected parameters, and the second to test it under different operating conditions. The first stage evaluates four factors affecting SiR performance : A) Alumina Trihydrate (ATH) filler loading, B) Dicumyl peroxide (DCP) concentration, C) mixing speed, and D) mixing time, using leakage current (LC) as the performance indicator, based on Inclined Plane Tracking (IPT) test at 60 and 360 minutes as per BS EN IEC 60587:2022 standards. The data was collected using DAQ equipment and LabVIEW software, filtered in Python, and imported into *Design Expert* Software to analyse the influence of factors and their interrelations on LC values. Initially, at 60 minutes, the interrelation factor of AB had the most significant impact on LC, but by the end of the test at 360 minutes, factor A was deduced as the dominant factor. Next, the optimised SiR blend with the lowest LC (0.690588 mA) at 360 minutes was found, which is Sample 5, consisting of 50 pphr of ATH, 0.5 pphr of DCP, a mixing speed of 70 rpm, and a mixing time of 10 minutes, with desirability of 1 and a good Capability Process Index (Cpk) of 2.14, ensuring the quality and consistency of the samples' reproducibility in manufacturing. To support these findings, additional analyses were conducted, including weight loss evaluation, mechanical testing of tensile strength, morphological examination via Scanning Electron Microscopy (SEM), and chemical characterization through Fourier Transform Infrared Spectroscopy (FTIR).The optimised sample showed the lowest LC, high tensile strength, and smaller FTIR peak changes after the IPT test compared to other samples. The surface image analysis using SEM revealed a distinct impact of ageing, which was particularly severe for samples with the lowest ATH and highest LC values. The optimised blend was then replicated for further analysis in the second stage, and the focus now shifts to identifying the endurance and performance of the optimised sample under several critical factors during SiR degradation, again under the IPT test. This time, the factors were set to A) voltage, B) contaminant flow rate, and C) contaminant concentration. The interrelations between the factors and their influence on SiR's LC values and the maximum withstandable LC of optimised SiR sample were discovered. In both periods of 60 and 360 minutes, factor C emerged as the most significant, followed by B and A. The maximum LC values that the optimised samples could withstand under various circumstances were also determined, and it was found that even when all factors were set to their maximum, the LC remained below 60 mA, in line with the standard requirements. In conclusion, the statistical analysis demonstrates that it is possible to optimise SiR to achieve excellent electrical, physical, mechanical, and chemical properties by adjusting material composition and processing parameters. The findings also revealed the interrelation between various factors and their impact on SiR performance, allowing for future adjustments to achieve a desired SiR with a specific LC output.

***ANALISIS ARUS BOCOR GETAH SILIKONE UNTUK APLIKASI PENEBATAN VOLTAN TINGGI***

## *ABSTRAK*

*Kajian terhadap bahan penebat luar Getah Silikone (SiR) polimer tertumpu kepada usaha meningkatkan prestasinya terhadap penuaan bagi membolehkan bahan ini mencapai jangka hayat yang lebih panjang. Bagi membangunkan bahan penebat luar yang optimum, kedua-dua komposisi bahan dan parameter pemprosesan telah dikaji menggunakan pendekatan Reka Bentuk Eksperimen (DOE) melalui perisian Design Expert dengan analisis faktorial penuh dua tahap. Kajian ini terdiri daripada dua peringkat: peringkat pertama bertujuan mengenal pasti campuran SiR terbaik berdasarkan parameter yang dipilih, manakala peringkat kedua menguji campuran tersebut di bawah pelbagai keadaan operasi. Peringkat pertama menilai empat faktor yang mempengaruhi prestasi SiR, iaitu: A) kandungan pengisi Alumina Trihydrate (ATH), B) kepekatan Dicumyl Peroxide (DCP), C) kelajuan pengadunan, dan D) masa pengadunan, dengan menggunakan arus bocor (LC) sebagai penunjuk prestasi berdasarkan ujian Penjejakan Satah Condong (IPT) selama 60 dan 360 minit mengikut piawaian BS EN IEC 60587:2022. Data dikumpul menggunakan peralatan DAQ dan perisian LabVIEW, ditapis menggunakan Python, dan dianalisis menggunakan perisian Design Expert bagi menilai pengaruh faktor dan interaksinya terhadap nilai LC. Pada awal ujian (60 minit), faktor interaksi AB memberikan kesan paling ketara terhadap LC, namun pada akhir ujian (360 minit), faktor A dikenalpasti sebagai faktor dominan. Seterusnya, campuran SiR optimum dengan nilai LC paling rendah (0.690588 mA) pada 360 minit telah dikenal pasti, iaitu Sampel 5 yang mengandungi 50 pphr ATH, 0.5 pphr DCP, kelajuan pengadunan 70 rpm, dan masa pengadunan 10 minit, dengan kebolehinginan bernilai 1 dan Indeks Proses Keupayaan (Cpk) yang baik sebanyak 2.14, yang memastikan kualiti dan kebolehulangan penghasilan sampel dalam proses pembuatan. Bagi menyokong penemuan ini, beberapa analisis tambahan telah dijalankan termasuk penilaian kehilangan berat, ujian mekanikal (kekuatan tegangan), pemeriksaan morfologi menggunakan Imbasan Mikroskop Elektron (SEM), dan pencirian kimia menggunakan Spektroskopi Transformasian Fourier Inframerah (FTIR). Sampel optimum menunjukkan LC paling rendah, kekuatan tegangan yang tinggi dan perubahan puncak FTIR yang lebih kecil selepas ujian IPT berbanding sampel lain. Analisis permukaan menggunakan SEM menunjukkan kesan penuaan yang ketara, khususnya pada sampel yang mempunyai kandungan ATH paling rendah dan nilai LC tertinggi. Campuran optimum ini kemudiannya dihasilkan semula untuk analisis lanjut dalam peringkat kedua yang menumpukan kepada penilaian ketahanan dan prestasi di bawah beberapa faktor kritikal semasa degradasi SiR, sekali lagi menggunakan ujian IPT. Kali ini, faktor yang dikaji ialah A) voltan, B) kadar aliran bahan kontaminasi, dan C) kepekatan bahan kontaminasi. Hubungan antara faktor dan pengaruhnya terhadap nilai LC serta nilai maksimum LC yang boleh ditahan oleh sampel optimum telah dikenal pasti. Dalam kedua-dua tempoh ujian 60 dan 360 minit, faktor C didapati paling signifikan, diikuti oleh B dan A. Nilai maksimum LC yang dapat ditahan oleh sampel optimum di bawah pelbagai keadaan turut ditentukan, dan didapati bahawa walaupun semua faktor berada pada tahap maksimum, nilai LC kekal di bawah 60 mA, selaras dengan keperluan piawaian. Sebagai kesimpulan, analisis statistik membuktikan bahawa bahan SiR boleh dioptimumkan untuk mencapai sifat elektrik, fizikal, mekanikal dan kimia yang sangat baik dengan pengubahan komposisi bahan dan parameter pemprosesan.*

*Penemuan ini turut mendedahkan hubungan antara pelbagai faktor dan kesannya terhadap prestasi SiR, membolehkan pengubahan pada masa hadapan untuk mencapai bahan SiR dengan keluaran LC yang dikehendaki..*

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## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF APPENDICES

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| ASTM | - | American Society for Testing and Materials |
| ATH | - | Aluminium Trihydrate |
| DAQ | - | Data Acquisition |
| DCP | - | Dicumyl Peroxide |
| DOE | - | Design of Experiments |
| EPDM | - | Ethylene-Propylene-Diene Rubber |
| FFT | - | Fast Fourier Transform |
| FTIR | - | Fourier Transform Infrared Spectroscopy |
| IPT | - | Inclined Plane Tracking |
| LC | - | Leakage Current |
| NR | - | Natural Rubber |
| OVAT | - | One Variable At a Time |
| Pphr | - | Parts Per Hundred Rubber |
| Rpm | - | Revolutions Per Minute |
| SEM | - | Scanning Electron Microscope |
| SiR | - | Silicone Rubber |
| THD | - | Total Harmonic Distortion |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| % | - | Percentage |
| A | - | Ampere |
| $Al_2O_3$ | - | Aluminium Oxide |
| cm | - | centimetre |
| g | - | gram |
| $g/cm^3$ | - | gram per cubic centimetre |
| Hz | - | Hertz |
| $I_{rms}$ | - | root mean square current |
| kN | - | kilonewton |
| kV | - | kilovolt |
| kΩ | - | kiloohm |
| mA | - | miliampere |
| ml/min | - | millilitres per minute |
| mm | - | millimetre |
| MPa | - | megapascal |
| µA | - | microampere |
| µS/cm | - | microsiemens per centimetre |
| $SiO_2$ | - | Silica/ Silicone Dioxide |
| V | - | Volt |
| $V_{pp}$ | - | peak to peak voltage |
| $V_{rms}$ | - | root mean square voltage |
| Ω | - | Ohm |