ELECTRICAL TREEING PROPERTIES OF SILICONE RUBBER/ORGANO MONTMORILLONITE NANOCOMPOSITES AS AN INSULATOR FOR HIGH VOLTAGE APPLICATIONS

ABDUL AZIM BIN ABD JAMIL

UNIVERSITI SAINS MALAYSIA
2015

ELECTRICAL TREEING PROPERTIES OF SILICONE RUBBER/ORGANO MONTMORILLONITE NANOCOMPOSITES AS AN INSULATOR FOR HIGH VOLTAGE APPLICATIONS

by

ABDUL AZIM BIN ABD JAMIL

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science

June 2015

ACKNOWLEDGEMENTS

In the name of Allah, Most Gracious, Most Merciful

Alhamdulillah, first of all, gratefulness to Allah Who gives strength and patience to me along the accomplishment of this thesis. I would like to express appreciation to my supervisor, Dr. Mohamad Kamarol Bin Mohd Jamil for sharing his knowledge in guiding and assisting me throughout my study. I would also like to express appreciation to my co-supervisor, Professor Ir. Mariatti Binti Jaafar for her comments and encouragement. Additionally to my field supervisor, Dr. Yanuar Zulardiansyah Arief and Dr. Nouruddeen Bashir Umar, I would like to express gratitude both of you for guiding me during my research at Universiti Teknologi Malaysia (UTM).

Also, special gratitude to Mohd Hafizi Bin Ahmad and all the staff from the Institute of High Voltage and High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia and School of Electrical and Electronics, Universiti Sains Malaysia which being kind and generous in accepting me among them. Finally, I would like to extend my deepest gratitude to my father, Abdul Jamil Bin Mohd Noor and my mother, Zaiton Binti Ahmad, my wife, Nur Syazana Binti Azahar, my son, Abdullah ‘Ammar Bin Abdul Azim, my father and mother in law, my siblings and friends for continuously giving encouragement and Du’a, which without it I plainly would not have submitted.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULTS AND DISCUSSION

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternating current
HVAC	High voltage alternating current
SiR	Silicone rubber
NR	Natural rubber
EPDM	Ethylene propylene diene monomer
PP	Polypropylene
POSS	Polyhedral oligomeric silsesquioxanes
XLPE	Cross-linked polyethylene
OMMT	Organo-montmorillonite
MMT	Montmorillonite
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
ATH	Aluminium trihydrate
MgO	Magnesium oxide
ZnO	Zinc oxide
KBr	Potassium bromide
NaCl	Sodium chloride
NaOH	Sodium Hydroxide
TIV	Treeing initiation voltage
TBT	Treeing breakdown time
TPL	Treeing propagation length
TEM	Transmission electron microscopy
FESEM	Field emission electron microscopy
FTIR	Fourier transform infrared

UV	Ultraviolet
PDF	Probability density function
CDF	Cumulutive distribution function

SIFAT-SIFAT POKOK ELEKTRIK GETAH SILIKON/ORGANO MONTMORILLONITE NANOKOMPOSIT SEBAGAI PENEBAT UNTUK APLIKASI VOLTAN TINGGI

ABSTRAK

Fenomena elektrik yang berlaku didalam bahan penebat polimer sebelum berlakunya kegagalan penebat dianggap sebagai pokok elektrik. Pokok elektrik boleh memberikan kesan yang buruk kepada kebolehpercayaan radas elektrik dan kebanyakkannya belaku didalam kabel voltan tinggi. Biasanya, pengisi nano digunakan untuk merencat pokok elektrik. Oleh itu, organo-montmorillonit (OMMT) telah dipilih sebagai perencat untuk mengkaji fenomena pokok elektrik kerana pengetahuan mengenai sifat-sifat elektrik dalam bidang penebatan voltan tinggi masih tidak mencukupi walaupun ia telah terbukti cemerlang dalam bidang-bidang yang lain. OMMT telah dicampurkan dengan getah silikon (SiR) yang telah digunakan sebagai bahan penebat polimer. Prestasi OMMT didalam SiR untuk melambatkan pokok elektrik telah disiasat dengan mengukur empat parameter iaitu voltan pemulaan pokok (TIV), masa pecahan pokok (TBT), panjang pembiakan pokok (TPL) dan kadar pertumbahan pokok elektrik. Prestasi OMMT didalam SiR ini telah dibandingkan dengan getah silikon tidak dipenuhi dan SiR/SiO_2 nanokomposit. Analisis morfologi juga telah dijalankan pada sampel SiR/OMMT nanokomposit dan SiR/SiO_2 nanokomposit dengan mengunakan TEM, FESEM dan FTIR. Keputusan eksperimen telah menunjukkan sampel SiR/OMMT nanokomposit telah menunjukkan prestasi yang cemerlang daripada sampel getah silikon tidak dipenuhi dan SiR/SiO_2 nanokomposit dengan sampel yang mempunyai 5wt% OMMT didalam SiR mencatatkan keputusan paling cemerlang. Penemuan menarik didalam kajian ini adalah struktur lapisan silikat daripada OMMT didalam SiR yang mana dilihat membantu meningkat sifat-sifat elektrik SiR untuk merencat pertumbuhan pokok elektrik. Penemuan dan keputusan eksperimen adalah sangat berguna kepada penyelidik didalam bidang voltan tinggi untuk menjelaskan potensi pengunaan SiR/OMMT nanokomposit sebagai bahan penebat polimer dalam aplikasi voltan tinggi.

ELECTRICAL TREEING PROPERTIES OF SILICONE RUBBER/ORGANO MONTMORILLONITE NANOCOMPOSITES AS AN INSULATOR FOR HIGH VOLTAGE APPLICATIONS

ABSTRACT

Electrical phenomenon that occurred in polymeric insulating material prior to the insulation failure is considered as an electrical treeing. Electrical treeing can bring adverse effect on the reliability of electrical apparatuses and it mostly occurred for high voltage cable. Normally, nanofiller were used to retard the electrical treeing, therefore, organo-montmorillonite (OMMT) was chosen as the inhibitors to study the electrical treeing phenomenon. The knowledge on OMMT in the electrical properties field of high voltage insulations is insufficient although it has been proven excellent in other fields. OMMT was mixed with silicone rubber (SiR) which is another well-known material that has been used as polymeric insulating material. The performance of OMMT in SiR to retard electrical treeing was investigated by measuring four parameters which are treeing initiation voltage (TIV), treeing breakdown time (TBT), treeing propagation length (TPL) and electrical treeing growth rate. This performance of OMMT in SiR was compared with unfilled silicone rubber and SiR/SiO_2 nanocomposites. Morphological analysis was conducted on samples of SiR/OMMT nanocomposites and SiR/SiO_2 nanocomposites by using TEM, FESEM and FTIR. Results from the experiment revealed that the performance of SiR/OMMT nanocomposites were excellent than the unfilled SiR and SiR/SiO_2 nanocomposites, plus the OMMT with 5wt% of in SiR recorded excellent results. Another interesting finding in this research was the OMMT layered silicate structure caused SiR to increase electrical properties and inhibit the growth of electrical treeing. Findings and results from the experiments are very useful for researchers in high voltage field in order to clarify the potential of using SiR/OMMT nanocomposites as polymeric insulating material in high voltage application.

CHAPTER 1

INTRODUCTION

1.1 Overview

Electrical insulation is very important and serves as a backbone for high voltage equipment. Any conductor parts in high voltage equipment must properly be insulated from nearby conducting object for the safety and reliability of the equipment and also for the safety of the personnel. Electrical insulation material can be classified into five types; liquid, solid, gas, vacuum and composite (Al-Arainy et al. 2005).

Nowadays, polymeric insulating materials have been widely used in high voltage equipment compared to ceramic insulating material because of its lightweight, good water repellence and resistance to pollution (Basuki and Lendy 2012). Main function of insulating material primarily meant to resist electrical stresses. It also should be able to withstand other stresses such as the insulation encounters during manufacture, storage and operation (Naidu and Kamaraju 2004).

However, during operation, degradation processes could be occurred in high voltage insulation system and it will eventually reduce the performance of the insulating material. In addition, under longer exposure of electrical stresses, leakage current could be generated and flow across the surface of the insulation material and cause the insulation material to be severely degraded. This phenomenon of degradation processes could reduce the insulation strength of the material and lead to the formation of electrical discharge. One of the major causes of insulation failure in high voltage equipment is initiated from electrical discharges (Al-Arainy et al. 2005; Engel 1990).

Normally, electrical discharges start in the medium of gas state (Kao 2004). Electrical discharge involves the process of atoms or molecules become electrical charged due to ionization by avalanches of hot carrier. Electrical discharges that do not bridge the electrodes are known as partial discharges (British Standard 4828 1985; IEC Standard 60270 1996; Kuffel et al. 2000). Partial discharges in high voltage application can be classified into four types which are surface discharge, internal discharge, corona discharge and electrical treeing (Kreuger 1989).

Electrical treeing is an electrical breakdown phenomenon which mainly occurs in high voltage insulation and brings adverse effect on the reliability of energy distribution (A.A.A. Jamil et al. 2012; Kao 2004). Electrical treeing can be described as interconnected channels generally filled with gas and it also involved electrical, chemical and mechanical processes (Freebody et al. 2011). Electrical treeing can occur in most solid dielectrics including glass and porcelain but it is more severe in polymers, rubbers and epoxy resins. Development of electrical treeing can be described in three stages namely initiation, propagation and breakdown stage (Malik et al. 1998).

The electrical treeing mostly could occur in high voltage cable as shown in Figure 1.1. Various studies have been conducted to inhibit the occurrence of electrical treeing in the high voltage cable. Generally, micro-filler was used to inhibit electrical treeing in solid insulating material (Fothergill et al. 1994; Ahmad et al. 2012). However, with the proliferation of technologies in the area of material engineering and high voltage engineering, researchers started to explore nanotechnology field and found nanofillers as potential electrical treeing inhibitors in polymeric insulating material (A. A. A. Jamil et al. 2012).

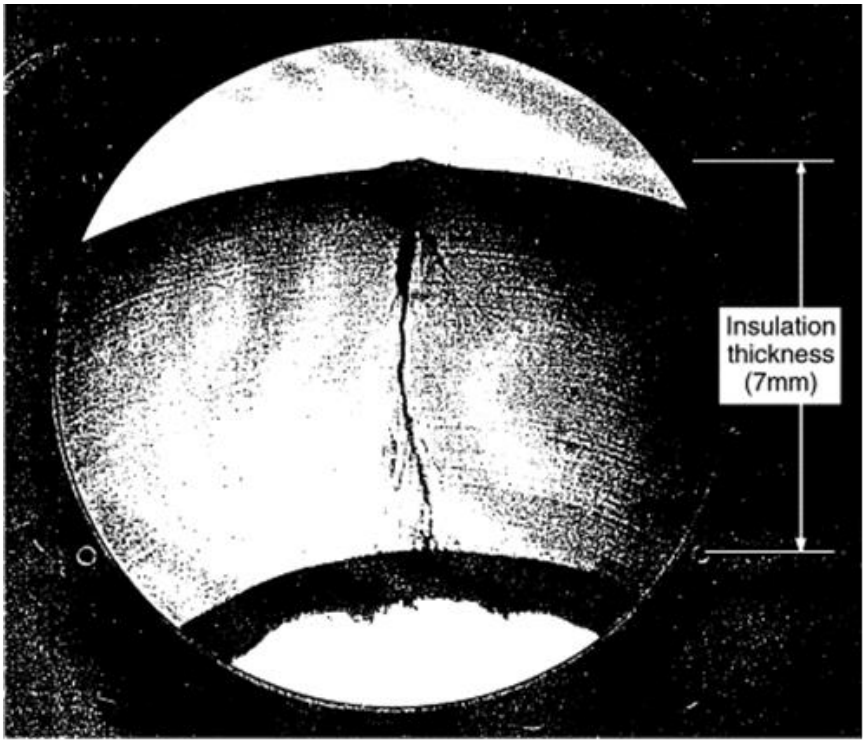

Figure 1.1 Electrical treeing through the total cable insulation (Kosaki et al. 1998)

Nanofillers have the advantages in terms of high surface area and interaction between polymer matrices compared to microfillers, which is a good retarding electrical treeing (Singha and Thomas 2008). Usually, nanofillers are mixed with polymer to improve the performance of polymeric insulating material and it is called as polymer nanocomposites. Silicone rubber (SiR) is widely used as an electrical insulating material because it abilities to maintain useful properties over a wide range of temperature, resistant to oxidation, possess low surface energy, and resists degradation from ultraviolet (UV) radiation (Yuan and Tian 2010; Mu and Feng 2007).

The most common nanofillers used as additives in various polymer matrices in electrical insulating material are Silicone Dioxide (SiO_2), Titanium Dioxide (TiO_2), Aluminium Trihydrate (ATH), Magnesium Oxide (MgO) and Zinc Oxide (ZnO) (Guastavino et al. 2005). Currently, material researchers have discovered a new organic filler which is the modified version of Montmorillonite (MMT), called Organo-Montmorillonite (OMMT) nanoclay. OMMT was modified with octadecylamine (Wahit et al. 2011).

OMMT have been proven in enhancing mechanical and thermal properties. Besides that, in packaging application, any addition of OMMT will increased the tensile strength and also the modulus (Ren et al. 2009). Furthermore, combination of OMMT with natural rubber (NR) will effectively improve the flame-retarding capabilities (Wang et al. 2012). However, in the field of high voltage insulation, the information about OMMT performance as a filler to enhance the insulating strength of a polymeric insulating material is still insufficient. In view of the foregoing, this dissertation presents the research studies of OMMT viability as nanofiller in SiR for retarding the growth of electrical treeing. Research studies of electrical treeing properties for SiR/OMMT nanocomposites were compared with SiR/SiO_2 nanocomposites which SiO_2 was commonly used as additives.

1.2 Problem Statement

SiR is widely used as an insulating material in many high voltage apparatuses because of its hydrophobic, excellent electrical and manufacture characteristics. However, SiR in not an excellent material for polymeric insulating due to the degradation process which normally occurred in high voltage insulation systems. SiR will not be able to insulate the conductor in high voltage apparatuses due to the long exposure of electrical stresses. Besides that, leakage current could be generated and flow across the surface of the polymeric insulating material and consequently caused the degradation of insulating material. Generally, electrical phenomenon occurred in polymeric insulating material prior to the insulation failure is considered as an electrical treeing. Electrical treeing can bring an adverse effect on the reliability of electrical apparatuses. Various studies have been conducted to inhibit electrical treeing phenomenon in high voltage apparatuses. Recently, researchers found that polymeric insulating material performance could be enhanced by adding nanofiller compared to micro sized filler. OMMT is clay nanofiller and it has better mechanical and thermal properties. However, the knowledge of electrical properties in the field of high voltage insulations is insufficient when determining the mixing of OMMT with polymeric insulating material. Therefore, the aims of this research are to study the electrical treeing properties of SiR/OMMT nanocomposite and compared with SiR/SiO_2 nanocomposites with different weight ratio.

1.3 Objectives

The objectives of this research are:

1. To investigate the effects of OMMT nanofiller in SiR on the electrical treeing initiation and propagation under HVAC stress.
2. To assess the performance of new OMMT nanofiller as an electrical treeing inhibitor.
3. To investigate the morphology analysis of SiR/OMMT nanocomposites to studies the potential to inhibit electrical treeing.

4. To compared the electrical treeing properties of SiR/OMMT nanocomposites to SiR/SiO_2 nanocomposites.

1.4 Contributions of the Research

This research work contributes:

1. Knowledge on the electrical treeing phenomenon in SiR mixtures with OMMT nanofiller and SiO_2 nanofiller
2. Morphological analysis result of SiR/OMMT nanocmposites and SiR/SiO_2 nanocomposites.
3. The findings from the experiments are very useful for researchers in high voltage field in order to clarify the potential of using SiR/OMMT nanocomposites as polymeric insulating material in high voltage application.

1.5 Scope of the Research

This research project primarily focused on the investigation of SiR/OMMT nanocomposite electrical properties as a new electrical treeing retardant material. The effect of the OMMT filler in SiR was compared with unfilled SiR and SiR/SiO_2 nanocomposites. In this investigation, leaf-like specimens were developed and online monitoring system was used to measure and record the parameters of electrical treeing. Electrical treeing parameters such as tree initiation voltage (TIV), tree breakdown time (TBT), tree propagation length (TPL) and electrical treeing growth rate was collected and analyzed. .

Morphological analysis was also performed to analyze the structure of SiR/OMMT nanocomposites material. Field emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM) were used to analyze the morphological analysis. The molecular structure of each nanocomposites was also analyzed by using Fourier transform infrared spectroscopy (FTIR). All morphological result were expected to support the qualitative discussion on electrical treeing phenomena in SiR/OMMT nanocomposites.

1.6 Outline of the Thesis

This thesis is organized into five chapters, which are the introduction, literature review, methodology, results and discussions, and conclusions. The outline of the thesis can be composed as follows;

Chapter 2 presents previously published works related to this research and the information were obtained from books, thesis, conference papers, reports and journals. Besides that, this chapter briefly explains about the current situation of electrical treeing phenomenon in high voltage application. In addition, this chapter also explains the role of polymeric insulating material, the formation of electrical treeing, and the statistic of electrical treeing failure in high voltage system. Furthermore it also clarify the research trend of electrical treeing in SiR and also the applications of polymer nanocomposites and the formation of charge trapping in high voltage system. On the other side, the application of SiR composites in high voltage system and the application of OMMT and SiO_2 nanofiller in polymeric insulating composite were also been discussed.

Chapter 3 discusses the research methodology and sample preparation of the research. The experimental procedures of electrical treeing parameters such as the TIV, TBT, TPL and growth rate of electrical treeing were explained in detail in this chapter. Besides that, this chapter also described the procedures of morphological analysis, such as Transmission Electron Microscopy (TEM), Field Emission Scanning Electron Microscopy (FESEM), and Fourier Transform Infrared Spectroscopy (FTIR).

Chapter 4 presents the results of the experiment, such as the TIV, TBT, TPL and growth rate of electrical treeing. Electrical treeing characteristics of SiR/OMMT nanocomposites were compared with the SiR/SiO_2 nanocomposites and the results will be analyzed and discussed. All morphological analysis result was used for qualitative discussion on electrical treeing phenomenon.

Chapter 5 presents the concluding remarks on the research and also recommendation for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will describe the current situation of electrical treeing phenomenon in high voltage application. In addition, this chapter will also explains about the role of polymeric insulating material, formation of electrical treeing, and statistic of electrical treeing failure in high voltage system. Besides that, this chapter will also clarify the research trend of electrical treeing in SiR. The applications of polymer nanocomposites and the formation of charge trapping in high voltage system were also discussed. Furthermore there's also revision on the application of SiR composite in high voltage system and the application of OMMT and SiO_2 nanofiller in polymeric insulating composite

2.2 Role of Polymeric Insulating Material in High Voltage System

In the past few years, polymeric insulating materials had become an important part in high voltage apparatus and it also triggered a revolution in the electrical system design (Montanari and Mazzanti 2002). High voltage conductors have to be properly insulated from the nearby conducting objects which might cause potential danger for the safety of the equipment, personnel as well as to the reliability of the power supply system. Therefore, proper insulation of high voltage conductors is of great significance. The main function of polymeric insulating materials in high voltage apparatus is to provide a high electrical resistance. In addition, polymeric insulating material should also be able to withstand electrical stresses encountered during manufacturing, storage and operation (Al-Arainy et al. 2005).

However, service degradation processes occur in high voltage systems which eventually reduce the performance of the polymeric insulating material. Thus, when insulating materials that were subjected to electrical stresses for a long time, create a path across the surface of the insulation with leakage current passing through the conducting path thereby leading to the formation of electrical discharges. Electrical discharges which normally start in the gas state, were created when atoms or molecules become electrically charged due to ionization by avalanches of hot carriers (Kao 2004). Electrical discharges that do not bridge the electrodes are known as partial discharges (Isa 2012). Partial discharges in high voltage application can be classified into four types which are surface discharge, internal discharge, corona discharge and electrical treeing (Bergius 2011)

2.3 Formation of Electrical Treeing in High Voltage System

Electrical treeing is a common failure mechanism occurs in polymeric insulating materials under the electric field stress (A. A. A. Jamil et al. 2012). Comprehensive study and understanding of the electrical treeing phenomena is very important in polymeric insulating material because it is widely implemented in high voltage system such as transmission cables. The occurrence of electrical treeing in polymeric insulating cable could lead to catastrophic electrical breakdown and finally yield to the power system failure. The electrical treeing can be described as interconnected channels generally filled with gas involving electrical, mechanical and chemical processes (Kao 2004). The electrical treeing and breakdown are closely linked phenomena in that the existence of the former often leads to the latter.

Mason is the first person to study the electrical treeing in the 1950s and he has observed that electrical treeing growth from cylindrical voids exposed to AC voltages for long periods of time. Mason indicated that discharge activity in the void eroded the surfaces and create non-conducting pits protruding into the solid material. Mason also concluded that the pits become conducting in the presence of the discharges, and raising the stress at the tip to intrinsic strength levels will create localised breakdown (Auckland and Varlow 1995; Mason 1955). The formation of electrical treeing can be classified into three stages, namely initiation, propagation and breakdown stages (Dissado and Fothergill 1992). In the initiation stages, electrical treeing can be detected when there is a formation of a micro void in an insulating material at the region of high electrical stress. The electrical treeing will be propagated and eventually growth when a fractal structure consists of fine channel evolved from a micro void. After a certain time and at critical electric field, the electrical treeing will bridge the gap and finally electrical breakdown will take place (Freebody et al. 2011; Barclay and Stevens 1992).

Fothergill et al has discussed the shape or patterns of the resulting tree and it can be described into three categories, which may be referred to tree-like or branched, bushy, and bush-branch as illustrated in Figure 2.1 (a) - (c) (Fothergill et al. 1994; Dissado and Fothergill 1992). Branched trees can described when multiple branched structure has exhibited with the diameter for a channel ranging from tens of microns in the trunk to around one micron in fine filamentary channels at the tip. Bush type trees existed when a densely packed hollow tubules appeared as a solid bush shaped mass when viewed from the side. Bush-branch trees are essentially bush trees with one or more branches forecasting from their boundary (Dissado and Fothergill 1992).

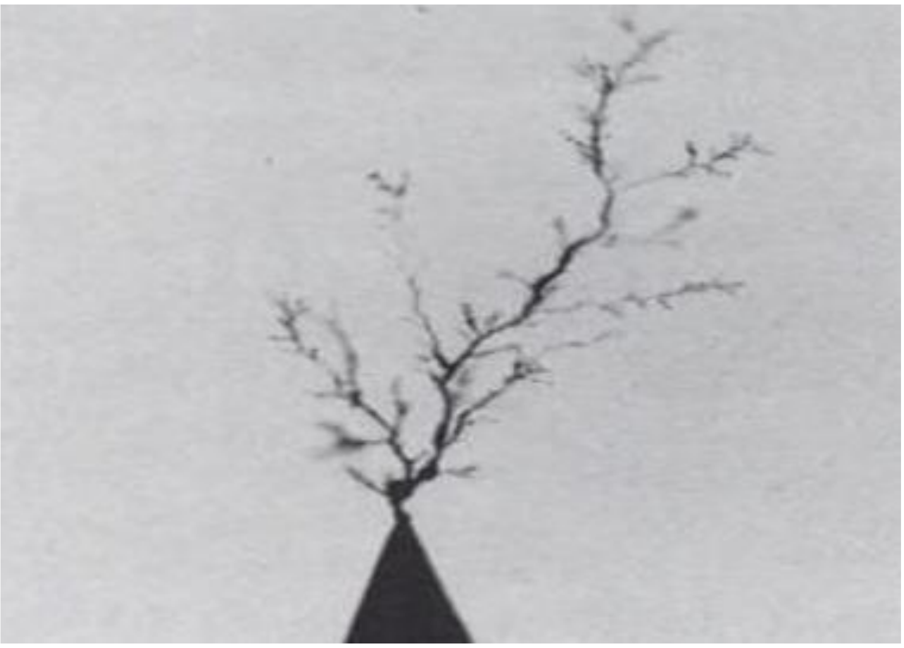

Figure 2.1 (a) Branch shape of electrical treeing

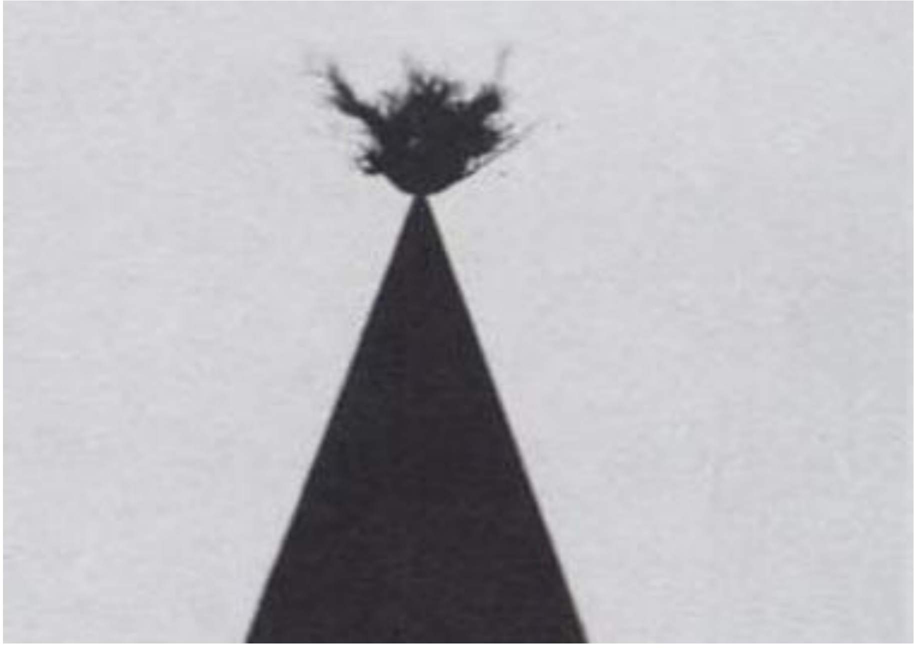

Figure 2.1 (b) Bush shape of electrical treeing

Figure 2.1 (c) Bush-branch shape of electrical treeing.

2.4 Statistics of Electrical Treeing Failure in High Voltage System

Electrical failures commonly occur in polymeric insulating material. From the statistic, the most common failed components in high voltage system was occurred in cable system, as shown in Table 2.1 (Bertling et al. 2002).

Table 2.1 Reports (1982-1990) Stockholm City area and 11kV cables (Bertling et al. 2002).

Failed components	Failures		Interruption		Customer affected	
	No.	Percentage	No.	Percentage	No.	Percentage
Bus bar	16	1.15%	10	1.49%	4604	1.10%
Circuit breaker	79	5.68%	21	3.14%	34453	8.21%
Disconnector	263	18.89%	53	7.92%	25004	5.96%
Earthing switch	7	0.5%	7	1.05%	5760	1.37%
Power transformer	174	12.5%	69	10.31%	16379	3.90%
Reactor	2	0.14%	0	0%	0	0%
Power capacitor	60	4.31%	52	7.77%	0	0%
Measuring transformer	3	0.22%	0	0%	0	0%
Fuse	12	0.86%	10	1.49%	120	0.03%
Overhead line	20	1.44%	19	2.84%	2927	0.70%
Cable system	435	31.25%	417	62.33%	325705	77.62%
Surge diverter	1	0.07%	1	0.15%	0	0%
Rectifier	299	21.48%	0	0%	0	0%
Control equipment	13	0.93%	9	1.35%	4450	1.06%
Other	8	0.58%	1	0.16%	200	0.05%
Total:	1392	100%	669	100%	419602	100%

Based on table 2.1, Cable systems record the highest numbers of component failures in Stockholm City, measuring to 31.25 percent and it have caused 62 percent interruption. As the result, 78 percent of cable systems customers at Stockholm City area were affected by the cable system failure. Analysis from the reports of the cable system failure are, 58.6 percent of these faults occurred because of material or method causes, 15.5 percent from the damage at the cable and 7 percent from the personnel as shown in Table 2.2 (Bertling et al., 2002).

Table 2.2 Supply interruptions caused by cable system failure at Liljeholmen Station, Stockholm City, Sweden (Bertling et al., 2002)

Cause of failure	Failure report	Percentage (%)
Damage	9	15.5
Personnel	7	12.1
Material and method	34	58.6
Unknown	8	13.8
Total	58	100

Bertling et al have identified six main causes of material and method implies. First is short circuit by the contact of different materials, for examples copper and aluminium in cable joints. Next, a tree like phenomenon which implies through the insulation will also causes the failures of cable systems. Furthermore, termination of cable, corrosion on the screen or jacket, and lack of oil insulation due to poor oil refill at the joints would lead to cable systems failure. In addition, “bent” damage could happen if the holes is not deep enough when laying the cable. Besides that, scratches at the insulation could also lead to cable systems failure due to wrong laying method or improper handling. Figure 2.2 summarizes the cable system failure in Stockholm City area as studied by Bertling and his research team in 2002 (Bertling et al. 2002).

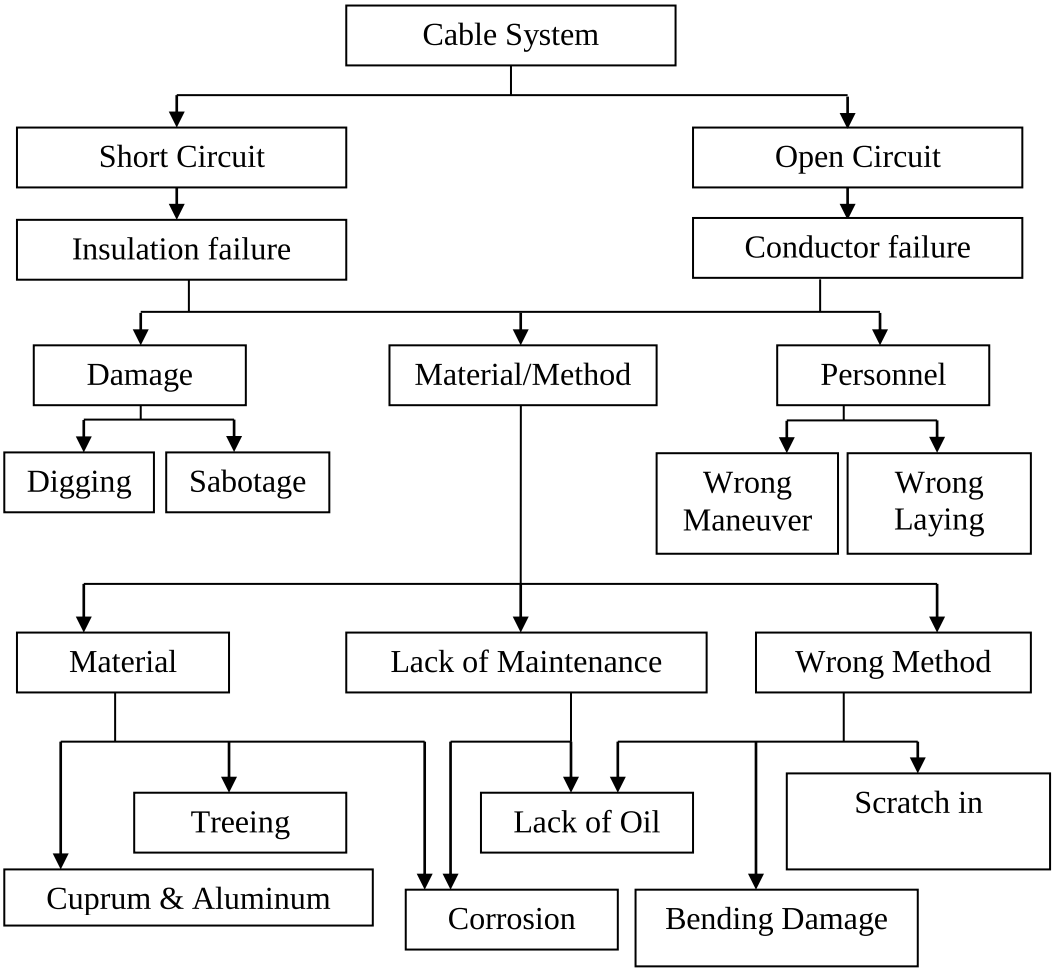

Figure 2.2 Summarize of cable system failure at Stockholm City (Bertling et al. 2002).

The failures of cable systems caused by electrical treeing may cause power system interruption. Electrical treeing generated in cable systems could form degradation of polymeric insulating material when it experiences an electrical stress. So far, researchers have found out that the additions of nanofiller in polymeric insulating material could increase the electrical properties of power cables. Roy et al. reported that the addition of SiO_2 nanofiller in polyethylene and cross-linked polyethylene cables increased the breakdown and voltage endurance of the cables. It is also attributes to the large interfacial region in the nanocomposites which responsible for the change in the defect size and reduction in charge mobility (Roy et al. 2005; Roy et al. 2007).

2.5 Research Trend of Electrical Treeing in Silicone Rubber

Numerous studies have been conducted to studies the phenomenon of electrical treeing in SiR. Many researchers used SiR as polymeric insulating material because of its excellent electrical properties. For example, Hosier et al. in their studies evaluate the performance and capabilities of a transparent SiR. The voltage range are between 8 kV to 18 kV with a needle-plane geometry. As the result, electrical treeing being formed over reasonable timescales. They also concluded that with increasing voltage, the electrical treeing became more complex (Hosier et al. 2011). Zhou et al. used physicochemical analysis especially different scanning calorimetry (DSC) to studies electrical treeing phenomenon in SiR. This analysis was conducted to detect the invisible degradation processes in electrical treeing ageing. They found that obvious reduction occurred for activation energy in non-treed samples compared to virgin samples (Zhou et al. 2009).

Du et al. also studied about electrical treeing phenomenon in SiR and found out that the electrical tree in SiR is a white gap tree channel which composed of silicone compounds instead of carbonized channel in XLPE (Du et al. 2009). Furthermore, Du et al. also studied the effect of ambient temperature to SiR in his research paper in 2011. They discovered that temperature have effect on SiR electrical treeing growth. At 30^{0}C, the pattern of electrical treeing channel was like branches of tree but at 60^{0}C and 90^{0}C, the bush tree became a dominant structure (B X Du et al. 2011).

In addition, Hozumi et al. and Rudi et al. discovered the capabilities of SiR to self-healing the damage occurred from electrical treeing phenomenon. Rudi et al. described in his research paper that SiR showed self-healing property after being degraded by electrical treeing. The length of electrical treeing decreased obviously after 48 hours. Furthermore, the partial discharge activity also decreased after self-healing occurred in SiR. On the other hand, Hozumi et al. also reported the same thing about self-healing of SiR. The tree gradually disappeared in parallel with the recovery of partial discharge initiation voltage. The 150 micrometres in length of cut off tree propagation length disappeared after 52 hours because of the capabilities of SiR to self-healing the damage from electrical treeing degradation (Hozumi et al. 2005; Rudi et al. 2012).

Some researchers have started to use nanofillers to enhance the capabilities of SiR as polymeric insulating material. For example, Du et al. have used nanosilica in SiR to form SiR nanocomposites. Inferred from the results, the tree initiation and breakdown time of SiR nanocomposites increased with nanofiller content. In addition, the tree structure for unfilled SiR and SiR nanocomposites were also different. The electrical treeing in unfilled SiR was faster compared to SiR nanocomposites (B. X. Du et al. 2011).Yuan-xiang et al. studied the effect of addition nanosilica in SiR and the results shown that increasing the content of nanosilica fillers will increased the tree initiation voltage. Besides that, the addition of nanosilica will caused the pattern of electrical treeing growth to became bush like trees which means that the branches get denser (Yuan-xiang et al. 2012)**.**

2.6 Applications of Polymer Nanocomposites in High Voltage System

Polymer nanocomposites was defined as a composites which consists of polymeric material and a reinforcing nanoscale in at least one dimension in nanometer scale (Koo 2006). Over the last decade, polymer nanocomposites have emerged as a new materials that circumvent classic composite material performance.

Polymer nanocomposites were developed in the late 1980s by commercial research organisations and academic laboratories. The term nanocomposites was used first in 1984 by Roy and Komarneni to emphasise the fact that the polymeric product consisted of two or more phases each in the nanometre size range (Kotsilkova et al. 2007; Sridhar Komarneni et al. 1997). Hussain et al. described that polymer nanocomposites was firstly commercialized by Toyota Central Research Laboratories in Japan when they reported that Nylon-6 nanocomposites have improved thermal and mechanical properties of the polymer matrix (Hussain et al. 2006).

Polymer nanocomposites have discovered new properties and exploited unique synergism between materials. The properties of polymer nanocomposites are remarkably different compared to conventionally filled polymer. The incorporation of few percent of nanosized filler would result to dramatic property changes and unlock the formerly unachievable property combinations (Kny 2009; Kotsilkova et al. 2007). Koo also reported four factors that affect the polymer nanocomposites properties; (i) synthesis methods such as melt compounding, solvent blending, in-situ polymerization, and emulsion polymerization; (ii) polymer nanocomposites morphology; (iii) types of nanofiller and their surface treatment; (iv) lastly is polymer matrix such as crystallinity, molecular weight, polymer chemistry, and weather thermoplastics, thermosets or elastomers (Koo 2006).

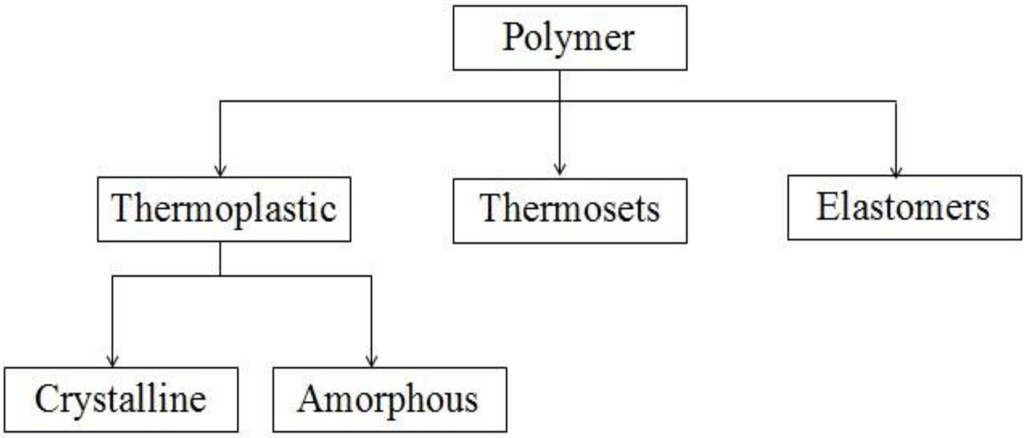

Figure 2.3 Structured type of polymer

Polymer matrix can basically be divided into three classes, which are thermoplastic, thermoset and elastomer as shown in Figure 2.3 (Al-Arainy et al. 2005). Thermoplastics referred to plastics, such as amorphous or crystalline. Both of it can repeatedly be softened by heating and solidified by cooling. Which is the same process for melting and cooling metals. Thermoplastic widely used in food packaging, automobile bumpers and some part of electrical insulation. Thermosets usually are three dimensional network polymers and it is strong and durable. Besides that, it’s usually used in automobiles and construction. Elastomers are rubbery polymers that can be stretched several times and rapidly return to their original dimensions when the applied stress is released. In addition, Elastomers are widely used in high voltage application such as outdoor insulator and underground cable because of it is hydrophobicity and excellent electrical properties. Table 2.3 shows classification of the polymers and it is examples.

Table 2.3. Classification of the polymer; thermoplastics, thermosets and elastomers (Al-Arainy et al. 2005; Brinson and Brinson 2008)

Thermoplastics	Thermosets	Elastomers
Polypropylene	Aminos	Silicone Rubber
Polyvinyl Chloride	Epoxides	Ethylene Propylene Diene Terpolymer
Polyamides	Polyurethanes	Natural Rubber
Polyesters	Phenolics	Nitrile Butadiene Rubber
Polystyrene	Polyethlene	Styrene Butadiene Rubber

Henk et al. and Nelson et al. work was reported as the earliest experiment on polymer nanocomposites in high voltage system for electrical insulation (Henk et al. 1999; Nelson and Fothergill 2004). Based on their research, there are unusual properties in polymer nanocomposites which were different compared to the base polymer and polymer microcomposites (Henk et al. 1999; Nelson and Fothergill 2004; Lau and Piah 2011). The most significant changes is when using polymer nanocomposite as electrical insulation, the dielectric breakdown strength enhanced. Not only enhancement of dielectric breakdown, the polymer nanocomposites have also enhanced others electrical properties such as permittivity, space charge formation, dissipation factor, and partial discharge.

Although polymer nanocomposite has been proven to enhance the electrical properties, there’s concern in the physics and chemistry of the property changes. Some researchers indicated that the interfacial area was the main factor that contributes to the drastically enhanced electrical properties (Lau and Piah 2011). Besides that, Nelson explains that the radius of nanofiller is correlated to the surface area. He indicated that when the size of nanofiller was reduced, the specific surface area becomes very large as shown in Figure 2.4 (Keith Nelson 2007). High surface to volume ratio of nanofillers caused the interfacial region between nanofiller and the matrix to have high volume of fraction, resulted from the electrical properties of enhanced polymer nanocomposites (Green et al. 2008).

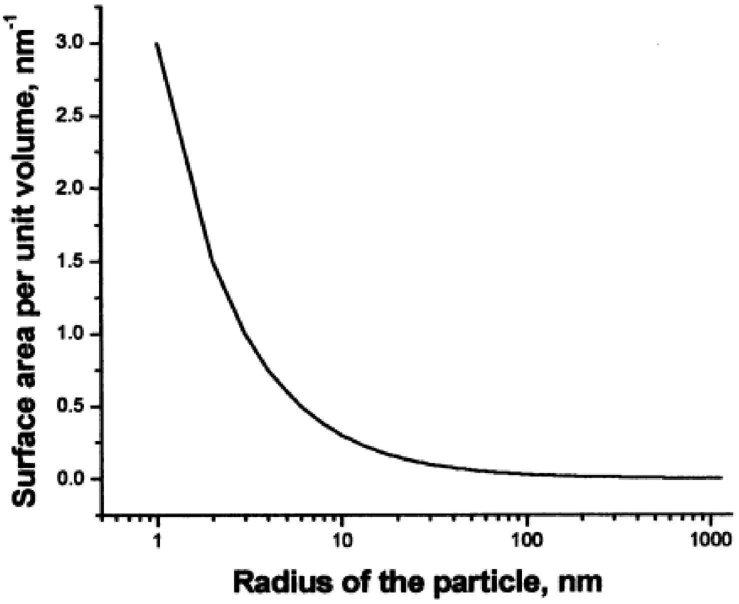

Figure 2.4 Surface area per unit volume polymer nanocomposite as a function of nanofiller size (Keith Nelson 2007)

2.6.1 Formation of Charge Trapping in Polymer Nanocomposites

Polymer nanocomposites have many advantages compared to polymer microcomposites. Addition of nanofillers in polymeric insulating material will significantly affected the electrical charge transport, dielectric breakdown and durability properties of materials (Fothergill, 2010). This significant effect was expected, by considering how morphology, chemical and physical structure of the polymer changed the addition of fillers. Consideration should also be given to electrostatic forces around the fillers which changed the electrical properties of the interaction zone between fillers and polymeric insulating material (Fothergill, 2010).

Lewis in his paper entitled “Nanometric Dielectric” described the existence of nanofillers in polymeric insulating material have created localized space charge or known as trapping site. The trapping site often utilized as a factor in electrical breakdown of solids. Lewis also stated that there are two kinds charge trapping existed (Lewis, 1994). Firstly, a moving charge may reach a points where continuing forward in the path direction is not available along the interface surface without activation to a higher energy state. Secondly, at chain ends and at kinks or crosslinking sites it become trapping site which trap some charge that moving within the energy band structure of polymer (Lewis, 1994).

Furthermore, Lewis research shown that local polarization and associated reorganization energy tend to strongly trap the charge. This situation will likely distort the polymer and as result, the electric field in the neighborhood trapped (Lewis, 1990). Furthermore, Danikas and Tanaka has made an assumption that the nanofiller reduced the charge carrier mobility and energy because of their extended surface area and their effect on changing the nature of the polymer. This phenomenon is the result of increasing voltage required for charge injection because the homocharge from trapping mitigates the electric field at the electrodes. Moreover, the key to the trapping mechanism came from the structure between the combination of polymer and nanofiller structure, and not from the polymer structure itself, where nanofiller present an elongates scattering path to the charge carriers has resulted from development of the charge layer (Danikas and Tanaka, 2009).

2.7 Application of Silicone Rubber Composite in High Voltage System

Silicone rubber (SiR) prepared from dichlorosilane were cross-linked or vulcanized by the action of heat in the presence of a vulcanizing agent. SiR is an elastomer which consists of silicone itself and contains carbon, hydrogen, oxygen and silicone atoms (Kornacka et al. 2006; Al-Arainy et al. 2005). Intermittent between silicon and oxygen atoms made up the backbone for SiR as shown in Figure 2.5. Hyde Dow Corning in 1940s commercialized first SiR when they demonstrated the thermal stability and high electrical resistance of silicones resin. SiR polymers were prepared by three step synthesis; chlorosilane synthesis, chlorosilane hydrolysis and the last step is polymerization and polycondensation (Colas 2005).

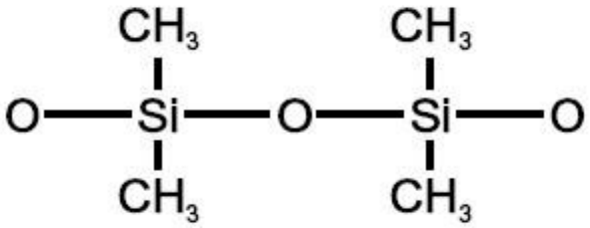

Figure 2.5 Molecular structure of SiR (Zhang et al. 2006).

The difference between other elastomer and SiR was the elastic behavior in SiR slightly changed when there’s adjustment in temperature. SiR have higher heat resistance, chemical stability, and better electrical insulation compared to organic polymers because of its siloxane bonds (Si-O) which formed the backbone of the silicone (Visakh et al. 2013). This siloxane bonds are more stable compared to polymers with a carbon (C-C) backbone such as Ethylene Propylene Diene Monomer (EPDM). The energy of C-C bonds is 348kJ/mol, as opposed to 444kJ/mol for Si-O (Holleman et al. 2001). Si-O bond remains stable when opposed