UNIVERSITI PUTRA MALAYSIA

FLASHOVER CHARACTERISTICS OF BENTONITE CONTAMINATED INSULATION SURFACES UNDER HIGH VOLTAGE CONDITIONS

HALIMATUSAADIAH BINTI RUSLI

FLASHOVER CHARACTERISTICS OF BENTONITE CONTAMINATED INSULATION SURFACES UNDER HIGH VOLTAGE CONDITIONS

By

HALIMATUSAADIAH BINTI RUSLI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,

in Fulfilment of the Requirements for the Degree of Master of Science

April 2014

COPYRIGHT

Abstract of thesis presented to the Senate of Universiti Putra Malaysia
in fulfillment of the requirements for the degree of Master of Science

FLASHOVER CHARACTERISTICS OF BENTONITE CONTAMINATED INSULATION SURFACES UNDER HIGH VOLTAGE CONDITIONS

By

HALIMATUSAADIAH BINTI RUSLI

April 2014

Chairman : Chandima Gomes,PhD

Faculty : Engineering

Insulator contamination is a major problem that causes flashover that will make the insulator to deteriorate and age faster than usual. This may jeopardize the security of high voltage systems and lead to damage and economical losses to the client. A number of investigations on insulation contamination have been published and most of them focused on the effects of salt compounds whereas only few of them use other materials as the contaminant. For that reason, this study has been carried out with the view of addressing the influence of bentonite as the main source of artificial pollution contamination on outdoor insulation characteristics in a high voltage system. Bentonite is one example of a good backfill material that was widely used as a conductivity enhancing material for grounding systems. Bentonite was used to provide a low earth resistance in the grounding systems used in lightning protection, power and signal systems. However this compound is easily puffed off during unloading and mixing operations. Therefore as the grounding systems are installed in construction sites, there is a high chance that bentonite dust will be spread with air and settle on nearby insulator surfaces. Such contamination may provide low resistive path for leakage streamers along the insulation surfaces of HV systems that may result surface flashover. Depending on the frequency (number of events per unit time), current amplitude, adherence to the surface and other environmental effects such surface flashover may accelerate degradation of insulation materials.

Experiments have been carried out at high voltage laboratories in Universiti Putra Malaysia, Universiti Teknologi Malaysia and Tenaga Nasional Berhad Research to accomplish the objectives. Perspex, polyethylene and rubber insulator have been selected for impulse and alternating voltage testing under clean and bentonite-contaminated surface conditions. The withstand voltage ($V_{50\%}$), voltage at breakdown, time to breakdown (t_b) and the behaviour of arcing path of discharge channel were investigated and all the data gathered has been subjected to statistical analysis which includes paired t-test. The outcomes indicate that the presence of bentonite contaminants has changed the insulator characteristics in certain circumstances such as the effects on the voltage at breakdown (under negative polarity), the 50% breakdown voltage (under negative polarity), and the time to

breakdown (under wet condition for both negative and positive polarity) and also promote the adherence of arcing path to the insulator surface which could lead to fast surface degradation. Findings of this research may assist power engineers in improving the characteristics of outdoor insulation materials in the future.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Sarjana Sains

CIRI-CIRI PENEBAT DI BAWAH PENGARUH BENTONITE SEBAGAI BAHAN PENCEMAR

Oleh

HALIMATUSAADIAH BINTI RUSLI

April 2013

Pengerusi : Chandima Gomes, PhD

Fakulti : Kejuruteraan

Pencemaran penebat adalah masalah utama yang menyebabkan percikan kilat yang akan menyebabkan penebat merosot dan penuaan terjadi dengan lebih cepat daripada biasa. Ini boleh menjejaskan keselamatan sistem voltan tinggi dan membawa kepada kerosakan dan kerugian ekonomi kepada pelanggan. Beberapa kajian terhadap pencemaran penebat telah diterbitkan dan kebanyakan mereka memberi tumpuan kepada kesan sebatian garam sebagai pencemar sedangkan hanya beberapa daripada mereka menggunakan bahan-bahan lain sebagai bahan cemar. Atas sebab itu, kajian ini telah dijalankan dengan tujuan menyelidik pengaruh bentonite sebagai sumber utama pencemaran buatan keatas ciri-ciri penebat dalam sistem voltan tinggi. Bentonite adalah salah satu contoh bahan kambus balik yang baik yang telah digunakan secara meluas sebagai bahan meningkatkan kekonduksian untuk sistem pembumian. Bentonite digunakan untuk menghasilkan rintangan bumi yang rendah dalam sistem pembumian yang digunakan dalam perlindungan kilat, kuasa dan sistem isyarat. Walau bagaimanapun sebatian ini mudah meruap semasa operasi memunggah dan mencampur. Oleh itu sekiranya sistem pembumian sedang dipasang di tapak pembinaan, terdapat peluang yang tinggi dimana debu bentonite akan merebak di udara dan mendarat pada permukaan penebat yang berhampiran. Pencemaran itu boleh menghasilkan jalan rintangan rendah untuk pita kebocoran di sepanjang permukaan penebat sistem voltan tinggi yang boleh menyebabkan percikkan kilat pada permukaan. Bergantung kepada kekerapan (bilangan acara setiap unit masa), amplitud semasa, pematuhan kepada permukaan dan kesan alam sekitar yang lain, percikkan kilat permukaan itu boleh mempercepatkan kemusnahan bahan penebat.

Eksperimen telah dijalankan di makmal-makmal voltan tinggi di Universiti Putra Malaysia, Universiti Teknologi Malaysia dan Tenaga Nasional Berhad Research untuk mencapai objektif tersebut. Perspex, polyethylene dan penebat getah telah dipilih untuk menjalani pengujian impuls dan voltan arus bolak balik di bawah keadaan permukaan bersih dan permukaan yang tercemar dengan bentonite. Voltan

tahan percikkan kilat ($V_{50\%}$), voltan sewaktu percikkan kilat, masa sewaktu percikkan kilat (t_b) dan tingkah laku melengkung jalan saluran percikkan telah disiasat dan semua data yang dikumpul telah melalui analisis statistik yang termasuk ujian t-berpasangan. Hasil menunjukkan bahawa kehadiran bahan cemar bentonit telah mengubah ciri-ciri penebat dalam keadaan tertentu seperti kesan pada voltan sewaktu percikkan kilat (di bawah kutub negatif), voltan tahan percikkan kilat, $V_{50\%}$ (di bawah kutub negatif), dan masa sewaktu percikkan kilat (di bawah keadaan basah untuk kutub negatif and kutub positif) dan juga menggalakkan jalan saluran percikkan kilat melalui diatas permukaan penebat yang boleh membawa kepada kemusnahan permukaan cepat. Hasil kajian ini boleh membantu jurutera kuasa dalam meningkatkan ciri-ciri bahan penebat luar di masa akan datang.

ACKNOWLEDGEMENTS

Firstly all praises are due to Allah S.W.T, thanks for giving me strength and knowledge to finish my final year project. I would like to take this opportunity to express my deepest gratitude to my project supervisor, Prof. Dr. Chandima Gomes who has assisted me persistently and determinedly. All your guidance, encouragement and advices will always be remembered.

I wish to express my warm and sincere thanks to co-supervisor Prof. Ir. Dr. Mohd Zainal Abidin b. Ab. Kadir for sharing his knowledge, judgment and also for giving his time to coordinate and examine my project.

I have been very fortunate to work with Ghasem Nourirad**,** Siow Chun Lim and all people in completing the experiment. In addition, I would like to thank IVAT and TNBR staffs for their supports and assistance.

My loving thanks to my family for their greatest support, motivation and love in the completion of this project. Last but not least, a bunch of thanks to all my friends and those who are involved directly or indirectly in helping me to complete this project for all their kindly support, assistance and suggestions.

I certify that a Thesis Examination Committee has met on 29th April 2014 to conduct the final examination of Halimatusaadiah binti Rusli on her thesis entitled " Flashover Characteristics of Bentonite Contaminated Insulation Surface Under High Voltage Conditions" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the relevant degree of Master of Science.

Members of the Thesis Examination Committee were as follows:

Dr. Maryam M Isa, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Dr. Hashim b. Hizam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Dr. Noor Izzri b. Abdul Wahab, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Dr. Zulkurnain. B. Abdul Malek, PhD
Associate Professor
Institute of High Voltage and High Current (IVAT)
Universiti Teknologi Malaysia
Malaysia
(External Examiner)

NORITAH OMAR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 23 June 2014

This thesis was submitted to senate of Universiti Putra Malaysia and has been accepted as fulfilment of requirement for degree of Master of Science. The members of the Supervisory Committee were as follows:

Chandima Gomes, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Zainal Abidin Ab Kadir, PhD
Ir, Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: ___________________

Name and Matric No.: ____

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____________________
Name of
Chairman of
Supervisory
Committee: ____________________

Signature: ____________________
Name of
Member of
Supervisory
Committee: ______________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Δv	Potential Differential
μs	Micro Second
A	Cross Sectional Area
A.V.	Alternating Voltage
BIL	Basic Impulse Insulation Level
CI	Confidence level
DC	Direct Current
HV	High Voltage
Hz	Hertz frequency
IEC	International Electrotechnical Committee
kV	Kilo Volt
l	Length
LMW	Low Molecular Weight
$NaCl$	Sodium
R	Resistance
s	Standard Deviation
SLR	Single-lens Reflex Camera
t_b	Time to Breakdown
TNB	Tenaga Nasional Berhad
U.S	United States
UV	Ultraviolet
V	Voltage
v_0	Initial Voltage
$V_{50\%}$	Flashover Voltage
V_b	Breakdown Voltage
ρ	Resistivity

CHAPTER 1

INTRODUCTION

1.1 Research Background

In recent years, the demand for electricity has increased tremendously the world over. This is due to economic growth especially in the industrial sector and thus the growth of high voltage transmission lines has also increased every year [1, 2]. It is important for the electrical supply companies to ensure the reliability and efficiency of their system, especially to protect against any faults that could cause damage and consequently economic loss for the client. To ensure the quality, reliability and adequate supply of electricity for consumers, the insulator coordination must be seriously taken into account. A stable system should have a proper insulation level system in order to avoid the probability of switching and dynamic overvoltages and also flashover of the insulator under normal or even polluted conditions [3].

Many studies have been undertaken to review insulation coordination and the outcome has led to various shade shape types and new materials found in order to make a better and improved quality insulator [4, 5]. Results from long term studies in insulation coordination of different shapes and materials of insulators have been designed to suit different geographical areas [6]. For example, polymeric insulators which are manufactured to endure contamination of their rubber housing are commonly used in polluted coastal areas while glass or ceramic are commonly used in hot areas that suffer high level of ultraviolet (*UV*) radiation [7].

Flashovers usually occur because of the insulation failure when an arc begins to propagate and ultimately bridges the insulator. The most common cause of insulation failure is the presence of discharge either within the voids in the insulation or over the surface of the insulation. However many parameters can influence the flashover characteristics. For example the environmental or weather conditions of the system that can lead to a degree of pollution of the insulators. This pollution is one of the main causes of flashover of electric lines. The pollution mechanically degrades the insulators and affects some of the electrical and mechanical characteristics of the insulating material.

Figure 1.1. Appearance of water presence on bare and RTV-coated porcelain insulators contaminated with cement [4].

Flashover due to contamination is a major problem for outdoor insulators in most countries especially in the U.S. Midwest region, pacific coast region, the coastal area of the southern region and localized areas in other regions [8]. This is because contamination is one of the most severe causes of promoting corona and arcing activity. An insulator begins to fail when contamination dust starts to land on the surface area of the insulator and combines with the other weather conditions such as fog, rain or dew. When the content of the contamination compound combines with water vapour at high relative humidity, it will form a conductive layer that allows a large current to pass through the insulator like a short circuit path. This is due to the decrease in resistance of the contamination path, thus leading to faster degradation and ageing [7].

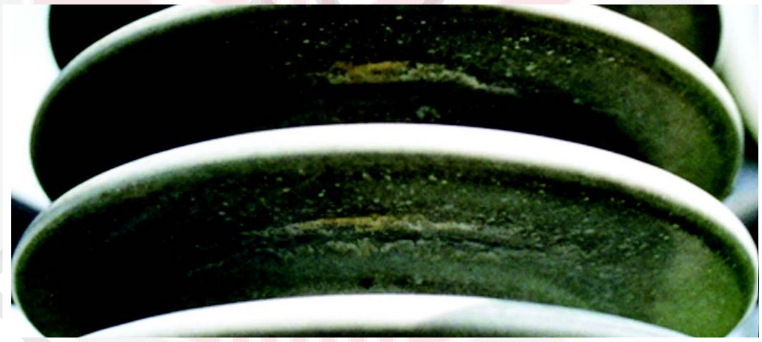

Figure 1.2. Surface of semi-conducting glazed insulator after one year long exposure to DC voltage in a marine environment [4]

Since contamination cannot be avoided in some circumstances especially near coastal, industrial, mining areas or construction sites, it is important to investigate the characteristics of contamination depositions on transmission line insulators for a better understanding of their influence.

1.2 Problem Statement

Insulator failure due to surface flashover is well known. This has led to numerous research studies over the last 50 years aimed at determining the cause that leads to flashover breakdown. One of the common reasons has been determined as the build-up of contaminants on the insulator surfaces [9].

Many contaminant types can be identified in both natural and industrial environments. The contaminants encountered by a material depend on its environment. For examples, insulators near coastal regions will accumulate heavy salt deposition whereas insulator at high altitude will encounter deposition or accumulation of ice and snow [7, 10, 11, 12]. Industrial areas generate various types of pollutants such as industrial dust, smoke, fiber suspensions, cement particles, various powders and aerosols which will land on electrical systems in the vicinity and in turn may provoke undesirable outcomes [13, 14]. Insulators placed in forests, near water masses and damp environments may gather various biological growth such moth, fungae, algae etc. [15, 16].

A number of investigations on insulation contaminants have been undertaken and published [10, 17, 18] whereby the majority looked into salts as the main artificial pollutant in order to study the performance characteristics of real insulators. However, other types of pollution also have been taken into consideration in several studies. For example soluble types of contaminant such as sugar, lime, etc. and non-soluble contaminants such as kaolin, cement, etc. [19, 20, 21].

In this research, a non-soluble type of pollutant, bentonite, is selected as the main source of artificial pollution. Several tests are conducted to determine the influence of this type of pollution constituent in terms of the insulator flashover characteristics such as voltage at breakdown, 50% breakdown voltage, and time to breakdown. Bentonite is chosen due to the abrupt increase in its usage in modern applications [22], especially in grounding systems. To date, numerous research studies have been conducted concerning the effectiveness of bentonite as a backfill material [23, 24, 25]. Due to its low resistivity, this material has become widely used as a conductivity enhancing material for grounding systems. However this compound is easily puffed off during unloading and mixing operations. Therefore as the grounding systems are installed in a construction site, there is a high chance that bentonite dust will contaminate the air and settle on any nearby insulator surface. No extensive study has been undertaken with regard to the effect of bentonite contamination on surface flashover insulators under impulse and alternating voltage conditions. Hence this research has been tasked to fulfil this requirement.

1.3 Research Aim and Objectives

A number of investigations on the behaviour of bentonite have been published but none of these were conducted from the point of view of being a contaminating material for outdoor insulation. In order to investigate the characteristics of an insulator in the presence of bentonite dust, laboratory tests are conducted under high voltage conditions. This research is aimed at:

1. To investigate the 50% breakdown voltage of flashover, voltage at breakdown, and time to breakdown of bentonite-contaminated insulators, under impulse conditions.

2. To investigate the breakdown voltage bentonite-contaminated insulators, under alternating voltage conditions.

3. To find the arc path of the surface flashover.

1.4 Scope of the Work

In order to achieve the objectives, the scope has been outlined to ensure that the project is conducted within its intended boundaries. Impulse test are completed in the Universiti Teknologi Malaysia Institute of High Voltage and High Current (IVAT) laboratory at Skudai, Johor, Malaysia where a Marx generator of 1.5 MV was used to generate the lightning impulse voltage. Meanwhile alternating voltage test is done in the Tenaga Nasional Berhad Research (TNBR) centre. The preliminary study in this regard has been completed in the Universiti Putra Malaysia High Voltage laboratory in order to test the hypothesis, to gain basic knowledge and to develop the design setup to be constructed in these experiments.

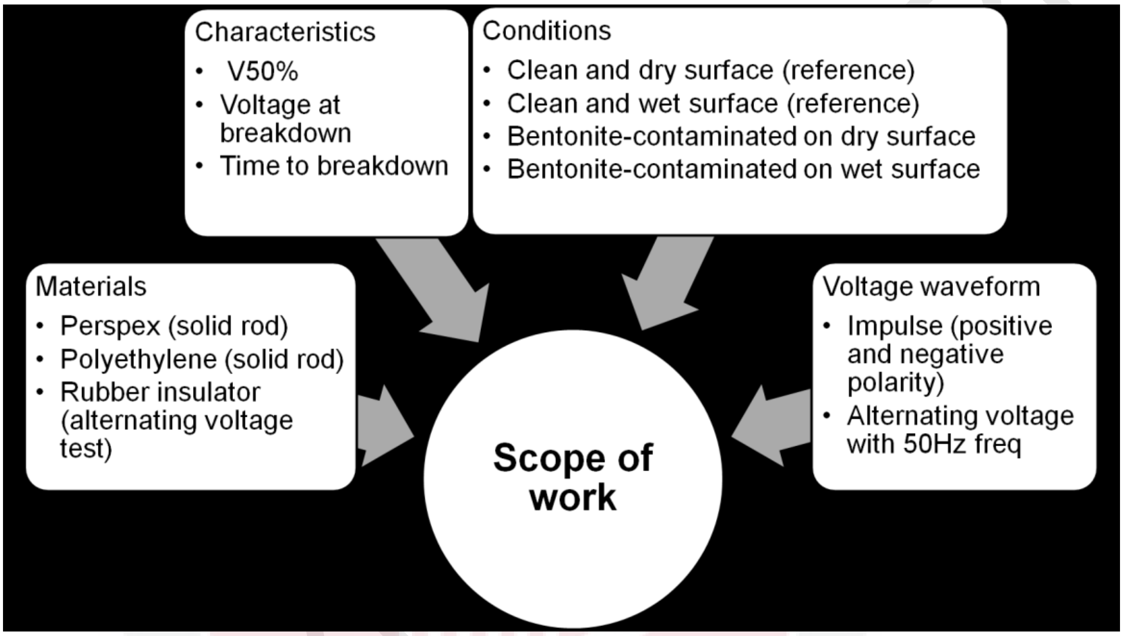

Figure 1.3. Scope of work

This project will review the performance of three different insulator sample materials, namely perspex, polyethylene and rubber (commercially used insulator) which are selected based on the reference from previous research [26]. The examination of characteristics of insulators includes the voltage at breakdown, 50% breakdown voltage and time to breakdown.

In order to study the effect of bentonite-contaminant, four conditions are considered throughout the experiments:

1. Dry and clean insulators surface (as reference)

2. Wet and clean insulators surface (as reference)

3. Dry and bentonite-contaminated insulators surface

4. Wet and bentonite-contaminated insulators surface

1.5 The Importance of the Research

In Malaysia, there are numerous sites where different types of pollution are released in various environments and cause quite a challenge when it comes to the performance of electrical insulation, especially in transmission and distribution systems. TNB Division Perak, Paka Thermal Power Station, YTL Pasir Gudang Power Station for example encounters coastal pollution as the system lines in part pass along coastal regions [27, 28, 29, 30]. In addition, today construction sites and even industrial zones increase their activities year by year that results in them becoming the main source of air pollution due to aerosols. Thus high voltage insulators in the vicinity will collect the particles whereby some of these particles such as salt, sand, cement, dust etc. can be significantly conducting once dissolved in rain water.

The condition become worse if there is a lightning strike or a high average of rain fall such as that often occurs in Malaysia. TNB Research has determined that the major problem faced by the lines is due to lightning strikes [31]. Referring to Figure 1.4 below, data from the Meteorological Department indicate that Malaysia has a high number of lightning strikes which may go up to even 200 lightning days per year (well above the world average of 28 days a year).

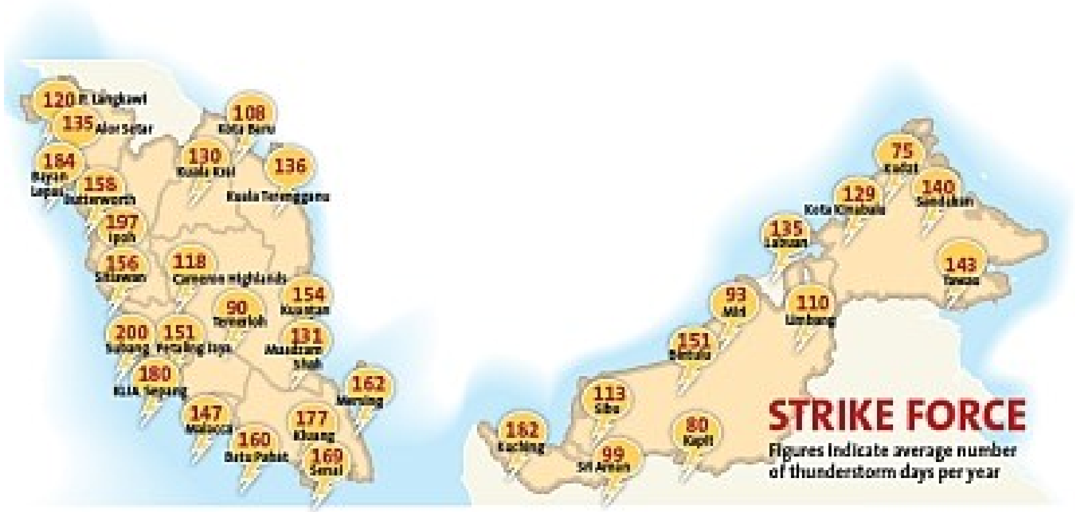

Figure 1.4. Observation of thunderstorm days per year at selected cities throughout Malaysia [32]

In other words, pollution can affect the characteristics of an insulator and thus degrade the insulator faster than that without pollution. Therefore electrical supply companies should be alerted about their surroundings and to act preventing the interruptions caused by faulty operations of the insulators. Pollution control is achieved mainly by (i) analyzing the severity of the pollution; (ii) controlling the situation of the pollution on the insulator; (iii) comparing the behaviour of different designs of insulators [7].

In order to avoid losses from pollution influenced flashover of an insulator, an experimental test by using artificial pollution can be done to study the external properties of the insulator. In this paper, the impulse and A.V. flashover performance of different types of materials is investigated and the results analysed for different flashover voltages and the discharge channels. The results of this research may assist as a reference for power engineering applications in the future.

1.6. Thesis Organization

This chapter presents the introduction to the research, the objectives targeted for this research, the significance of the research which is related to the investigated problem as well as the scope and finally an overview of the structure of this thesis.

Chapter two discusses the literature review of this project which comprises of pollution flashover mechanism, insulation characteristics, type of pollution, and application of bentonite in electrical systems.

Chapter three elaborates the experimental framework. It starts with the development of the experimental setup, the type of test and analysis that will be done and the parameter that will be taken into account.

Chapter four discusses the final results of the research. The results obtained from the analysis in term of voltage at breakdown, 50% breakdown voltage and time to breakdown will be analysed. This chapter will also review the obtained results in the context of a comparison of previous researcher.

Finally, chapter five concludes on the findings and objectives of the project related to flashover characteristics of contaminated insulators. At the end of this chapter recommendations are put forth for the future research work for modelling purpose.

REFERENCES

Ahmad Rafdi Endut and Idris Jajri, “Analysis of Residential Electricity Consumption: Is Reform Needed?” . Retrieved from www.uniten.edu.my/newhome/uploaded/admin/research/centres/oepre/papers 2014

“Energy Cost on the Rise; Demand for electricity is also steadily increasing”. Retrieve from

http://www.singingriver.com/Document/smepa_insert_august08.pdf. 2014

“Extra High Voltage AC Transmission Engineering”, Rakosh Das Begamudre, New Age International publisher. 3rd Edition, pp. 236-258.

S. M. Gubanski, "Modern Outdoor Insulation—Concerns and Challenges", *IEEE Electrical Insulation Magazine,* Vol. 21, No. 6, pp.5-11, November/December 2005.

H. Ye, J. Zhang, Y. M. Ji, W. Y. Sun, K. Kondo and T. Imakoma, "Contamination Accumulation and Withstand Voltage Characteristics Various Type of Insulators", *7th International Conference on Properties and Application of Dielectric Materials*, June 2003.

IEC 60815-2: Selection and Dimensioning of High Voltage Insulators intended for use in Polluted Conditions, Part 2: Ceramic and glass insulators for a.c. systems.

Ramos Hernanz, Jose A., Campayo Martin, Jose J, Motrico Gogeascoechea, Joseba, Zamora Belver, Inmaculada, "Insulator pollution in transmission lines". Retrieved from http://www.icrepq.com/icrepq06/256-hernanz.pdf. 2013

IEEE Committee Report, "A survey of the problem of insulator contamination in the United States and Canada-II", *IEEE Trans. Power App. Syst.,* vol. PAS-91, no. 5, pp. 1948-1954, Sept./Oct. 1972.

“Electric Power Generation Transmission and Distribution”, Leonard L. Grigsby, CRC press Taylor and Francis Group, 3rd Edition, pp 11-20, 2012.

Kazuhiko Takasu, Takatoshi Shindo and Noboru Arai, "Natural Contamination Test of Insulators with DC Voltage Energization at Inland Areas", *IEEE Transaction on Power Delivery,* Vol. 3, No. 4, pp. 1847-1853, Oct. 1988.

Ahmad S. Ahmad, Hussein Ahmad, Razali b. Jidin, T. Tamsir, S. Shahnawaz Ahmed and Z. Buntat, "Contamination of High Voltage Insulator in the East Coast of Peninsular Malaysia", *IEEE Power System Technology, Proceedings. PowerCon,* Vol.3, pp.1223-1228, Dec. 2000.

Huafeng Su, Zhidong Jia, Zhenting Sun and Zhicheng Guan," Field and Laboratory Test of Insulator Flashover under Conditions of Light Ice Accumulation and Contamination", *IEEE Transaction on Dielectric and*

Electrical Insulation, Vol. 19, No. 5, pp. 1681-1689, Oct. 2012.

Hongwei Mei, Liming Wang and Zhicheng Guan," Influence of Sugar as a Contaminant on Outdoor Insulation Characteristics of Insulators in a Substation", *IEEE Transaction on Dielectric and Electrical Insulation,* Vol. 19, No. 4, pp. 1318-1324, Aug. 2012.

X. Lin, Z. Chen , X. Liu, K. Morita, R. Matsuoka and S. Ito,"Natural Insulator Contamination Test Results on Various Shed Shapes in Heavy Industrial Contamination Area", *IEEE Transaction on Electrical Insulation,* Vol. 27, No. 3, pp. 593-600, June 1992.

S.M. Gubanski , A. Demfalk , S. WallstrOm and S. Karlsson, "Performance and Diagnostics of Biologically Contaminated Insulators", *Properties and applications of Dielectric Materials,* Vol.8, pp.23-30, June 2006.

Jing Wang, S.M. Gubanski, J. Blennow, Sevil Atarijabarzadeh, Emma Stronberg and Sigbritt Karlsson, " Influence of Biofilm Contamination on Electrical Performance of Silicon Rubber Based Composite Materials", *Dielectrics and Electrical Insulation, IEEE Transactions,* Vol.19, pp. 1690–1699, Oct 2012.

R. S. Gorur, S. Sundhara Rajan and O. G. Amburgey, "Contamination Performance of Polymeric Insulating Materials Used for Outdoor Insulation Applications", *IEEE Transaction on Electrical Insulation*, Vol. 24, No. 4, pp. 713-716, Aug. 1989.

B. F. Hampton," Flashover mechanism of polluted insulation", IEEE Transaction on Electronic and Power, April 1964.

R. Sundararajan and R. S. Gorur, "Role of Non-soluble Contaminants on the Flashover Voltage of Porcelain Insulators", *IEEE Transaction on Dielectrics and Electrical Insulation,* Vol. 3, No. 1, pp. 113-118, Feb. 1996.

M. El-A. Slama, A. Beroual and H. Hadi, "Influence ofPollution Constituents on DC Flashover of High Voltage Insulators", *IEEE Transaction on Dielectrics and Electrical Insulation,* Vol. 20, No. 2, pp. 401-408, April 2013.

K. C. Holte, J. H. Kim, T. C. Cheng, Y.B. Kim and Y.Nitta, "Dependence of Flashover Voltage on the Chemical Composition of Multi-component Insulator Surface Contaminants", *IEEE Transaction on Power Apparatus and System,* Vol. PAS-95, No. 2, pp. 603-609, April 1976.

Arthur G. Clem and Robert W. Doehler, "Industrial application of Bentonite", Tenth National Conference on Clays and Clays Minerals, pp.272-283, 2010.

M. B. Kostic, Z. R. Radakovic, N. S. Radovanovic, M. R. Tomasevic-Canovic, "Improvement of Electrical Properties of Grounding Loops by using Bentonite and Waste Drilling Mud", *IEE Proc-Gener. Transm. Distrib.,* Vol. 146, pp. 1-6, Jan. 1999.

Warren R. Jones, "Bentonite Rods Assure ground Rod Installation in Problem

Soils", *IEEE Transaction on Power Apparatus and System,* Vol. PAS-99, No. 4, pp. 1343-1346, July 1980.

Z. R. Radakovic and M. B. Kostic, "Behaviour of Grounding Loop with Bentonite during a Ground Fault at an Overhead Line Tower", IEE Proc-Gener. Transm. Distrib., Vol. 4, pp. 275-278, July 2001.

Chandima Gomes, Vernon Cooray, Mahbubur Rahman, " BreakdownCharacteristics and Optically Visible Discharge Path of Surface Flashover", *IEEE Conference on Sustainable Utilization and Developement in Engineering and Technology*, pp. 111-116, Oct. 2012.

Md. Abdus Salam, Hussein Ahmad, Syed Ahmad Fuad, Ahmad S. Ahmad and Tarmidi Tamsir, "Development of Mathematical Relation between ESDD and Wind Velocity for a Contaminated Insulator in Malaysia", *International Conference on Properties and Application of Dielectric Materials,* June 2000

Ahmad S. Ahmad and Saad Ahmed, "Analytical Assessment of Industrial Contamination Level on Outdoor High Voltage Insulators at Western Region of Peninsular Malaysia", *International Conference on Intelligent and Advance System,* pp. 934–938, Nov. 2007.

Ahmad S. Ahmad, Hussein Ahmad and Md. Abdus Salam, "Sea Salt Contamination Pattern on High Voltage Insulators In Littoral Region of Peninsular Malaysia", Conference on Electrical Insulation and Dielectric Phenomena, Vol.2, pp. 670 – 673, Oct. 1999.

Ahmad S. Ahmad, Hussein Ahmad, Md. Abdus Salam, T. Tamsir, Z. Buntat, M. W. Mustafa, "Prediction of Salt Contamination on High Voltage Insulators in Rainy Season Using Regression Technique", IEEE *TENCON,* Vol. 3, pp. 184-189, Sept 2000.

A.A.M. Zin and S.P.A. Karim, "The Application of Fault Signature Analysis in Tenaga Nasional Berhad Malaysia", *IEEE Trans. on Power Delivery,* Vol. 22, No.4, pp 2047-2056, 2007.

A. Sia and E. Tai. Land of lightning. *The Star Online*. Retrieved May 17, 2009 from http://thestar.com.my/lifestyle/story.asp?file=/2009/5/17/lifefocus/3895023&sec=lifefocus. 2009

A. C. Baker, M. Farzaneh, R. S. Gorur, S. M. Gubanski, R. J. Hill, G.G. Karady and H. M. Schneider," Insulator Selection for AC Overhead Lines with respect to Contamination", *IEEE Transaction on Power Delivery,* vol. 24, no. 3, July 2009.

Wilhelm H. Schwardt, Jacobus P. Holtzhausen and Wallace L. Vosloo, "A Comparison Between Measured Leakage Current and Surface Conductivity During Salt Fog Test", *IEEE AFRICON, Conference in Africa,* Vol.1, pp. 597-600, Sept. 2004.

Muhsin Tunay Gencoglu and Mehmet Cebeci, "The pollution flashover on high voltage insulators", *Electrical Power System Research 78,* pp. 1914-1921, 2008.

NGK Insulators, LTD. Retrieved from www.ngk.co.jp/english/products/power/technical/anti/anti.html. 2013.

Jing Wang, Xi-dong Liang, Lin-hua Chen and Yu Liu, "Combined Effect of Different Fields on the Motion Characteristics of Dust Particles Around the Insulators", *Electrical Insulation and Dielectric Phenomena (CEIDP),* pp. 373 – 376, Oct, 2011.

F. Zedan and M. Akbar, "Performance of HV Transmission Line Insulator in Desert Conditions", *IEEE Transaction on Power Delivery,* Vol. 6, No.1, pp. 439-447, Jan, 1991.

Zheng J. C., Wang Z. And Liu Y. W., "Influence of Humidity on Flashover in Air in the Presence of Dielectric Surface", *Proceedings of IEEE Conference Region 10 on Computer, Communication, Control and Power Engineering, TENCON' 93,* pp. 443-449, 1993.

Lin Yang, Yanpeng Hao, Licheng Li and Yuming Zhao,"Comparison of Pollution Flashover Performance of Porcelain Long Rod, Disc Type, and Composite UHVDC Insulator at High Altitudes", *IEEE Transaction on Dielectric and Electrical Insulation,* Vol. 19, No. 3, pp. 1053-1059, June 2012.

Zhang Renyu and Zheng Jianchao," Progress in Outdoor Insulation Research in China", *IEEE Transaction on Electrical Insulation,* Vol. 25, No. 6, pp. 1125-1137, Dec. 1990.

Liu Xianggheng and Bai Jianqun," Selection on Insulation Level of HVAC Power Lines of Operating in High Altitude Polluted Area", *Proceedings of the Second IEEE International Conference on Properties and Applications of Dielectric Materials,* Vol.1, pp.268-271, 1988.

Fochi Wang, Chengrong Li, Yuqian Zhao, Yongjiang Bi, Bo Zhang, "The characteristic of concrete polluted composite insulators", *Properties and Applications of Dielectric Materials. ICPADM*, pp. 146-149, 2009.

Zhicheng GUAN, Kang Niu, Gongmao Peng, Fuzeng Zhang, Liming WANG and Bernhard Lutz, "Hydrophobicity Transfer Property of Silicone Rubber Material", *International journal of Electrical Engineering and Informatics,* Vol. 4, No. 2, July 2012.

D. Koenig, "Surface and Ageing Phenomena on Organic Insulation Under the Condition of Light Contamination and High Electric Stress", *NORDIS,* pp. 17-35, June 1994.

Michael G. Danikas, Ramanujam Sarathi, Pavlos Ramnalis and Stefanos L. Nalmpantis, "Analysis of Polymer Surface Modifications due to Discharge Initiated by Water Droplets under High Electric Fields", *World Academy of science, Engineering and Technology,* Vol. 26, 2009.

Konstantinos Karakoulidis, Michael G. Danikas and Paschalis Rakitzis, "Deterioration Phenomena on polymeric Insulating Surface due to Water Droplet", *Journal of Electrical Engineering,* Vol. 56, No. 7-7, pp. 169-175, 2005.

E. A. Cherney, "RTV Silicon - A High Tech Solution for a Dirty Insulator Problem", *IEEE Electrical Insulation Magazine,* 1995.

Ahmad S. Ahmad, Hussein Ahmad and Md. Abdus Salam, "Sea Salt Contamination Pattern on High Voltage Insulator In Littoral Region of Peninsular Malaysia", *Conference on Electrical Insulation and Dielectric Phenomena,* pp.670-673, 1999.

Wenjun Zhou, Ming Liu, Shinian Liu, Mengfei Peng, Jianhui Yu and Chengke Zhou, "On the Mechanism of Insulator Cleaning Using Dry Ice", *IEEE Transaction on Dielectric and Electrical Insulation,* Vol. 10, No. 5, October 2012.

W.A.V Weerawardena and H. M. Wijekoon, "Analysis of Transient Overvoltage in Medium Voltage Distribution Network of Ceylon Electricityboard", Sri Lanka

J. Brooks, "Guideline for Overhead Design", Network Lines Standards Manager, ERGON ENERGY, Ref. P56M02R09 Ver. 1.

T. C. Cheng and H. I. Nour, "A Study on the Profile of HVDC Insulators", *IEEE Transaction on Electrical Insulation, Vol. 24 No. 1,* February 1989.

Lin Xiaonan, Chen Zhongde, Liu Xinping, Chu Kuangyu, K. Morita, R. Matsuoka and S. Ito, "Natural Insulator Contamination Test Results on Various Shed Shapes in Heavy Industrial Contamination Area in Shanghai Under A.C. Energized and De-energized Conditions", *3rd International Conference on Properties and Application of Dielectric Materials*, pp. 961-964, July 1991.

H. Ye, J. Zhang, Y. M. Ji, W. Y. Sun, K. Kondo and T. Imakoma, "Contamination Accumulation and Withstand Voltage Characteristics Various Type of Insulators", *7^{th} International Conference on Properties and Application of Dielectric Materials*, June 2003.

IEC 60815-1: 2008 Selection and Dimensioning of High Voltage Insulators intended for use in Polluted Conditions, Part 1: Definitions, information and general principles.

S. Venkataraman and R. S. Gorur, "Prediction of flashover voltage of non-ceramic insulators under contaminated conditions", *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol.13, pp. 862-869, Aug, 2006.

R. Grim, and N. Guven, *Elsevier Science Publishing Co., Inc., New York, N.Y.* (1978).

Siow Chun Lim, Chandima Gomes and Mohd Zainal Abidin Ab Kadir, "Characterizing of Bentonite with Chemical, Physical and Electrical Perspectives for Improvement of Electrical Grounding Systems", *Int. J.*

Electrochem. Sci., Vol. 8, 2013.

"Volclay-Wyoming Bentonite", *Data no. 100, American Colloid Company, Skokie, IL*, pp. 12-13, 1970.

M.V Villar and A Lloret, *Applied Clay Science*, 26 (2004) 337.

Y.-H. Shen, Chemosphere 44 (5) (2001) 989.

W. R. Jones, *IEEE Transactions on Power Apparatus and Systems*, PAS-99 (1980) 1343.

A. R. Hileman, "Insulation Coordination for Power System". New York. *Marcel Dekker, Inc,* 1999.

Juan A. Martinez, and Ferley Castro-Aranda, "Tower modelling for lightning analysis of Overhead Transmission Lines", *IEEE Power Engineering Society General Meeting,* Vol. 2, pp.1212–12167, June, 2005.

C. Gomes, V. Cooray, F. Roman, L. Gao, M. Rahman, "Flashover paths and other characteristics of long gaps bridged by a dielectric surface", *Institute of High Voltage Research, Uppsala University, Sweden,* 1996.

L. Gao, C. Gomes, V. Cooray, F. Roman, "Comparison of long sparks in air and over an insulator surface", *Conference on High Voltage Engineeriing Symposium,* 22-27, August 1999.

IEC 60-1. International standard High Voltage Test Technique. Part 1: General definitions and test requirements. Second edition 1989-11. Second Impression 1991.

"Electrical Engineer's Reference Book", M. A. Laughton CEng., and D. J. Warne CEng, FIEE, 6th Edition, pg.982-1030, 2003.

Halimatusaadiah Binti Rusli, Chandima Gomes, and Zainal Kadir, "ARC-phobic and Other Characteristics of Surface Flashover", *Progress In Electromagnetics Research Symposium*, March 2012

Bingbing Dong, Xiangliang Jiang, Jianlin Hu, Linchun Shu and Caixin Sun, "Effects of Artificial Polluting Methods on AC Hlasover Voltage of Composite Insulators", *IEEE Transaction on Dielectrics and Electrical Insulation*, Vol.19, pp. 714-722, Apr. 2010.

MS IEC 60507:1991, "Artificial pollution tests on high-voltage insulators to be used on ac systems", 2010.

W. J. Dixon, "The Up-and-Down Method for Small Sample", *Journal of the American Statistical Association,* Vol. 60, No. 312, pp. 967-978, Dec. 1965.

Valerie J. Easton and John H. McColl. Statistic Glossary. Retrieved from www.stats.gla.ac.uk/steps/glossary/confidence_intervals.html. 2013

GraphPad Software. Retrieved from www.graphpad.com/guides/prism/6/statistic/index.htm?. 2013

Generalizing to a Population: Confidence Limits. Retrieved from www.sportsci.org/resource/stat/generalize.html. 2013

H. Woodson and A. McElroy, "Insulators with Contaminated Surfaces, Part II: Modeling of Discharge Mechanisms", *IEEE Transaction Power Apparatus and Systems, PAS-89,* pp. 1858-1867, Nov. 1970.

David C. Jolly, "Contamination Flashover, Part II: Flat Plate Model Tests", *IEEE Power Engineering Society,* pp. 2443- 2451, Nov. 1971.

B. K. Gautam, S. Matsumura, K. Sakanishi, R. Matsuoka and M. Ito, "Effect of core diameter of cylindrical polymer insulators on contamination flashover voltage – part I", *IEEE Transaction Electrical Electronic Engineering,* Vol. 1, pp. 298 – 305, 2006.

Chuyan Zhang, Liming Wang, Zhicheng Guan and Fuzeng Zhang, "Pollution Flashover Performance of Full-scale ±800 kV Converter Station Post Insulators at High Altitude Area", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 20, pp. 717-712, No. 3, June 2013.