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Study of the dielectric degradation of XLPE and EPR power cables by switching impulses

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STUDY OF THE DIELECTRIC DEGRADATION OF XLPE AND EPR POWER CABLES BY SWITCHING IMPULSES

By

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STUDY OF THE DIELECTRIC DEGRADATION OF XLPE AND EPR POWER CABLES BY SWITCHING IMPULSES

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The insulation of the high voltage power cable will be placed under higher electrical stress by switching surges during the power system operation. The switching surge weakens the power cable insulation and it leads to failure of cables. It has a significant effect on the aging of the insulation material that affects the lifetime of the power cables.

This research studies the electrical degradation of 15 kV XLPE and EPR power cables insulation by applying 100, 500, 1000 and 5000 switching impulses of 100 kV. The status of the polymer cable insulation aging is evaluated by the measurement of partial discharge level and ac breakdown voltage. Partial discharge measurements are taken throughout the aging process at specific intervals of applied impulses. The ac breakdown voltage is also measured at the end of the accelerated aging process.

DEDICATION

I would like to dedicate this research to my beloved parents, Mr. M.R.Shrestha, and Mrs. R.D.Shrestha, brother Prajwal Shrestha and my advisor Dr. Stanislaw Grzybowsi.

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At last, I would like to thank my family and friends for their support to achieve this goal.

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CHAPTER I

INTRODUCTION

1.1 Introduction

The research has been conducted on 15 kV Cross-linked Polyethylene (XLPE) and Ethylene Propylene Rubber (EPR) power cables of the electric ship power system. The objective of this project is to gain new insights into the electrical degradation of power cable insulation that is exposed to the electrical stresses present in ship electrical systems. The degradation of electric ship power cable insulation in distribution lines has been carried out due to the electrical stress caused by switching surges. Switching is one of the main sources of surge overvoltages in a power system. The different loads, inductive and capacitive, are supplied by distribution lines of an electric ship that is switched on and off in the system during operation. The switching operations due to various loads cause over voltage transient in a power cable [1]. The various loads supplied by the electric ship distribution lines also cause over voltages in power cables. It is a well known fact that these high voltage switching surges have a significant effect on the aging of the cable insulation which directly affects the lifetime of the power cable. To understand this phenomenon, the ship board high voltage cables are aged by switching impulses. The partial discharge measurement results, which are taken throughout the aging process, allow shipboard power system designers to better understand the electrical aging phenomenon. This understanding will then assist in the determination of the most reliable shipboard cable, as well as an estimation of the cable's expected lifetime, although many factors other than aging by switching impulse must be considered before making such determinations.

High voltage power cables for the electric ship use solid insulation materials: Cross-linked polyethylene (XLPE) and Ethylene propylene rubber (EPR). During operation, the insulation of the cables will be placed under high electrical stress, including the overvoltages caused by switching. The aging of cable insulation is accelerated by applying switching impulses. Papers [12] and [13] discussed the behavior of high voltage EPR and XLPE cables due to switching impulses. According to IEC 505, aging can be defined as irreversible deleterious change to the service ability of insulation systems. The accelerated aging test is done to estimate the life of newly developed power cables that are used in the power system. It correlates remaining ac dielectric strength and applied operating voltage stress for aged cables [18]. The switching surge weakens the cable insulation and it leads to the failure of cables. The processes of the electrical degradation and the aging of the cable insulation under switching impulses are not well known at the present time. The degradation of insulation in a power cable is evaluated by the measurement of partial discharge parameters and ac breakdown voltage.

In the distribution of the electrical energy, the invention of polyethylene cables brought a big change in the insulation of cables [2]. PE cables have been gradually replaced by polymer XLPE and EPR cables. Today, two main types of polymer insulation are used in cables:

(a) Cross-linked polyethylene (XLPE)

(b) Ethylene propylene rubber (EPR)

To perform better, the cable insulating material should have high dielectric strength, low thermal resistivity, long life, and stability with wide range of temperature, low loss tangent and economically viable [3]. The cable insulation must withstand high impulse voltages and ac voltage. The dielectric loss of cable insulation can be calculated by measuring tanδ. The cable insulation should resist electrical treeing and partial discharge for better performance and durability. The high dielectric strength, low conductivity, low dissipation factor, and tree resistant make XLPE and EPR cable insulation suitable for cable. EPR cable has also superior operating temperatures, so it is widely used in commercial and industrial applications. Now, power cable industries are focusing mainly on XLPE and EPR cables since technical developments and improvement on cable insulation are taking place.

The breakdown mechanism under applied impulse voltages is different from applied dc or low frequency ac. Solid insulating materials have very high electrical resistivities and high dielectric strengths below certain temperatures. The insulation may contain gas voids or impurities particles. When cable insulation is under high electrical stress, partial discharge takes place in a void or cavity. It leads later to the breakdown of the cable. The breakdown strength of the cable insulation is affected by the time span during which the voltage is applied. The applied voltage can be ac, dc or impulse. Though the breakdown of solid insulation is influenced by various factors such as temperature, humidity, pressure, duration of test, voltage duration but the breakdown mechanism of solid insulation is more difficult to understand than that of gases [4]. The primary process of breakdown mechanism in solid insulation can be intrinsic, thermal or erosion.

Cables under high electrical stress can form cavities and voids in cable insulation. It is widely reported that cavities and voids are responsible for producing partial discharge in insulation. Cavities are filled with gas or liquid of lower breakdown strength than solid. It cause damages to surrounding solid insulation and can finally cause breakdown in a cable. Breakdown is due to the higher electric field intensity in the cavity than in the dielectric around it.

Partial discharge occurs in the insulation when it significantly experiences higher electric field. It does not completely bridge the insulation between electrodes. It is discussed a lot that the effects of partial discharge can be very dangerous on power cables, which can ultimately cause complete failure. The partially bridging of electrodes takes place when voltage is applied. The partial discharge can be internal discharge occurring in cavities or voids, surface discharge occurring at the surface boundary of insulation, discharges occurring at gaseous dielectric and continuous impact of discharges in solid dielectrics forming treeing. The partial discharge affects the life of insulating materials and it is significant in insulation during aging. It deteriorates the insulating material causing chemical transformation. The partial discharge occurred in insulation depends upon the types of voltage applied and its duration.

The relationship between the partial discharge and lifetime of insulated materials is not clearly understood and still under investigation. The condition of deteriorated cable insulation can be evaluated by partial discharge measurement level. The degradation of XLPE and EPR cable insulation by switching impulse, which is evaluated by partial discharge activity, is discussed in paper [1]. The different parameters used in partial discharge activity are partial discharge inception voltage, partial discharge extinction voltage, pulse count and apparent charge (partial discharge magnitude). Finally, ac breakdown voltage is applied to the cables to evaluate the cables and to determine the remaining dielectric strength of cables.

1.2 Overview of Thesis

The thesis describes the tests and results performed at the MSU High Voltage Laboratory. The accelerated aging, ac breakdown voltage, and partial discharge testing as a diagnostic tool are used to study the behavior of 15 kV XLPE and EPR cable. The objective of this research is to investigate the effects of switching impulse voltage on the aging of the XLPE and EPR cable insulation and to determine both the reliability of power cables and expected life time, although many factors other than aging by switching impulse should be considered. Three cable samples were selected for the tests. They are named as sample A, B and C for XLPE and EPR cables. Standard switching impulse of 100 kV is applied on cable samples. The switching impulse is obtained from 4-stage, 8 kJ impulse generator. XLPE and EPR cables are applied with 0, 100, 500, 1000 and 5000 switching impulses. The degradation in cable insulation is evaluated by partial discharge activity. The indicator DDX- 7000 is used to measure the partial discharge level at power frequency of 60 Hz. The AC breakdown voltage is then measured to determine the remaining dielectric strength of the XLPE and EPR cables.

1.3 Outline of Thesis

Chapter 2 provides the literature review on the related study. It gives a brief description on the power cables and the insulation degradation. Chapter 3 discusses on the experimental set up for cable testing. Chapter 4 details on the results obtain from the experimental study. Chapter 5 provides the conclusion and future work of the study.

CHAPTER II

LITERATURE REVIEW

This chapter briefly explains the development of different cable insulation from paper insulation in 1890 to polymeric cables in 1960s. Later, this chapter deals with the different technique used to evaluate the cable insulation.

2.1 Review on Development of Power Cables

Power cables are classified according to the insulation materials used but mainly, they are categorized into three types [6]:

- Paper-oil insulation
- Synthetic insulation
- Gas Insulation

The cable insulated with impregnated paper was first installed in 1890 by Ferranti for operating 10 kV. It was improved later with introduction of shielded conductor in 1914 by Martin Hochstadter. Impregnated paper insulation in cables was commonly used in power transmission and distribution for voltage of 12.5 kV and higher [7]. Paper is impregnated with a dielectric fluid (oil). The use of oil with reservoir controls the expansion of voids in cables and improved voltage to 69 kV and higher. It can be oil filled (OF) cable and pipe-type OF (POF) cable. OF and POF cables under pressure are extremely difficult in splicing and terminating. These types of cable are difficult to install and operate due to leak possibility [8]. The high resistance and free of internal discharge are important features of oil impregnated cable and provides stability but a small quantity of water can be detrimental to OF cable [6]. The insulation of cable is degraded if it comes in contact with water. Using of sheath around the cable protects it from absorption of water or moisture.

The use of different cable insulation materials depends upon rated voltage, current and type of cable. The oil-impregnated OF cable is mainly used for extra high voltage applications. PVC cable is applied on low voltage rating whereas EPR and XLPE cables are used for medium voltage and undergoing through improvement to implement for high voltage application. The high permittivity and significant dielectric losses with increasing temperature are the main reasons to limit PVC cable to low voltage application [11]. There is dramatic change in cable insulation after the development of polyethylene in 1941. The polyethylene has high molecular weight so it has better electrical properties. The polymer dielectric cables started becoming popular in power application after 1975. The demand for the polymer cables increases with the advent of underground residential distribution (URD) systems.

In cross-linked polyethylene, the different polyethylene chains are linked together and considered to be branched polyethylene where the branch is connected to a different PE chain [2]. In ethylene propylene rubber, ethylene monomer is polymerized with propylene to produce EPR. XLPE performs in a better way than other PE cable with respect to thermal aging, thermal deformation and environmental stress cracking whereas it is able to maintain its characteristics of breakdown strength, dissipation factor and permittivity. Introduction of jacket in XLPE cable also improves its performance by not allowing insulation being contact with water and moisture as water presence in cable insulation under high voltage stress is one of the prime reason for premature loss of cable life due to water treeing. It leads to early breakdown of cable [2].

Grzybowski, Rakowska, and Thompson [10] studied that different factors, such as electric field, moisture, temperature, and ionizing radiation, initiate and accelerate the aging of PE. They mentioned that the different degradation factors and the aging time of PE are correlated. The partial discharges in PE cable result in tree formation and degradation of insulation. The PE cable is replaced by XLPE cable due to its superior high temperature properties and better resistance to water treeing. The addition of carbon black and mineral fillers in its insulation helped to reduce its prices and also make it able to resist severe environmental conditions [11]. XLPE cables are becoming popular in URD networks and successfully replacing PE. The XLPE cables can operate at rating temperature of 90^{o} C while PE cables can operate at rating temperature of 70^{o} C. During 1970s, XLPE cables replaced paper OF cables in power distribution at a voltage rating of 69 kV. Later on, XLPE cables of voltage rating 115 kV and 138 kV were also commissioned. It further improved the XLPE cables to apply for 345 kV applications [6]. EPR cable came into power applications in the 1980s but it was not widely used during that time due to its higher price. R. Arright [11] described that EPR cables replaced butyl rubber because of its better withstanding feature related to partial discharges and it provides good resistance to thermal aging. In addition to this, it operates at a high temperature: 90º C under steady- state conditions, 130º C under overload conditions and 250º C under short circuit conditions. The advantage of EPR cable is that it is reluctant to thermal aging, weathering, ozone, chemicals and tracking [6]. It has better flexibility and reduced sensitivity to water treeing.

XLPE and EPR cables have become successful in replacing OF cable in low voltage and medium voltage applications as they are easy to install and easy to splice and terminate. These cables are believed to be free from the water problem but actually they are found to be more vulnerable to water than to paper cables as water has a severe effect on the aging of these cables [11]. Martin and Hartlein [43] tested the sections of service aged polymer cables in the laboratory that were removed from several locations on the Georgia Power Company System. From the test results, they found that cables were free from partial discharge but all cables contained water treeing. The sensitivity to water of the insulation is increased with the increasing voltage gradient. This results in the breakdown of whole insulation above specific electrical stress. But effect of water on insulation can be improved by reducing impurities. However, the over sheath, metallic screen, and semiconducting layers reduce water penetration in the insulation. Due to the high electric field present at a effect of sharp point, the cable failures occur mainly in joints and termination.

S. Grzybowski, E. Robles and O. Dorlannes [16] state that the highest electrical stress occurred at the junction surface between the semiconducting polyethylene and insulating polyethylene. The stress influences the performance and behavior of the cables. The techniques should be improved in termination to enhance the reliability and electrical performance of the cables. The dissipation factor of insulation is increased when there is degradation in the cable insulation.

2.2 Cable Structure

Power cables consist of one, three or four metallic core conductors that are surrounded by insulating material. Polymer cables are classified according to their insulation such as PVC, PE, XLPE or EPR. Figure 2.1 presents the typical polymer power cable.

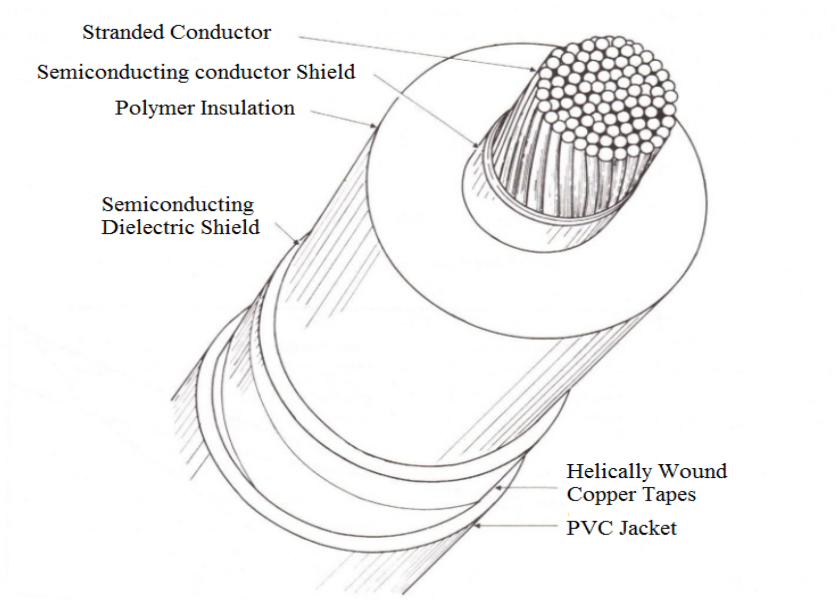


Figure 2.1 Polymer power cable [6]

It has sheathing materials, which are very important for various protecting applications, and especially URD cable that requires armoring for mechanical protection

[3]. In power cables, aluminum and copper are mainly used as conductors. Aluminum is more commonly used than copper due to its cheapness and flexibility. Conductors can be solid or stranded in shape and stranded is done to provide flexibility to cable. The insulation in the cable is to provide enough space between conductor and the electrical ground to prevent dielectric failure. The insulating material of the cable must possess long life, economical, easy installation, and high dielectric strength. The insulating materials used for the cables are paper, synthetic, rubber, or gas. Defects in the insulation are the prime reason for breakdown and defects can be voids, cavities, protrusions or contaminants [6].

Protrusions enhance electrical stress on the insulation. A semiconducting layer over the conductor reduces protrusions into the insulating layer and controls partial discharge. It helps to smooth the electric field to protect from early breakdown of insulation. The Cable sheath or jacket protects the cable from water, corrosion, anti-weathering and anti-aging. PVC or PE is used as a cable sheath. Cables are grounded so that any leakage charge accumulated in the cable during operation can be passed through the ground wire.

2.3 Breakdown Mechanism

The function of solid insulation in the cable is to insulate and provide mechanical support to the conductor [4]. The polymer cables that are in service in power systems are vulnerable to different stresses such as electrical, thermal, mechanical and environmental stress. Electrical stress is one of the prime causes that leads to breakdown of the cables.

While people have become reasonably successful at finding out the breakdown mechanism in gases, the breakdown in solid insulation still looks vague and several researches are going on solid breakdown.

G. Bahder, T. Garrity, and M. Sosnowski [39] postulated a model of electrical aging and breakdown of high voltage insulated cables. They verified the model with the results obtained in the tests. In the model, it is assumed that development of craters at the discharging voids is responsible for the electrical aging and breakdown of the cable insulation. According to authors [39], electrical aging of insulation is a local phenomenon that occurs if the applied voltage stress exceeds the threshold voltage stress. The voids or cavities, which are near to the local sites, consist of large projections caused by protrusions or contaminants. These voids are considered to cause breakdown in insulation. The breakdown voltage in insulation is determined by the voltage stress that starts in insulation near to the gaseous void, after partial discharge takes place in voids and due to the dielectric strength of the insulation [39]. A method is developed to determine the threshold voltage by means of voltage breakdown tests and the tests indicate that the breakdown voltage decreases with an increase of time of applied voltage above the threshold voltage [39].

M.M Epstein, B.S. Bernstein, and M.T. Shaw in [19] discussed about the aging mechanism that causes the breakdown in solid dielectric materials. Though several theories and models describe about the aging phenomena in solid dielectric materials, they still cannot figure out the reliable life of the dielectric cables [20]. Gherardi, Metra, and Vecellio [43] used test models to study aging and breakdown phenomena in polymer insulation under electrical, thermal and environmental stress. The study shows the behavior of defects in insulation and effects of different stress in insulation. From the test model, it is concluded that results should be compared with the data obtained from the full size cables. J. Crine, S. Pelissou, and J. Parpal mentioned in [27] that ac breakdown strength and dielectric loss of new and aged power cables vary with the insulation contamination, oxidation and crystallinity. These parameters have the main effect on conductor shield and changes with service aging due to contaminated shield and increased oxidation in the conductor. It is noted that breakdown is initiated in these particular region. The breakdown of the solid dielectric materials depends on the insulation nature and the morphology, environment, and temperature. There are three main theories that describe the breakdown mechanism of solid [3, 4].

- Intrinsic breakdown
- Thermal breakdown
- Electrochemical

Intrinsic breakdown is attained when the sample under test is pure and homogenous and there are no external discharges though the sample is stressed. During the process, temperature and environmental conditions are controlled. The intrinsic strength is difficult to attain experimentally. Intrinsic breakdown occurs when the energy balance between gain and loss of energy is disregarded as an electron obtains energy from electric field to cross the energy gap from the valence to the conduction band [4, 6]. The difference between the intrinsic breakdown and avalanche breakdown is that avalanche breakdown depends on dielectric thickness. Intrinsic breakdown is also known as electronic breakdown since it occurs due to electronic behavior of dielectric, and temperature plays no role on it [3]. It is quite difficult to attain the intrinsic breakdown of solid insulation as thermal breakdown or electromechanical breakdown can occur due to stress instead of intrinsic breakdown. Intrinsic breakdown theory was first proposed by Frohlich in 1947, and the criteria for breakdown was to determine the electrical stress when dielectric acquires a field-enhanced conductivity [3, 6]. The intrinsic breakdown can be accomplished in 10^{-8} sec. The electric stress required for an intrinsic breakdown is 10^{6} V/cm [4].

Thermal breakdown in solid insulation takes place when the rate of heating exceeds the rate of cooling during temperature rise. When the insulation is stressed, heat is generated within the dielectric due to conduction currents and dielectric losses. Thermal breakdown occurs when the thermal equilibrium in solid insulation cannot be maintained and it occurs as the rate of heating exceeds the rate of cooling in insulation. The resistivity of the solid dielectric is decreased when the temperature is increased and then a dielectric loss is increased too. During the high electrical stress in insulation, heat is produced in dielectrics due to losses and polarization. It leads the breakdown of insulation due to continuous rise in temperature [3]. It is discussed in paper [16] that the morphological structure of high voltage cable test samples varies in different parts of the cables after test specimens are tested before and after thermal aging. The results from the testing show that the morphology of cable is different for a test sample after thermal aging than that of a new sample. It was found that the aged samples contain several micro-voids, which are responsible for partial discharges and treeing mechanisms. Steady state thermal breakdown and impulse thermal breakdown are two cases that are considered for thermal breakdown in solid insulation [6].

Another type of breakdown that is common in solid insulation is erosion breakdown. Insulation contains voids or cavities, impurities, defects which can act as initiating points for breakdown. These cavities may occupy gas or liquid whose breakdown strength is lower than solid so, the electrical stress is higher in cavities than solid dielectric materials [4]. The breakdown is initiated in cavities when applied voltage across cavities is higher than its breakdown value. Erosion breakdown occurs in insulation when voltage across cavities or voids formed in solid insulation exceeds the breakdown value. Figure 2.2 shows different types of defects that occur in insulation of polymer cables.

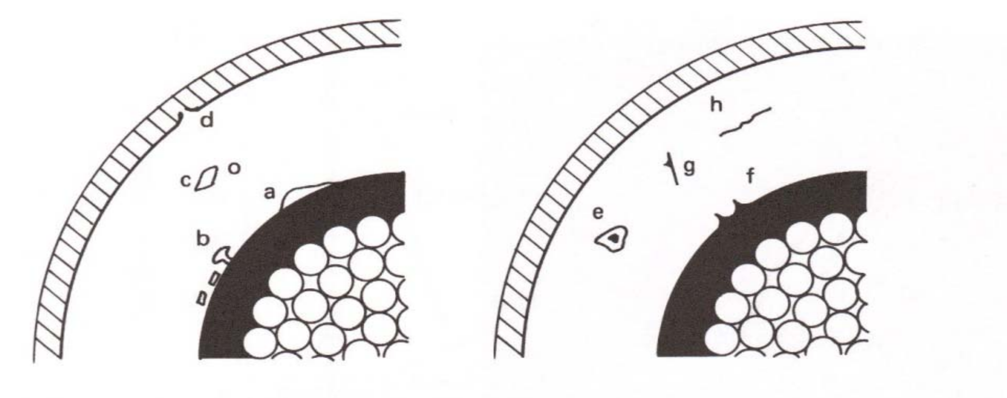


Figure 2.2 Different types of defects in polymer cable insulation [16, 6]

a. Loose semi-conductive screen
b. Bubbles caused by gas-evolution in the conductive screen

c. Cavities due to shrinkage or gas-formation in insulation

d. Defects in the core-screen

e. Inclusion of foreign particles that separate gases

f. Protrusions or projections on the semi-conductive screen

g. Splinters

h. Fibers

2.4 Review on Partial Discharge Mechanism

Partial discharge is a type of electrical discharge that does not completely bridge the insulation between electrodes. In another word, “partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation” [4]. The OF cables are supposed to be free from partial discharge since they are designed to be cavity free while polymer cables, such as XLPE and EPR cables, are easily susceptible to partial discharge and lead to breakdown [6]. It is widely reported that defects in the insulation are the main reason for the occurrence of partial discharges in polymer power cables. The paper [1] discussed that increasing partial discharge activity signifies of the insulation degradation in both EPR and XLPE cables. Mostly insulation defects are due to manufacturing failure and degradation during operation. It is essential for the cable manufacturing companies to take necessary care to reduce defects in cables during manufacture so that partial discharge can be minimized. Partial discharge within a range in insulation is acceptable. The partial discharge testing helps to evaluate the condition of the cable insulation and leads to taking the necessary action before situation gets worse. Excessive partial discharge can result in serious degradation of the cable insulation and can cause the premature failure of the cable insulation.The presence of partial discharge can be detected by visual, audible, ultrasonic, or electrical methods. It is mentioned in paper [14] that partial discharge testing can be done on power cable insulation online or with external voltage source that indicates insulation degradation. Different diagnostic methods are used to detect and locate the partial discharge from the damaged and defected power cables installed in systems.

Partial discharge characteristics depend on the location, type and size of the defects. It also depends on applied voltage, type of insulating material, operating temperature and duration of time [14]. The partial discharge testing can be severely affected by interferences with background noise, earthing, external discharge, electromagnetic radiation, and main supply [15]. Disturbances reduce the sensitivity of the measuring equipment and affect the test results. E. Gulski in [32] developed the statistical tools to evaluate the partial discharge in high voltage devices. He proposed that phase resolved partial discharge analysis could work as a complimentary tool to the conventional partial discharge detection and helps to provide additional information about discharge sources. Discharges in the test circuit can be from terminations, coupling capacitors, connecting leads, high voltage source and background noise. For the precise reading, it is essential that the disturbance is minimal and testing area is shielded and screened properly.

There are two different phenomena of partial discharge occurred in polymer cables [4, 6]:

1. Internal discharge
2. Surface discharge

Internal discharge occurred in cavities in a solid dielectric. Surface discharge occurs at the surface of insulation and around the sharp point of an insulating material. Among these two discharges, internal discharge is the main cause for breakdown of cables. The intensity of discharge depends upon the voltage applied and its duration. If insulation is exposed with discharge for a long time, it deteriorates the cable insulation and affects its lifetime. The relationship between the partial discharge and cable insulation has been an interesting subject of study and research. Due to this, partial discharge measurement techniques play an important role to evaluate the effect of partial discharge on cable insulation and its life.

The partial discharge detection and measurement technique are based on the observation of these phenomena [5]:

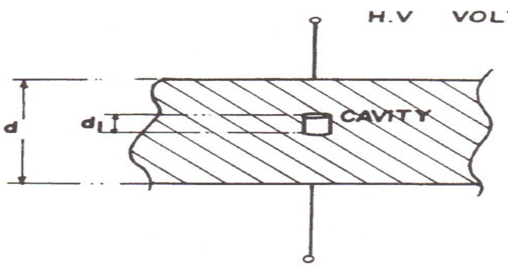
- Electrical pulse currents
- Dielectric losses
- Radiation
- Sound
- Chemical reactions

A partial discharge occurring in materials produces a current pulse and a detector produces a current or a voltage signal at its output proportional to the charge of the current pulse at its input. A Partial discharge pulse is a voltage or current pulse that is due to a partial discharge occurring within materials under test. The detector circuit measures the pulse [5]. Apparent charge q of a partial discharge pulse is that charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the partial discharge current pulse itself [5]. It is usually expressed in picocoulombs (pC).

During the measurement of partial discharge in the insulation, the partial discharge inception voltage and the extinction voltage are also measured. Partial discharge inception voltage V_i is the applied voltage at which continuous partial discharges are observed in the test sample, when the voltage applied to the sample is slowly increased from a lower value at which no partial discharges are observed. Similarly, partial discharge extinction voltage V_e is the applied voltage at which repetitive partial discharges cease to occur in the test sample, when the voltage applied to the sample is gradually decreased from a higher value at which partial discharge pulse quantities are observed [5]. It is mentioned in [39] that the origin of the electron, which starts the partial discharge, may be determined on the basis of partial discharge inception voltage stress.

Partial discharge inception voltage and extinction voltage are used as a parameter for the partial discharge activity in the insulation of the cables. The different trends of inception voltage and extinction voltage that appeared in XLPE and EPR cables show the change occur within the cable insulation due to aging [1]. After the measurement of partial discharge, the aging of the cable is evaluated by applying AC breakdown voltage and the remaining dielectric strength of aged cable is determined.

Figure 2.3 shows a cable insulation sample with a void on it and Figure 2.4 presents equivalent circuit diagram.



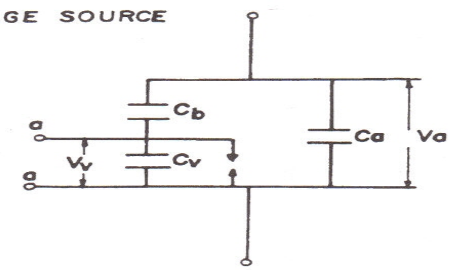


Figure 2.3 Cavity in insulation [3]

Figure 2.4 Equivalent circuit [3]

In Figure 2.4, it is seen that the capacitance of a sample is denoted by C_a. C_v represents the capacitance of the cavity or void and C_b is the capacitance denoting above and below the void capacitance. V_a is the alternating voltage applied to the cable sample. E_v is the electrical stress across the void. When this voltage is higher than the voltage across void V_v, that causes the initiation of the discharge in the void and partial discharge starts taking place.

The voltage across the void [3]

$$V_v = V_a/(1+(d/d_1-1)/\varepsilon_r) \tag{2.1}$$

Here, d and d_1 are the thickness of the sample insulation and the void. ε_r is the relative permittivity.

Similarly, the inception voltage that initiate discharge across the cavity [4]

$$V_{di} = E_v d_1/(1+(d/d_1-1)/\varepsilon_r) \tag{2.2}$$

Figure 2.5 shows voltage and current waveforms during partial discharge activity in a cavity of solid insulation under alternating voltages. V_a is the applied voltage and V_i is the inception voltage that initiates the partial discharge. In Figure 2.5, when V_v reaches breakdown value V_i of the gap, the cavity may breakdown. The voltage across the cavity if no breakdown occurs is shown as a dotted line. A partial discharge occurs when V_v reaches V_i. Then voltage V_v collapses and gap extinguishes. Then the voltage across the cavity begins increasing again until it reaches V_i and a new discharge takes place. During the increasing process of voltage, many discharges occur. Similarly, during the process of reducing the applied voltage, the cavity discharges when voltage across it reaches – V_i [3,4].

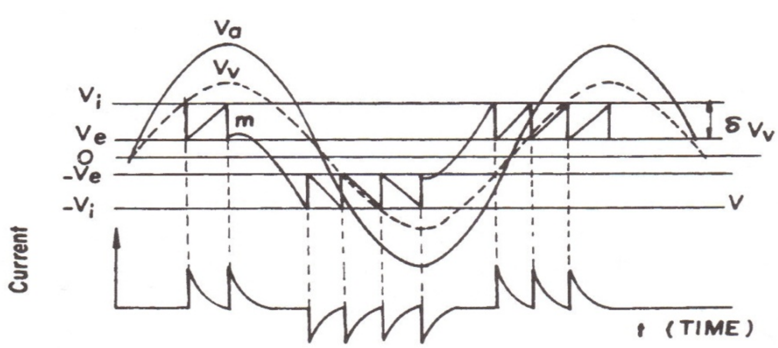


Figure 2.5 ac voltage and current during partial discharge activating in a void [3]

Figure 2.6 presents the general test circuit used to measure the partial discharge activity. It is also known as straight detection method. Here the coupling device is in series with the coupling capacitor and the test sample is grounded.

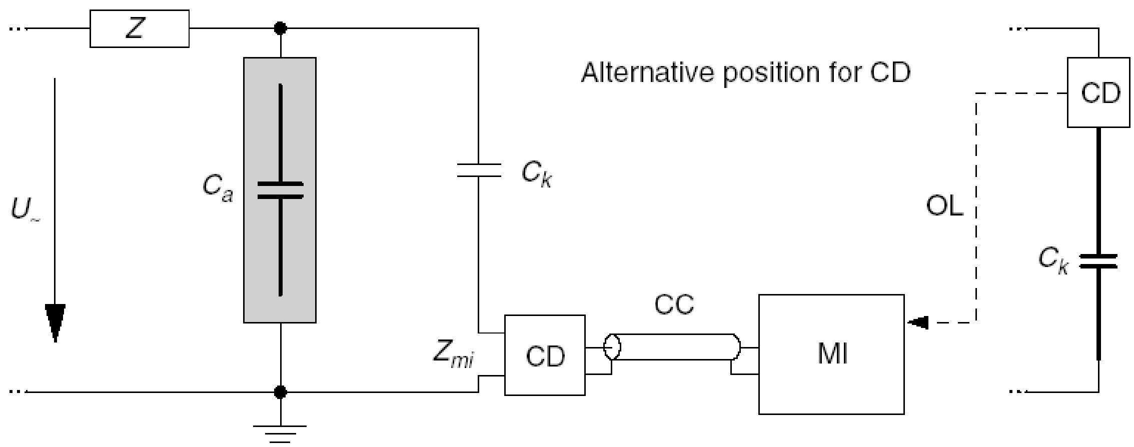


Figure 2.6 Basic partial discharge test circuits [4]

U high- voltage supply

Z_{mi} input impedance of measuring system

CC connecting cable

C_a test object

C_k coupling capacitor

CD coupling device

MI measuring instrument

Z filter

2.5 Effect of Treeing on XLPE and EPR Cables

Treeing is a process of pre-breakdown in solid dielectric materials due to partial discharges and it progresses to form a tree in a solid dielectric insulation under electrical field stress [6, 20]. Basically, treeing can be initiated by partial discharge, mechanical fatigue and charge injection. When electric field is very high, it can even occur in low applied voltage. It is widely reported that treeing can sometimes cause total breakdown of solid insulation material and polymer cables, such as XLPE and EPR, are more susceptible to it. The failure of power cables due to treeing phenomena was a major problem in 1970s and many power utilities investigated to find the main cause for this breakdown. Bahder, Katz, and Lawson [29] investigated polymer cables that were rated between 15 kV and 22 kV and were in service for several years. From their investigation, it was found that those cables are affected with treeing. Even new cables were seen with the treeing effect and it was considered to be due to foreign materials presence in insulation during cable manufacturing process. Mainly the sources of treeing are considered to be voids, cavities, impurities, mechanical defects, and projections. Since these defects weaken the dielectric strength of the insulating materials, it enhances the electrical stress and partial discharge activity.

Electrical treeing and water treeing are two common form of treeing. Electrical tree is developed rapidly within hours or weeks in solid dielectric to form hollow tubes and water is not necessary for it whereas water tree is developed slowly after months, years in insulation to form discreet voids and water contact or moisture is required for the development of water trees [2].

The effect of water treeing in power cable insulation was first reported in 1971 though the electrical treeing was discovered before [21]. According to publication [21], water trees occur with a small spot on the insulation interface and spread out to grow as the voltage is increased with time. Water treeing phenomenon is still not completely understood and the possibility of its occurrence in a new cable needs more investigation. Bahder, Dakin, and Lawson [22] mentioned that water treeing does not help to enhance partial discharge in solid dielectric insulation whereas partial discharge activity is affected by electrical treeing. J. Densley [27] presented the laboratory investigation on power cables that were examined in National Research Council of Canada. According to his research, it was found that there is no occurrence of partial discharge from water trees and partial discharge occurs after electrical trees are initiated form water trees.

M.T.Shaw and S.H.Shaw in [17] mentioned that several power cables, which were affected from treeing in service, were studied to find out how trees are formed and to investigate treeing initiation mechanism. According to trees pattern, they are categorized into different types: bow ties, plumes, dendrites, delta, strings, broccoli, and vented trees [6, 21]. Among these, bow ties and vented trees are the most common one found in solid dielectric material. Bow ties mainly occur in voids and contaminants within the insulation whereas vented trees appear at the insulation interface between the electrodes.

C. Katz and M. Walker [30] tested 35 kV EPR and XLPE cables which were in service for seven years. They found out that those cables were affected mostly with bow tie trees and vented trees. To evaluate those cables, ac and impulse voltage breakdown strength were applied. It was noticed that impulse breakdown strength is higher than ac breakdown strength. The same phenomenon is also observed in paper [31]. It is evident that treeing is affected by high impulse breakdown strength. Many researchers have simulated defects artificially to observe the initiation and growth of trees by inserting a needle into a tested insulation. It is observed that electrical tree occurs due to the high electrical stress at the sharp point of the needle [21, 22 and 23]. S. Grzybowski and R. Dobroszewski in [23] present the results of needle tests conducted on 15 kV insulated cables and the results of these investigations indicate clear correlation of the growth rate of electrical trees and development of partial discharges inside the channels. The results obtained from ac breakdown test indicate that the dielectric strength of polymer insulated cable is affected by water treeing [43]. It is mentioned in paper [22] that though trees are usually initiated and grown with ac voltage, they can also occur by impulse voltage in the presence of high voltage stress. It is observed that electric field stress that occurred at treeing is enough to cause the breakdown in cavities but not enough to breakdown the solid insulation immediately. Figures 2.7 and 2.8 show the electrical trees and water trees found in cable insulation.

The occurrence of treeing in cable insulation slowly leads to the breakdown of the cable since it reduces ac breakdown strength and this phenomenon is mentioned in paper [22, 23, 24 and 25]. Shaw and Shaw in [21] proposed the mechanism for the tree initiation and its growth. They discuss about the mechanical mechanism (cracking) and chemical mechanism (oxidation) on the initiation and growth of trees in solid dielectrics. It is generally known that water trees disappear from insulation when it's dry and reappear again if it's wet. It is evidently seen the conversion of water trees to electrical trees. This conversion has been seen on both bow tie trees and vented trees. The growth of electrical trees from water trees is seen in two different directions. It can either develop in the direction of water tree growth or growing back straight through water tree [26].

The water tree can be transformed into electrical tree when the water tree in the dielectric is enough to enhance the initiation stress to develop the electrical tree.

Though occurrence of treeing in power insulated cables is one of the major reasons for the breakdown of the cables, it can be reduced by improving in design of the power cables. The breakdown of the cables due to water and electrical treeing can be improved by reducing contaminants, defects, and protrusions in cable insulation. There are many approaches discussed to reduce and eliminate treeing in polymer power cable [21, 28]. Cables free of contaminants, voids and smooth interfaces between semicon layer and insulation are reported to be less susceptible to treeing under normal operating conditions [28]. It is proposed in paper [21] that reliability of cables is not possible unless the treeing problem is reduced or improved. It can be achieved by taking certain care: improvement in insulation materials, design improvement, handling of installations, improved inspection testing and cable testing.

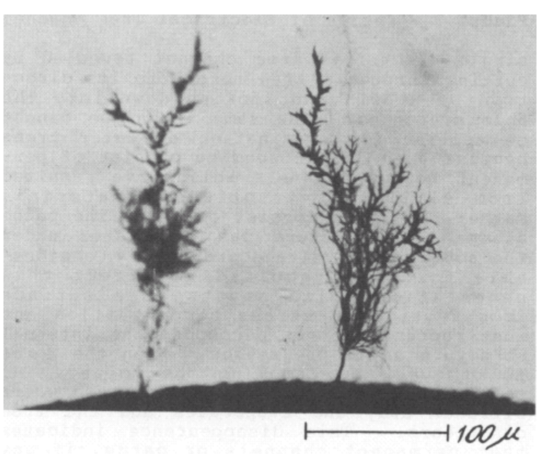


Figure 2.7 Electrical Trees [38]

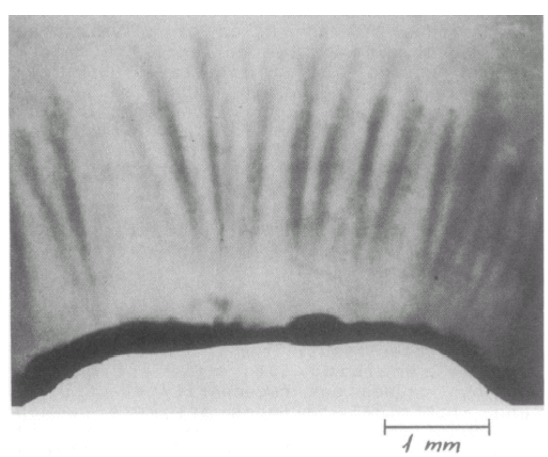


Figure 2.8 Water Trees [38]

2.6 Effect of Switching Impulse on Cable Insulation

Switching operation in the distribution of the power system produces the switching overvoltage. This switching surge has impact on the insulation of the cable and further leads to the breakdown of the cable insulation. Since loads supplied by the distribution lines are switched on and off in the power system, it causes switching transients in the line [1]. Switching surge, which is generated during the operation of the system, is one of the main sources to exert electrical stress on the power cables. Since it is well known that the switching surges have an adverse impact on the behavior of cable insulation, the detailed study about the switching stress on cables is essential.

The cable insulation should be in good condition to supply electrical power securely and reliably without any outage. Yoda and Sekii [41] discussed about the degradation of XLPE insulated cables due to impulse voltages. They found that the impulse breakdown strength of the cables decreases gradually even when the cables are subjected to an impulse voltage lower than the breakdown strength. The results of the test also showed that the obtained data are considerably scattered and the ac breakdown strength of cable is decreased after being subjected to impulse voltages. Though much of the research and investigations have been done on the behavior of EPR and XLPE insulated cables under the stress of ac voltage, the characteristics of those cables under switching impulse stress are still less known despite the severity and frequency of such stress [12, 13 and 17]. The insulation of the cable will be under electrical stress due to the transient over voltage and cavities are formed in the insulation. These cavities have the significant role in the breakdown of the cable. In another word, switching impulse is an important factor in aging the cable insulation.

Grzybowski, Trinka, and Fulper [1] presented the degradation in XLPE and EPR cable insulation as a result of switching impulses. It was verified by partial discharge test and ac breakdown test. The degradation in cable insulation was observed only after 5000 impulses were applied. This similar phenomenon is also observed in papers [12, 13]. It is mentioned in paper [1] that tested XLPE and EPR cables should be applied with several switching impulses to have a better understanding in degradation of cable insulation by switching stress.

Figure 2.9 shows the polymer cables used in power system distribution and switching surges will be generated during the operation of switch S3.

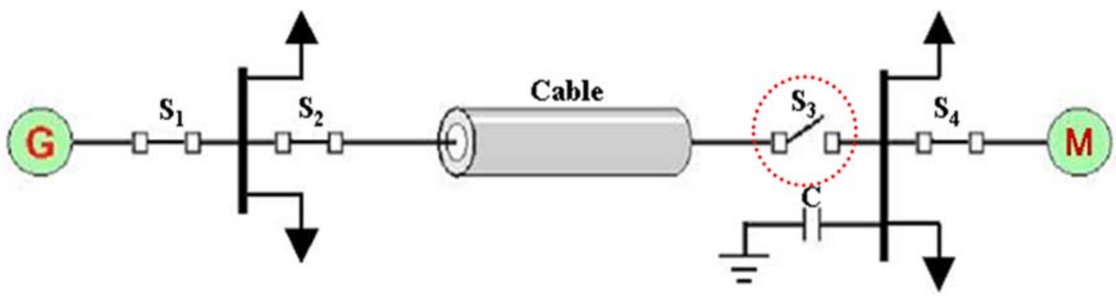


Figure 2.9 Polymer cable in distribution power system

By definition "switching impulse is an impulse with a front duration of some tens to thousands of microseconds" [9]. Figure 2.10 shows the wave shape of full switching impulse generated by impulse generator. The standard switching impulse is given by

T_p/T_2 = 250/2500 μs. Tp is the time to peak and T_2 is the time to half value. There is certain tolerance level for the standard switching impulse and specific impulse. The tolerance limit of peak value, time to peak and time to half value is ±3%, ±20% and ±60%.

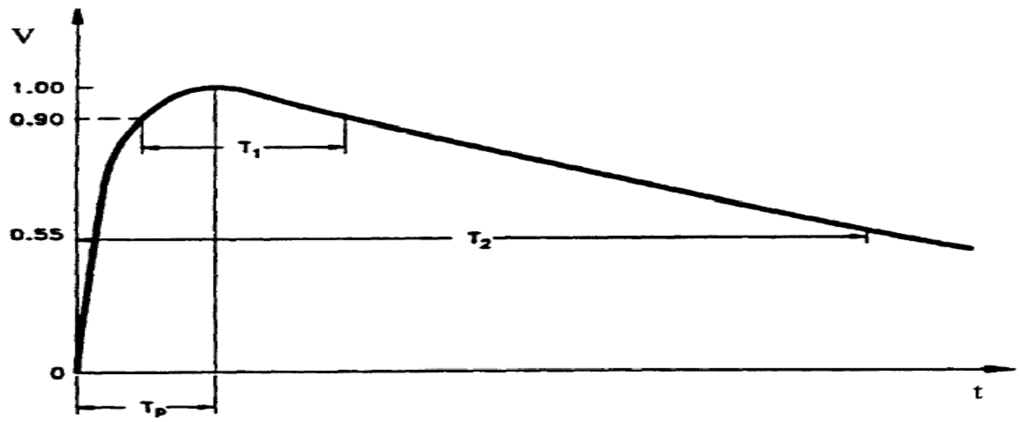


Figure 2.10 Full Switching Impulse [9]

The behavior of EPR and XLPE cables under the switching impulse stress are presented in publications [12] and [13]. Both perform well under switching impulses in dry condition. The cables do not show any sign of aging for specific number of switching impulses and the dielectric strength of cable is still good in severe conditions. The similar phenomenon is also presented in paper [1].

The effect of switching impulses on the XLPE and EPR cable samples is evaluated by partial discharge activity and the analysis is presented in three-dimension plots [1]. In the paper [1], the degradation on the XLPE and EPR insulation is determined by measuring the pulse count, inception voltage, extinction voltage, and apparent charge magnitude. The changes in these parameters evidence that degradation has taken place in cable insulation. The authors discussed the phenomenon on the development of the cavities in the insulation due to the impulse stress [1].

In summary of this chapter on literature review, the development of power cables and its structure are presented. This chapter provides the detail information on breakdown mechanism and partial discharge mechanism in solid insulation. It also discusses about the treeing effect on polymer cables and the effect of switching impulse on cable insulation.

CHAPTER III

EXPERIMENTAL SETUP OF CABLE TESTING

Two types of 15 kV polymer cables, Cross linked Polyethylene (XLPE) and Ethylene Propylene Rubber (EPR), are used as the test samples for the experiment and study. The experiment is conducted on three samples A, B, and C for each XLPE and EPR cables. The chapter deals with the technique and procedure to evaluate power cables under electrical switching stress and to determine the ac breakdown voltage. The condition of cable insulation is evaluated by partial discharge measurement.

3.1 Cable Sample Preparation

The test samples of the experiment are 15 kV XLPE and EPR cables. The tested 15 kV XLPE cable consists of the following configuration: stranded copper conductor, semi-conductive sheath, XLPE insulation, semiconductor layer, copper conductor tape, and PVC jacket. The copper conductor bundle consists of 19 strands, 14 AWG wire with diameter of 10 mm. The XLPE insulation is of 5.50 mm thickness. Semiconductor layer above the insulation is of 0.91 mm thickness. Copper conductor tape is 0.11 mm in thickness and outer PVC jacket is 2.10 mm in thickness. Similarly 15 kV EPR cable also consists of 5 layers: stranded copper conductor, EPR insulation, semiconductor layer, copper conductor tape, and PVC jacket. The dimension of the copper conductor is the same as that of the XLPE cable. The semiconductor sheath wrapped above the conductor is 0.44 mm in thickness. The EPR insulation is 5.68 mm in thickness. Figures 3.1 and 3.2 show the cross-section diagram of 15 kV XLPE and EPR cables.

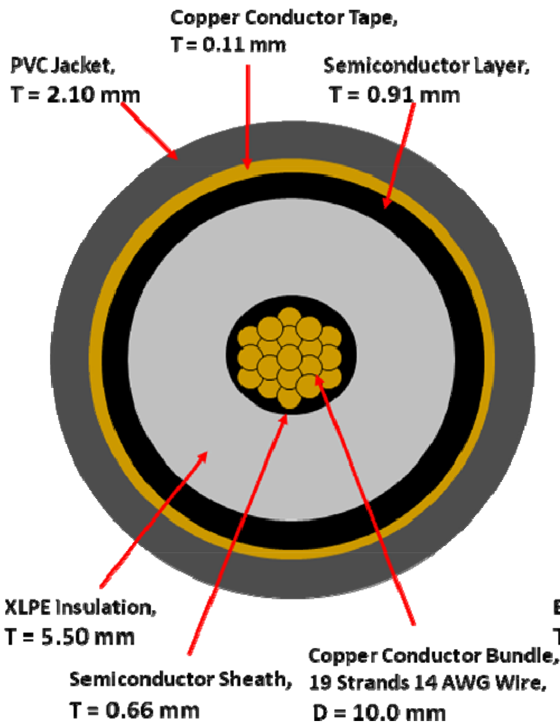


Figure 3.1 Cross section of XLPE cable

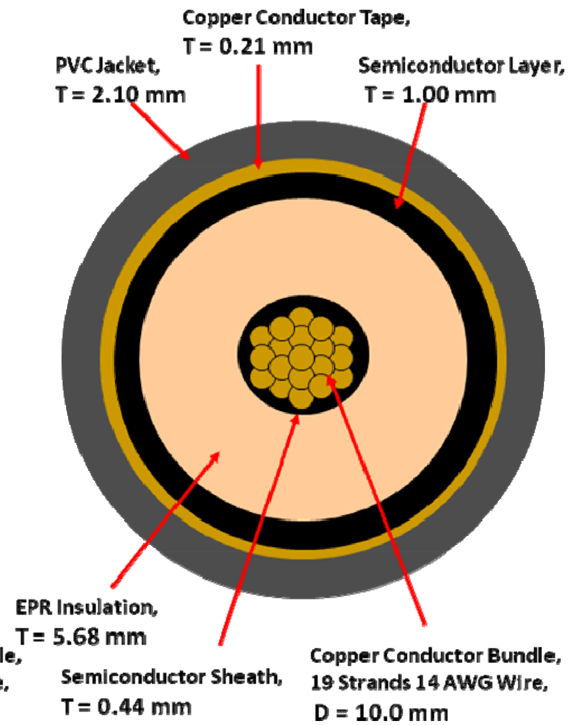


Figure 3.2 Cross section of EPR cable

The semiconductor layer and copper conductor tape are 1 mm and 0.21 mm in thickness. The PVC jacket is 2.10 mm in thickness. The sample cables for testing were prepared as 3m long segments. Figures 3.3 and 3.4 show the configuration and dimension of the test samples.

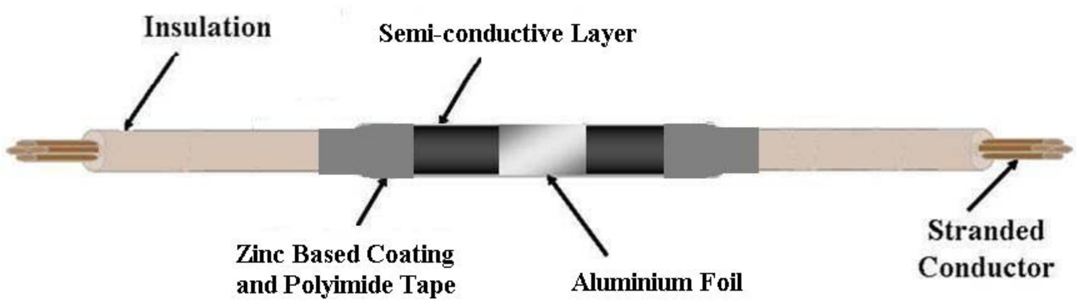


Figure 3.3 Diagram labeling the parts of the XLPE and EPR cable specimen

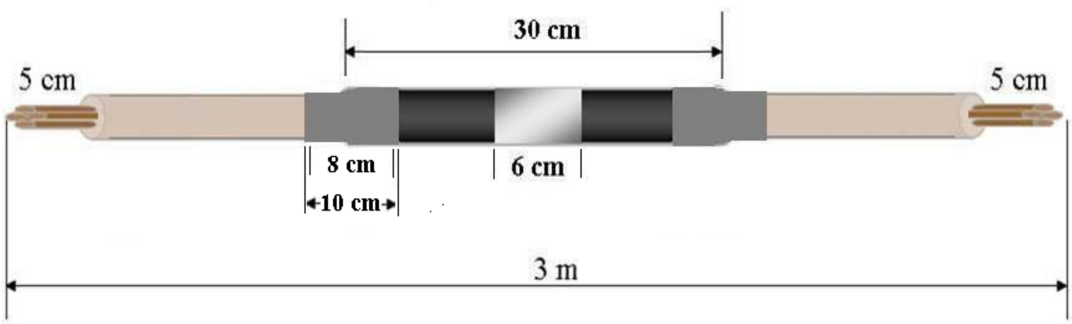


Figure 3.4 Diagram labeling the dimension of the XLPE and EPR cable Specimen

During the sample preparation, the outer PVC jacket and copper tape were removed completely. At both end of test sample, both insulation, and semi-conductive layer of 5 cm were removed leaving only 19 stranded copper conductors. The semi-conductive layer of the cable was stripped back from both ends of the test sample leaving only 30 cm segment in the middle. To prevent cuts in the insulation during the sample preparation, the stripping of the semi-conductive layer was done with extra care. This is done because insulation of the test sample can be weaken due to cut mark and may likely create a place to occur breakdown. To prevent from this problem and for better reading, the semi-conductive layer was peeled off with nose pliers instead of using a utility knife.

A 6 cm wide aluminum foil was attached on the surface of the semi-conductive layer and then connected to the ground. A shielding system was selected to reduce the surface flashover when the switching impulses were applied [1]. To reduce the surface discharge, a zinc based semi-conductive coating of 4 cm length was sprayed above the insulation and the semi-conductive layer. A 10 cm non-static polyimide tape with low conductivity was also wrapped on the zinc- based coating to measure the partial discharge properly. This technique of preparing samples was proven to be effective to meet the demand of the experiment. The experiment, which was conducted on EPR and XLPE cables, consisted of three samples each: A, B and C. Each sample consisted of 5 sub groups. These sub groups were applied with 0, 100, 500, 1000 and 5000 switching impulses.

3.2 The Switching Impulse Generator and Measurement System

An impulse generator is used as the testing equipment to age the XLPE and EPR cables. The standard switching impulses were generated from a 4-stage, 8 kJ impulse generator. In this experiment, switching impulses of 100 kV magnitudes were applied to test samples as the aging force. The actual switching surges caused by power system operations are irregular in wave shape and difficult to simulate. According to IEEE standard 4-1995, standard switching impulses of 250/2500 μs were applied. But the tolerance level of standard switching impulse is considered during the measurement. The switching impulses were measured for voltage magnitude and shape using a voltage divider system connected to the test object. The voltage from the divider is displayed on a 14-bit high voltage digitizer, which displays each waveform as impulses were applied to the test object. The switching impulses were applied on the test samples at the rate of 2 impulses per minute.

The experiment was conducted at ambient temperature of 20 ºC. The five different specific switching impulses of 0, 100, 500, 1000, and 5000 were applied to different test samples. Figure 3.5 shows the test samples connected with the voltage divider and impulse generator. One end of the sample was connected to the power source and the other end was left floating. Two cables were connected in parallel so that 100 kV switching impulse could be applied at same time. The 100 kV switching impulse magnitude is the basic switching impulse insulation level (BSL) values corresponding to the cable rating. Figure 3.6 represents the standard switching impulse of 100 kV magnitude of the test voltage applied on the cable samples.

Figure 3.5 Cable samples connected with Impulse Generator and Voltage Divider

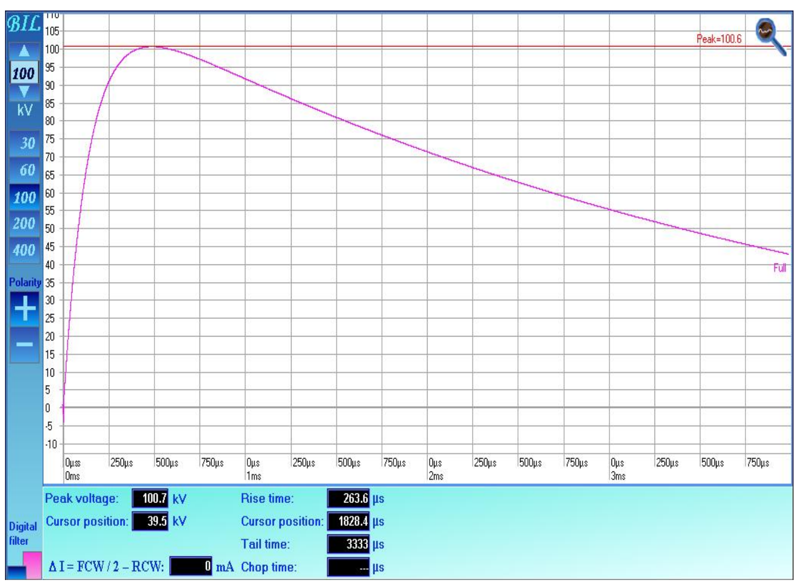


Figure 3.6 Switching impulse wave shape obtained from Impulse generator

3.3 Partial Discharge Measurement

Hipotronics DDX-7000 digital discharge detector was used to detect and measure partial discharge activity in the cable insulation. It is a computer controlled measuring instrument that takes the small signals generated by partial discharge activity in insulation and processes them so that they can be measured and displayed [33]. This detector utilizes the electrical method to detect partial discharge.

Figure 3.7 DDX-7000 Digital discharge detector

It measures the partial discharge by measuring the flow of electric charge in an insulating material during a breakdown: in a void, along a surface, or in free air. Since the electrical charge is moving through insulation, a voltage is measured. The measured voltage is proportional to the partial discharge present in the insulation. The measured signal is displayed as a pulse on an oscilloscope. Figure 3.7 shows the DDX-7000 digital discharge detector used in measuring partial discharge in the cable insulation. The partial discharge parameters were measured at power frequency of 60 Hz. The partial discharge parameters measured were partial discharge inception voltage, partial discharge extinction voltage, pulse count, and apparent charge (PD Magnitude). These parameters were measured throughout the aging process.

The pulse count and partial discharge magnitude were recorded in the 10-second time frame at 18 kV, 60 Hz. To observe the aging phenomena during the aging process, three-dimension analysis of partial discharge was performed. Figure 3.8 presents a basic high voltage circuit used to measure the partial discharge activity.

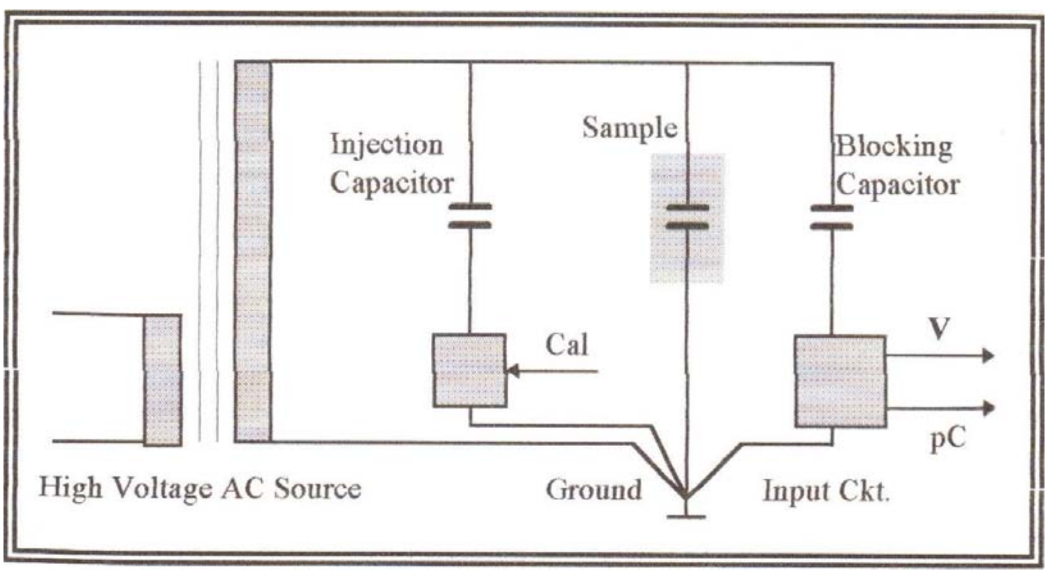


Figure 3.8 Test circuit for partial discharge measurement [33]

After a specific number of switching impulses applied to the samples, partial discharge measurement was performed. Partial discharge measurements were taken for 0 (new samples), 100 impulse samples, 500 impulse samples, 1000 impulse samples and 5000 impulse samples. On cable samples that were applied with 500 switching impulses, partial discharge measurements were recorded at every 100 impulses. The cable samples that were applied with 1000 impulses, partial discharge measurements were taken at each 200 impulses. Similarly, the cable samples that were applied with 5000 impulses, partial discharge measurements were recorded at every 500 impulses.

A single phase ac transformer was used as the high voltage source for partial discharge measurement. The power rating of this transformer is 40 kV, 2 kVA.

3.4 ac Breakdown Measurement

Hipotronics ac dielectric test sets are used to provide ac test power for a variety of capacitive, inductive or resistive loads. The testing unit is designed for extremely low noise levels. The ac voltage source of 250 kV, 60 kVA, 60 Hz was used to evaluate the ac breakdown voltage of cable samples. The ac breakdown voltage of the cable samples was evaluated after applying a specific number of switching impulses. At the end of the aging process, ac breakdown voltages of all testing cable samples were measured immediately to evaluate the remaining dielectric strength. During the ac breakdown test, the tested sample was immersed in the mineral oil to smooth the electric field on its surface. One end of the cable sample was connected with the high voltage source of the transformer and the other end was left floating. Duct seal was also used at the both end of the copper conductor of the cable sample to reduce the electric field. The ground wire was connected on the aluminum foil at the middle of the cable sample. Figure 3.9 shows the cable sample submerged in the mineral oil during the ac breakdown test.

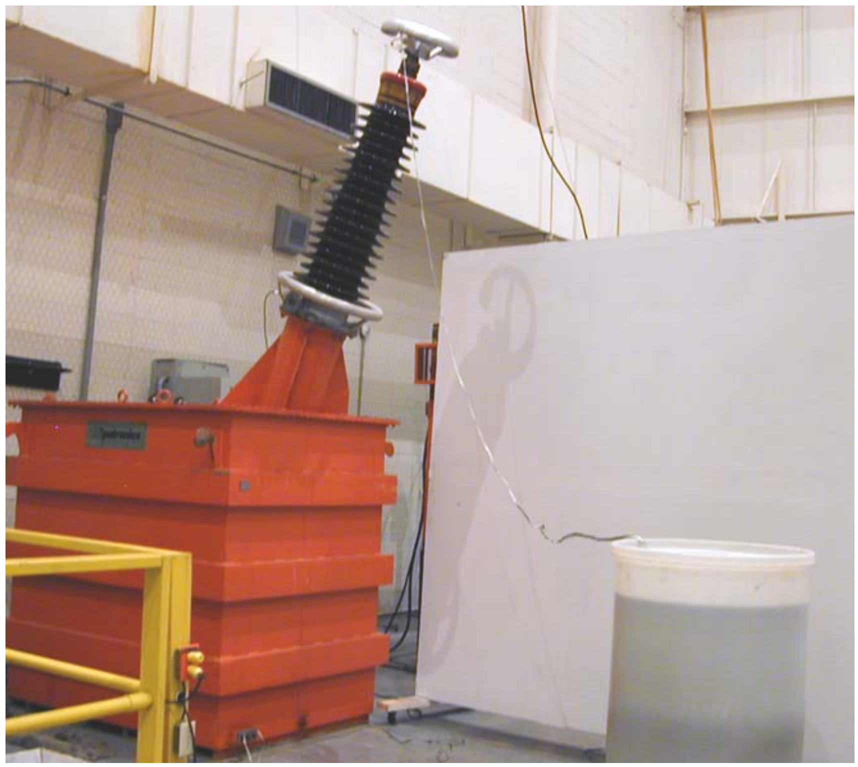


Figure 3.9 Cable sample in oil container during ac breakdown test

CHAPTER IV

RESULTS

In this chapter, ac breakdown test determines the remaining dielectric strength of the aged cable. The ac breakdown voltage of the 15 kV XLPE and EPR cable samples was evaluated after applying specific number of switching impulses. The degradation in the cable insulation due to the switching impulses was evaluated by measuring partial discharge activity. The results obtained from the partial discharge measurement test and ac breakdown test in XLPE and EPR cable samples are presented in this chapter. The result is obtained by taking the average of three samples: A, B and C.

4.1 Partial Discharge Results

The partial discharge measurements are performed on the 15 kV XLPE and EPR test samples. In partial discharge measurement, partial discharge analysis is performed on the new test samples and the aged samples. The results present the partial discharge parameters measured during the partial discharge activity. The different partial discharge parameters measured are partial discharge inception voltage, partial discharge extinction voltage, partial discharge magnitude (Apparent charge), and partial discharge pulse count. The presented data are the average of the three samples A, B and C.

4.1.1 Partial Discharge Inception and Extinction Voltage

Test samples are aged for the specific number of switching impulses and then partial discharge measurements data are recorded. During the measurement, partial discharge inception voltage and partial discharge extinction voltage are measured. The partial discharge analysis is done for 10 sec time frame at 18 kV, 60 Hz to determine the apparent charge magnitude. Partial discharge measurements are performed on five different groups of A, B, and C cable samples. The average of the measured A, B and C cable samples for specific applied impulses was calculated for the analysis. The five different groups of each sample are applied with 0 (new samples), 100, 500, 1000, and 5000 switching impulses.

For the 500 switching impulse samples, partial discharge measurements were performed at each interval of 100 switching impulses. With the 1000 switching impulse samples, partial discharge measurements were recorded at every interval of 200 switching impulses. Lastly, with the 5000 switching impulse samples, partial discharge measurements are measured at each interval of 500 switching impulses.

4.1.1.1 Partial Discharge Inception and Extinction Voltage for New Samples

Table 4.1 PD inception voltage of new XLPE and EPR cable samples

Type of Cable Sample	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
XLPE	19.8	20.5	15.5	18.6
EPR	18.9	16.4	18.3	17.9

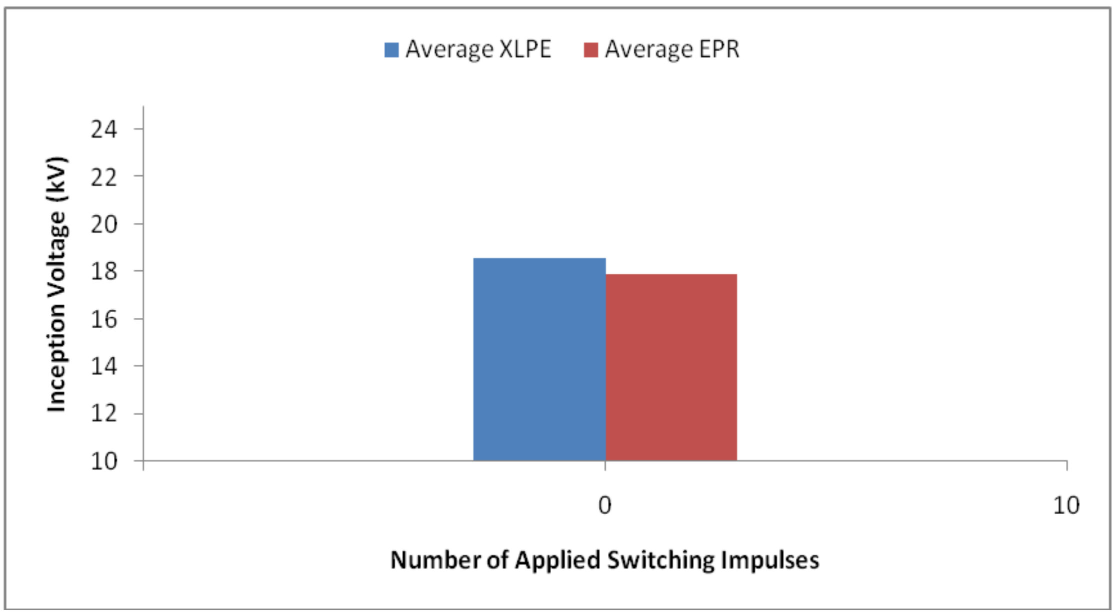


Figure 4.1 Average PD inception voltage of three new XLPE and EPR cable samples

Table 4.2 PD extinction voltage of new XLPE and EPR cable samples

Type of Cable Sample	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
XLPE	18.6	19.4	14.3	17.4
EPR	17.6	15.5	17.1	16.7

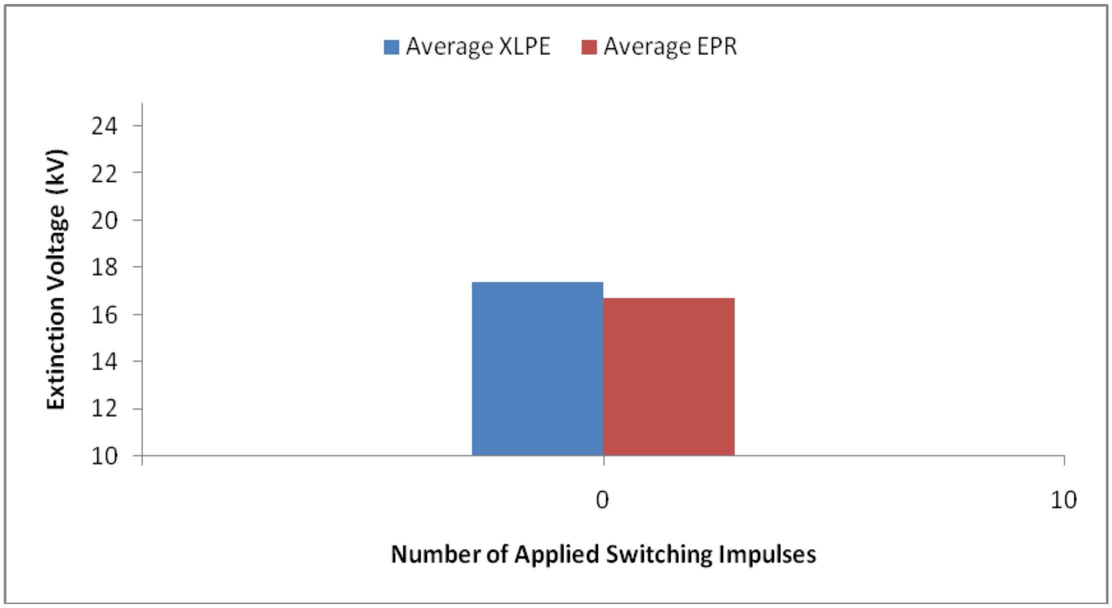


Figure 4.2 Average PD extinction voltage of three new XLPE and EPR cable samples

The partial discharge measurements (inception and extinction voltage) are performed on new XLPE and EPR cable samples and the results are shown in the Table 4.1, Table 4.2 and Figure 4.1. The average inception voltage of new XLPE and EPR cable samples is 18.6 kV and 17.9 kV. The average extinction voltage of new XLPE cable samples is also higher than that of new EPR cable samples, Figure 4.2.

4.1.1.2 Partial Discharge Inception and Extinction Voltage for 100 Applied Impulse Samples

Table 4.3 PD inception voltage of XLPE cables for 100 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	20.8	19.4	16.5	18.9
100	18.5	16.6	15.3	16.8

Table 4.4 PD inception voltage of EPR cables for 100 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	18.4	19.1	15.2	17.5
100	16.9	19.4	15.5	17.2

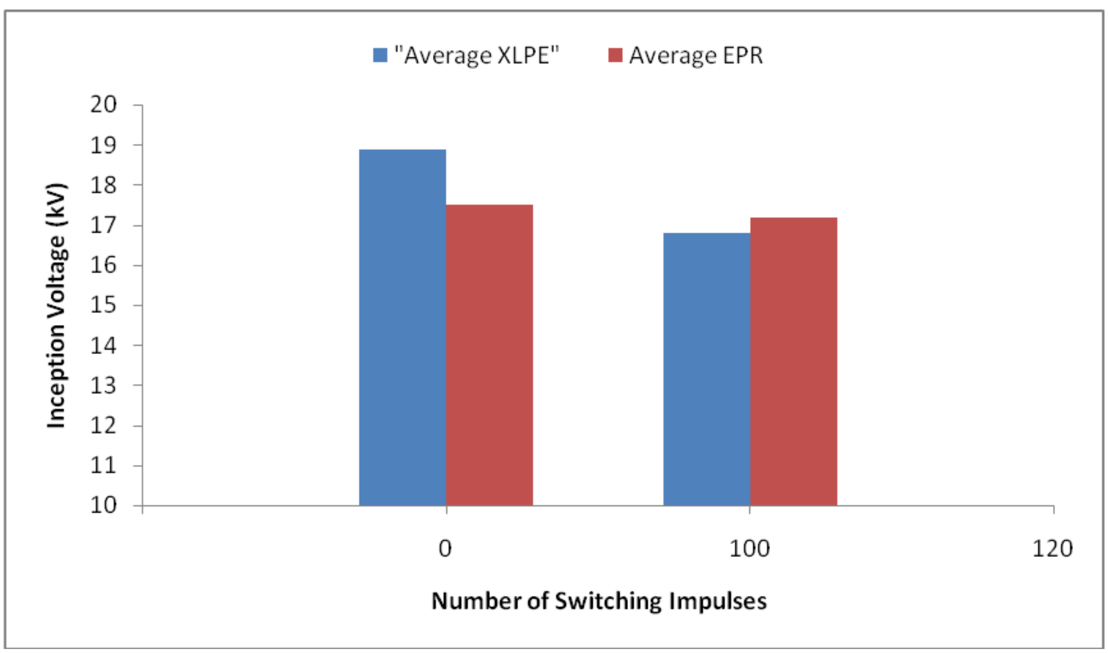


Figure 4.3 Average PD inception voltage of three XLPE and EPR cable samples for 100 applied switching impulses

Table 4.5 PD extinction voltage of XLPE cables for 100 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	19.7	18.6	14.7	17.7
100	17.5	15.7	14.1	15.8

Table 4.6 PD extinction voltage of EPR cables for 100 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	17.3	17.8	14.4	16.5
100	15.7	18.3	14.6	16.2

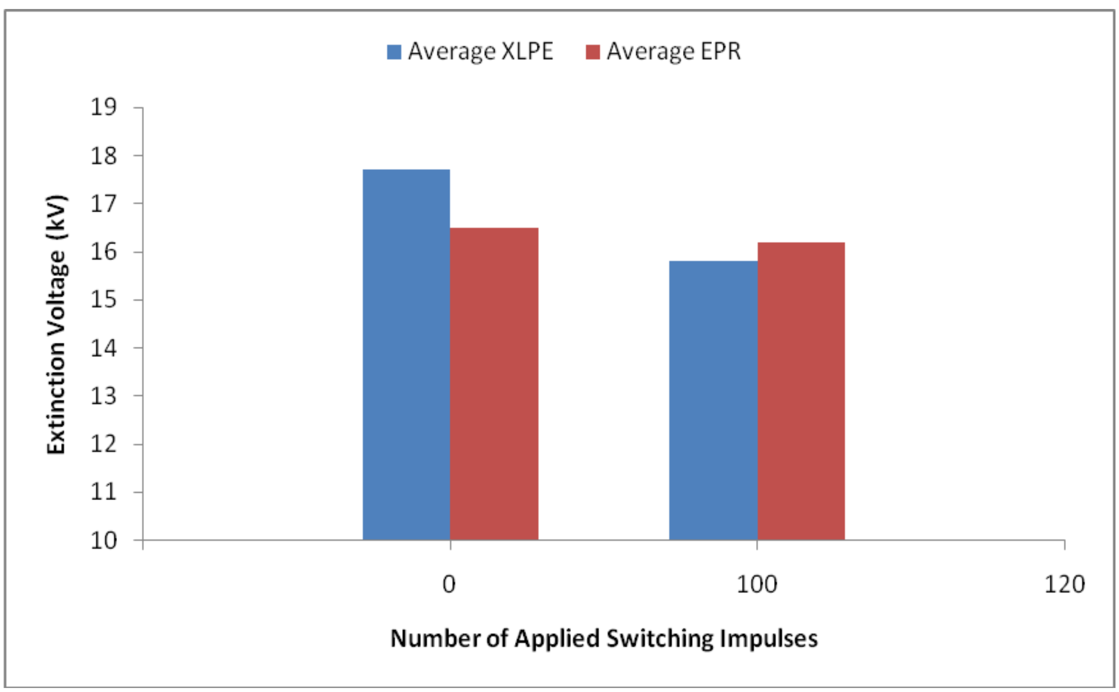


Figure 4.4 Average PD extinction voltage of three XLPE and EPR cable samples for 100 applied switching impulses

Tables 4.3, 4.4, 4.5 and 4.6 present the partial discharge activity performed on cable samples that were applied with 100 switching impulses. The 100 switching impulses have also observed no high impact on the cable insulation and it shows no effect of partial discharge. The average inception voltage of XLPE and EPR cable samples for 100 impulses is 16.8 kV and 17.2 kV respectively. The data obtained from the measurement of these cable samples shows that there is no effect of the impulses on the cable samples that is presented in Figures 4.3and 4.4. From the graphs, XLPE cable samples have slightly higher inception and extinction voltage than EPR cable samples for applied 0 switching impulses while EPR cable samples have higher inception and extinction voltage for than that of XLPE cable samples at 100 impulses.

4.1.1.3 Partial Discharge Inception and Extinction Voltage for 500 Applied Impulse Samples

Table 4.7 PD inception voltage of XLPE cables for 500 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	21.2	17.8	16.9	18.6
100	15.5	14.2	15.7	15.1
200	20.9	15.1	16.6	17.5
300	19.4	14.8	14.9	16.3
400	18.6	13.9	13.8	15.4
500	20.5	16.6	13.5	16.8

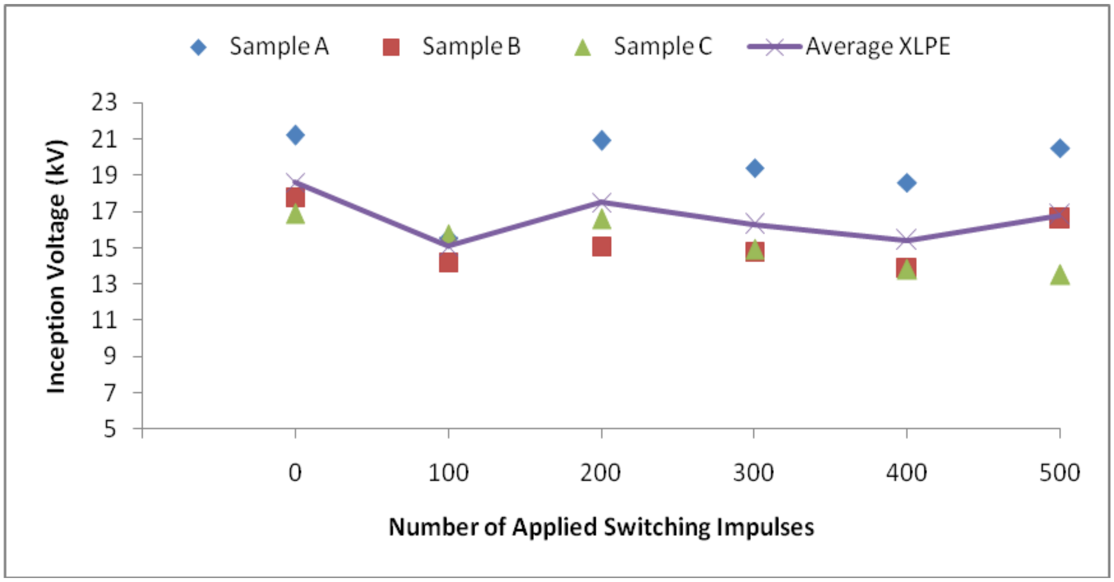


Figure 4.5 PD inception voltage of three XLPE cable samples for 500 applied switching impulses

Table 4.7 presents the partial discharge inception voltage of XLPE cable samples measured during the partial discharge activity. The average inception voltage shows small changes during 500 switching impulses.

Table 4.8 PD inception voltage of EPR cables for 500 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	17.8	16.7	16.9	17.1
100	17.9	14.8	16.7	16.4
200	18.6	17.9	14.2	16.9
300	19.3	17.5	15.8	17.5
400	16.7	19.7	14.9	17.1
500	20.4	18.9	14.5	17.9

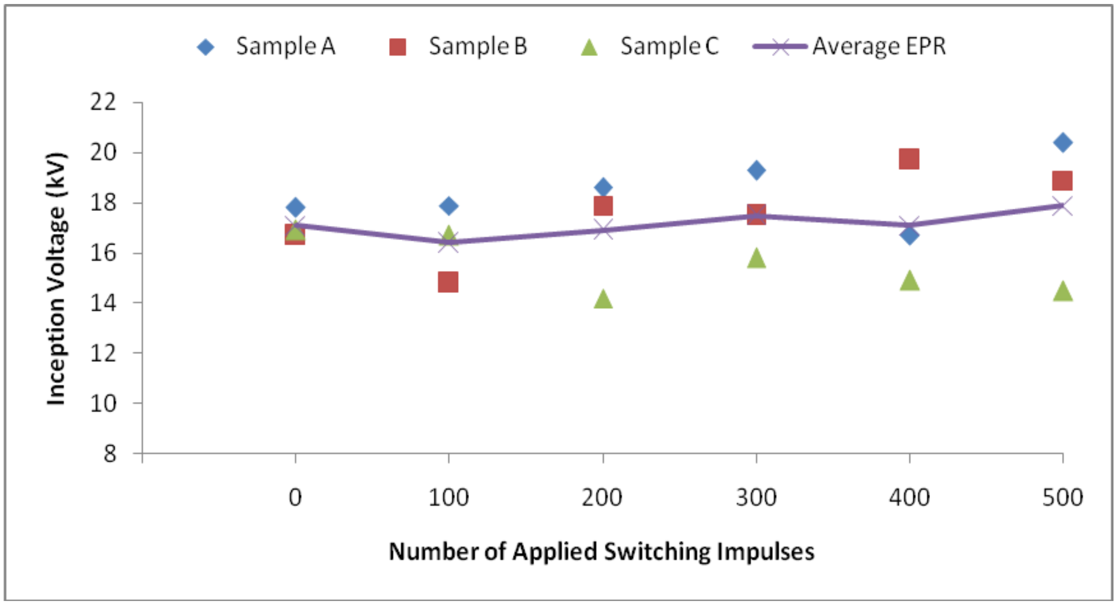


Figure 4.6 PD inception voltage of three EPR cable samples
for 500 applied switching impulses

The average partial discharge inception voltage trend of EPR cable samples for 500 impulses is shown in Figure 4.6. The inception voltages of measured samples at 0 and 500 impulses are 17.1 kV and 17.9 kV respectively.

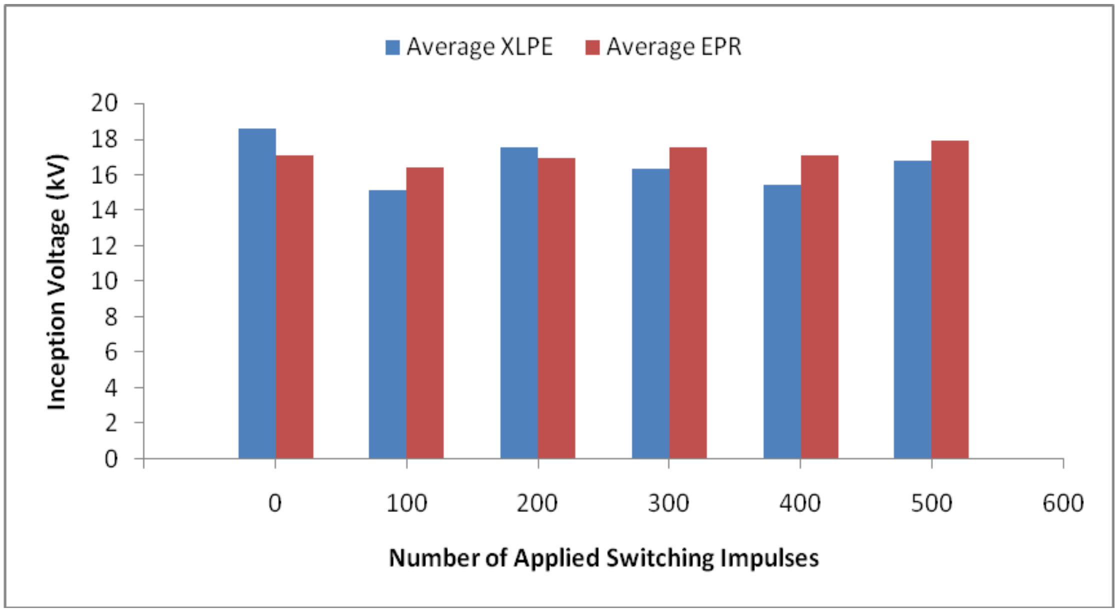


Figure 4.7 Average PD inception voltage of three XLPE and EPR cable samples for 500 applied switching impulses

The average inception voltage measured for XLPE cable samples varies from 18.6 kV to 16.8 kV. Similarly, the average inception voltage recorded for EPR cable samples changes from 17.1 kV to 17.9 kV. The average inception voltage of XLPE is a decreasing trend whereas EPR is an increasing trend.

Table 4.9 PD extinction voltage of XLPE cables for 500 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	19.2	16.5	15.9	17.2
100	13.9	13.1	14.2	13.7
200	19.7	14.3	15.8	16.6
300	18.3	13.1	13.6	15.0
400	17.4	13.2	12.7	14.4
500	19.6	15.9	12.9	16.1

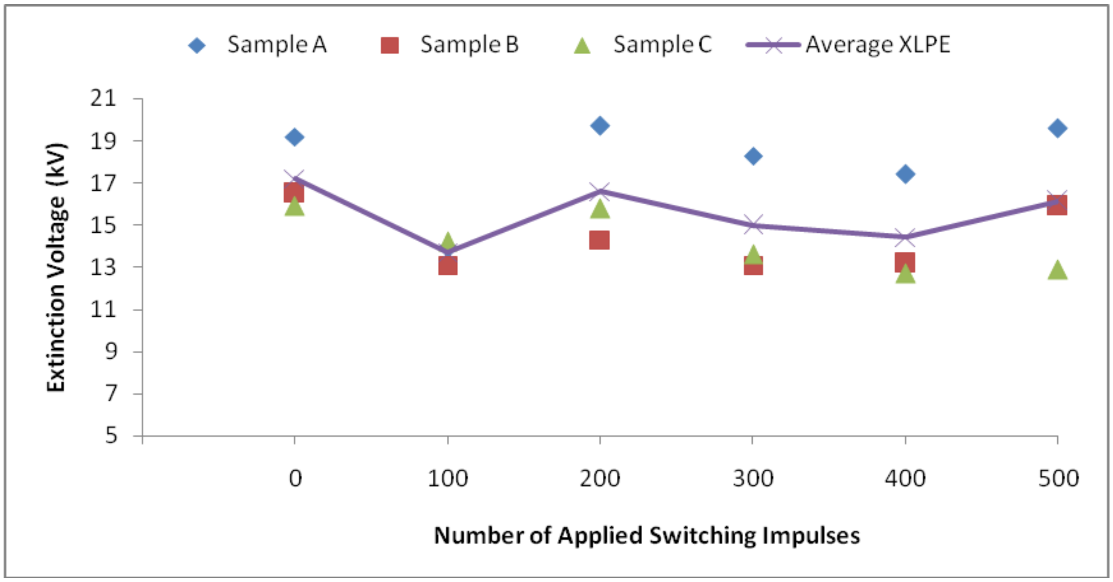


Figure 4.8 PD extinction voltage of three XLPE cable samples for 500 applied switching impulses

The average partial discharge extinction voltage of XLPE cable samples for 500 applied impulses is shown in Figure 4.8. The average extinction voltage measured show decreasing trend from 17.2 kV to 16.1 kV respectively.

Table 4.10 PD extinction voltage of EPR cables for 500 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	16.3	16.7	15.8	16.2
100	16.8	14.1	15.7	15.5
200	17.2	16.8	13.5	15.8
300	17.9	14.1	14.4	15.4
400	14.1	18.6	13.8	15.5
500	18.7	17.7	14.1	16.8

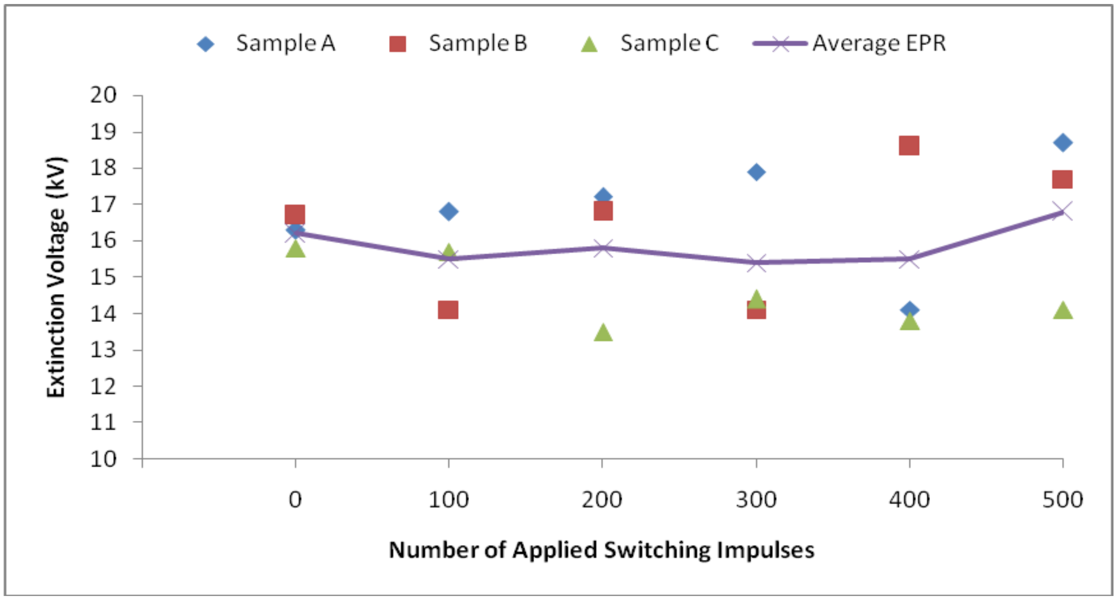


Figure 4.9 PD extinction voltage of three EPR cable samples for 500 applied switching impulses

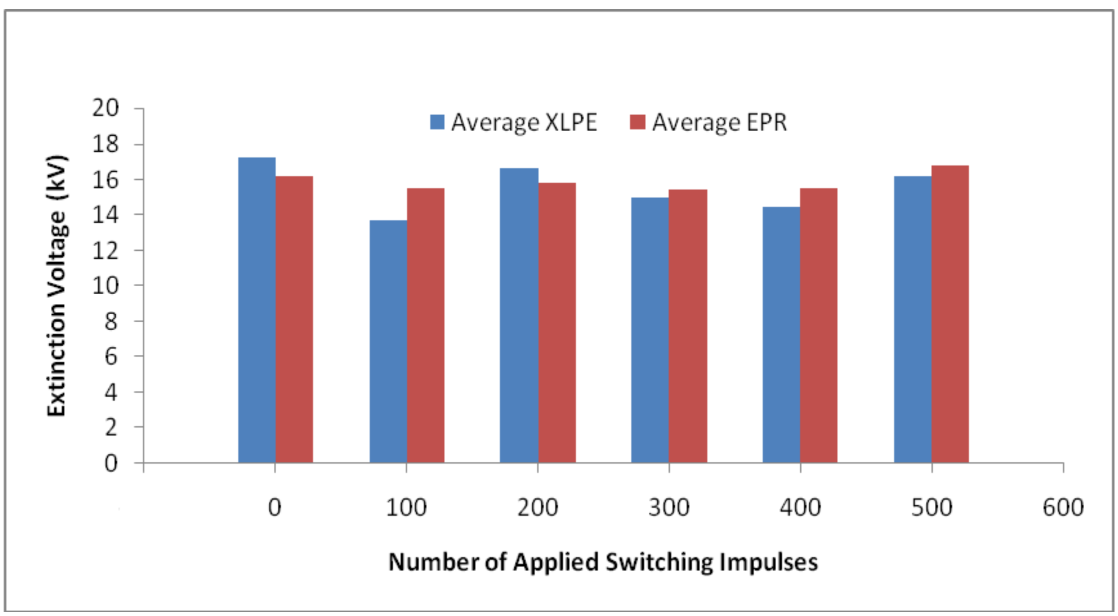


Figure 4.10 Average PD extinction voltage of three XLPE and EPR cable samples for 500 applied switching impulses

Tables 4.7, 4.8, 4.9, and 4.10 show the measured partial discharge activity on cable samples that were applied with 500 switching impulses. Tables 4.7 through 4.10 present the partial discharge inception voltage and extinction voltage for XLPE and EPR cable samples. From the data obtained, it signifies that no significant degradation in insulation has taken place on cable samples for these specific applied impulses. It can be noted in Figures 4.7 and 4.10.

4.1.1.4 Partial Discharge Inception and Extinction Voltage for 1000 Applied Impulse Samples

Table 4.11 PD inception voltage of XLPE cables for 1000 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	15.8	17.8	16.9	16.8
200	16.1	16.5	17.2	16.6
400	19.8	16.3	15.7	17.2
600	18.2	14.2	14.9	15.7
800	17.0	16.2	16.7	16.6
1000	17.4	14.5	15.3	15.7

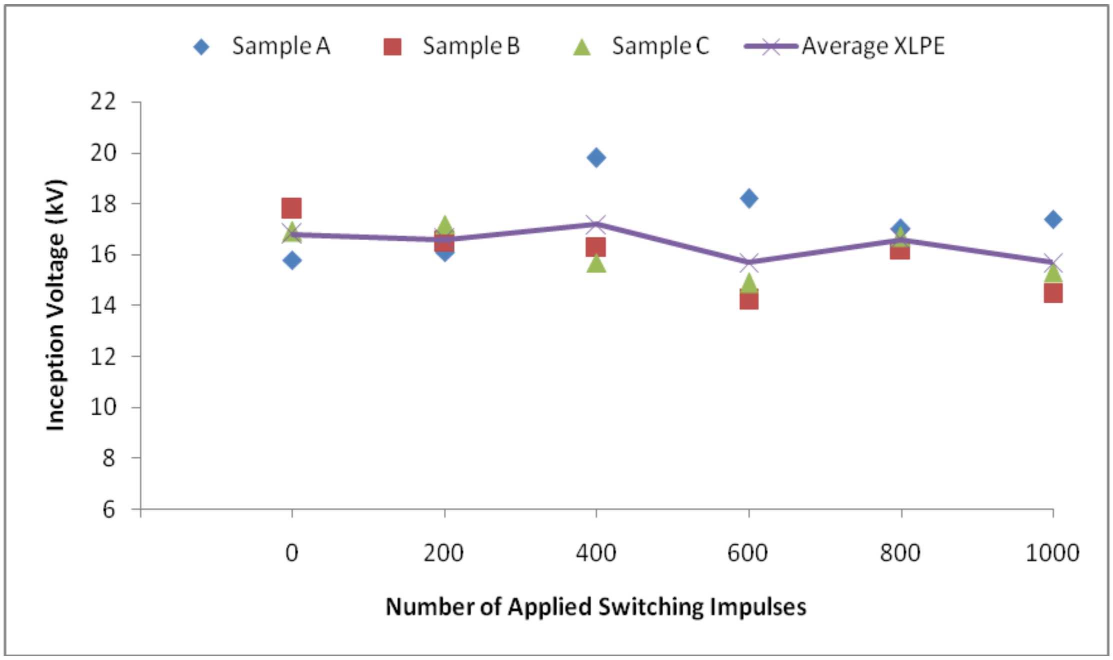


Figure 4.11 PD inception voltage of three XLPE cable samples for 1000 applied switching impulses

Table 4.12 PD inception voltage of EPR cables for 1000 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	16.8	17.9	18.3	17.6
200	15.5	14.7	16.4	15.5
400	12.6	14.7	13.6	13.6
600	13.5	17.6	15.7	15.6
800	13.2	15.7	15.1	14.7
1000	13.3	13.8	16.7	14.6

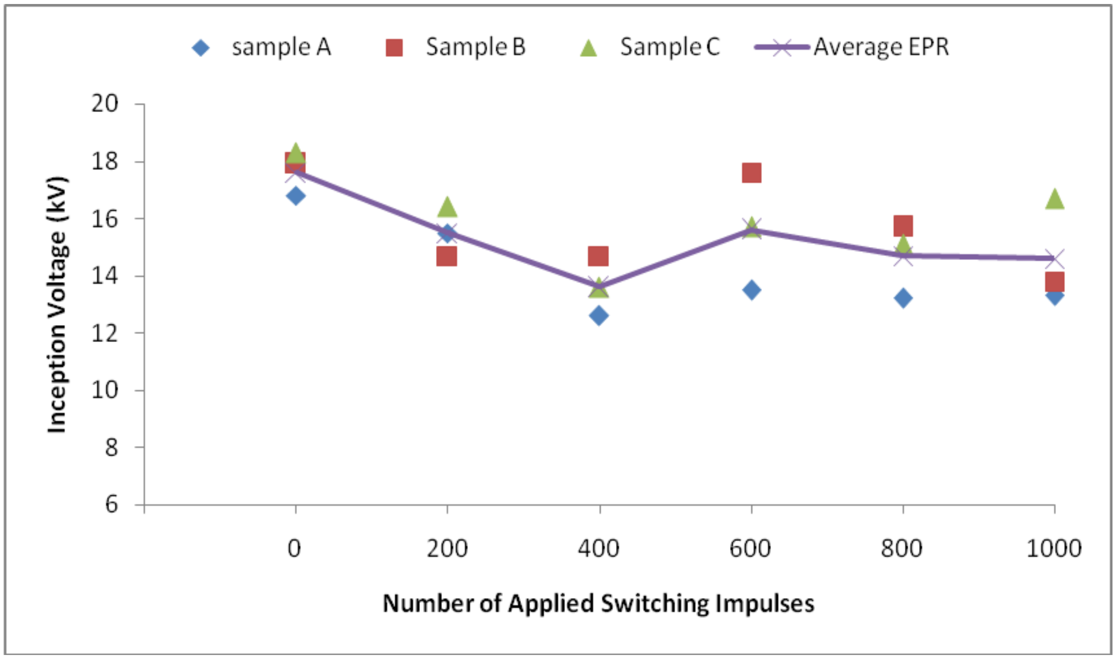


Figure 4.12 PD inception voltage of three EPR cable samples
for 1000 applied switching impulses

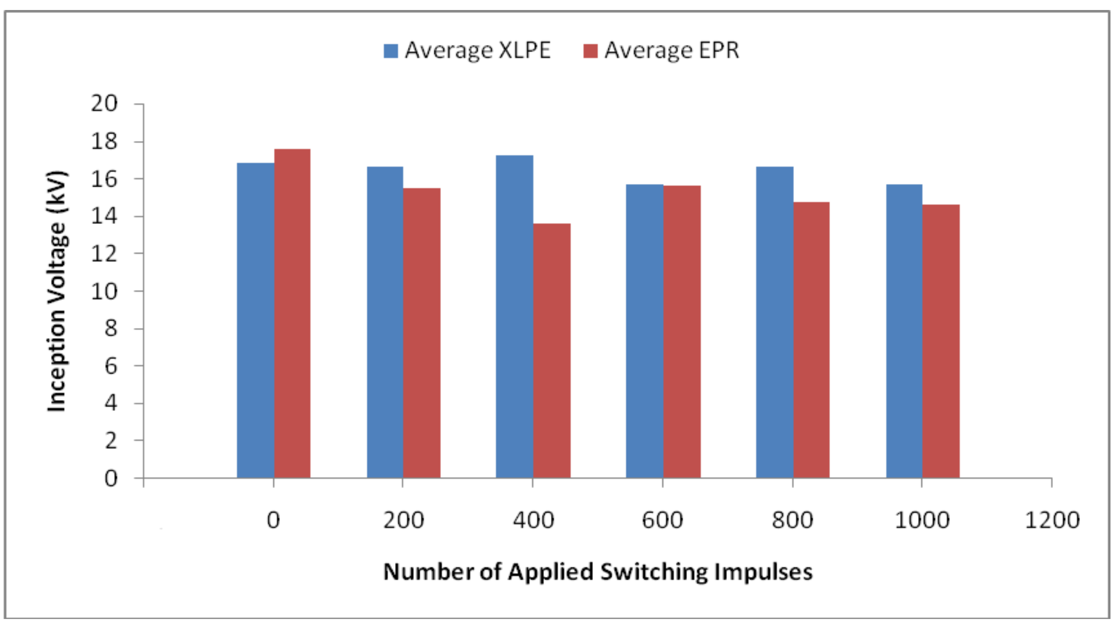


Figure 4.13 Average PD inception voltage of three XLPE and EPR cable samples
for 1000 applied switching impulses

From Figure 4.13, it is seen that the average partial discharge inception voltage of XLPE cable samples is less than EPR test samples for 0 switching impulses and higher for other applied switching impulses.

Table 4.13 PD extinction voltage of XLPE cables for 1000 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	14.2	15.7	15.2	15.1
200	13.5	14.8	15.9	14.7
400	18	14.7	14.6	15.7
600	16.9	12.1	12.8	13.9
800	15.7	15.4	14.5	15.2
1000	16.4	14.5	14.1	15.0

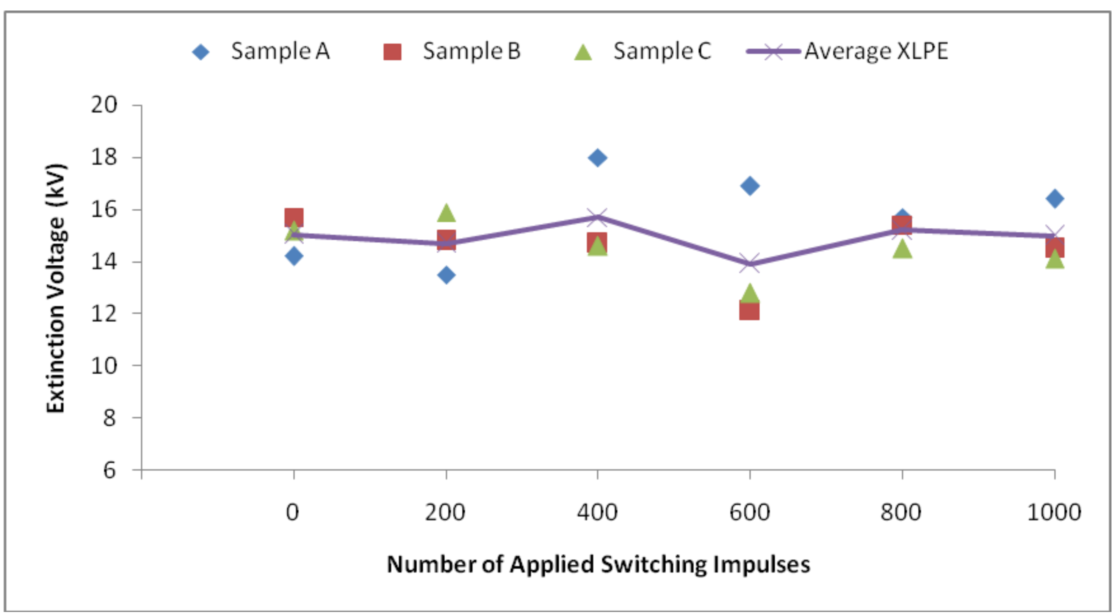


Figure 4.14 PD extinction voltage of three XLPE cable samples for 1000 applied switching impulses

Table 4.14 PD extinction voltage of EPR cables for 1000 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	15.8	17.2	16.8	16.6
200	14.0	14.1	15.7	14.6
400	11.2	14.3	12.7	12.7
600	11.8	16.8	14.6	14.4
800	10.8	14.6	14.1	13.1
1000	11.4	12.7	15.6	13.2

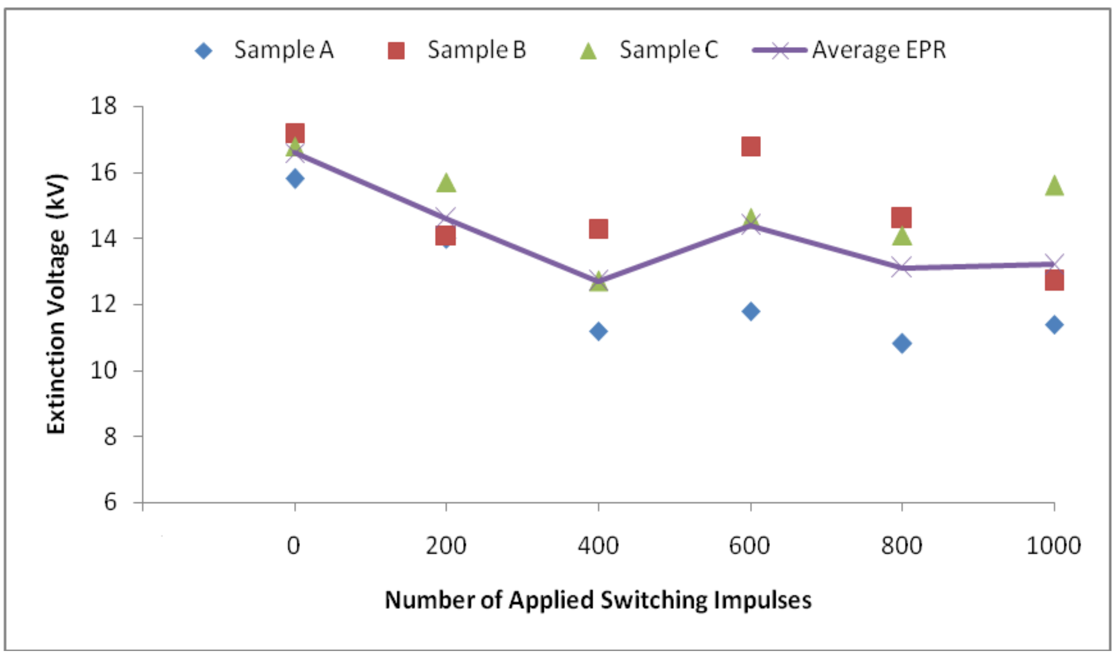


Figure 4.15 PD extinction voltage of three EPR cable samples for 1000 applied switching impulses

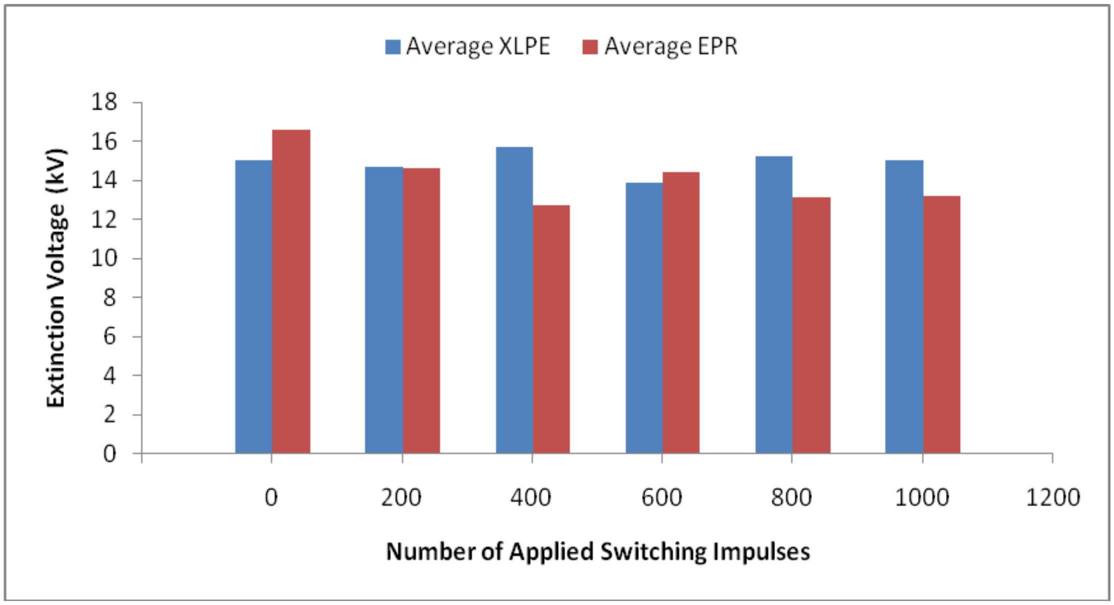


Figure 4.16 Average PD extinction voltage of three XLPE and EPR cable samples for 1000 applied switching impulses

Partial discharge inception voltage and extinction voltage for cable samples of 1000 switching impulse results are presented in Tables 4.11 through 4.14. They are shown in Figure 4.13 and Figure 4.16. The inception and extinction voltage of XLPE cables remain almost constant whereas EPR cable samples show slight decreasing trend in inception voltage and extinction voltage. The average inception and extinction voltage of XLPE is better than that of EPR cable samples for applied 1000 switching impulses.

For the number of switching impulses from 0 to 1000, the trend in average partial discharge inception voltage of XLPE cable samples is from 16.8 kV to 15.7 kV while the trend in average inception voltage measured for EPR cable samples is recorded from 17.6 kV to 14.6 kV. Though XLPE cable samples show slightly better performance in partial discharge activity than EPR cable samples but it can be concluded that XLPE and

EPR cable samples do not show much sign of degradation in cable insulation after specific switching impulses are applied. This can be observed in Figures 4.13 and 4.16. The average extinction voltage measured for both XLPE and EPR cable samples show the similar trends that have been observed while measuring the inception voltage of both XLPE and EPR cable samples. The cable samples are not much affected by 1000 switching impulses. The similar behavior has been observed and mentioned in papers [12] and [13].

4.1.1.5 Partial Discharge Inception and Extinction Voltage for 5000 Applied Impulse Samples

Table 4.15 PD inception voltage of XLPE cables for 5000 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	21.8	16.8	18.7	19.1
500	20.5	15.1	16.6	17.4
1000	17.4	14.5	14.9	15.6
1500	16.4	14.1	14.8	15.1
2000	15.5	13.1	13.7	14.1
2500	14.9	14.6	14.6	14.7
3000	14.3	12.9	13	13.4
3500	14.2	13.6	13.9	13.9
4000	14.2	10.8	12.3	11.7
4500	13.4	10.1	11.9	11.8
5000	13.1	11.9	13.1	12.7

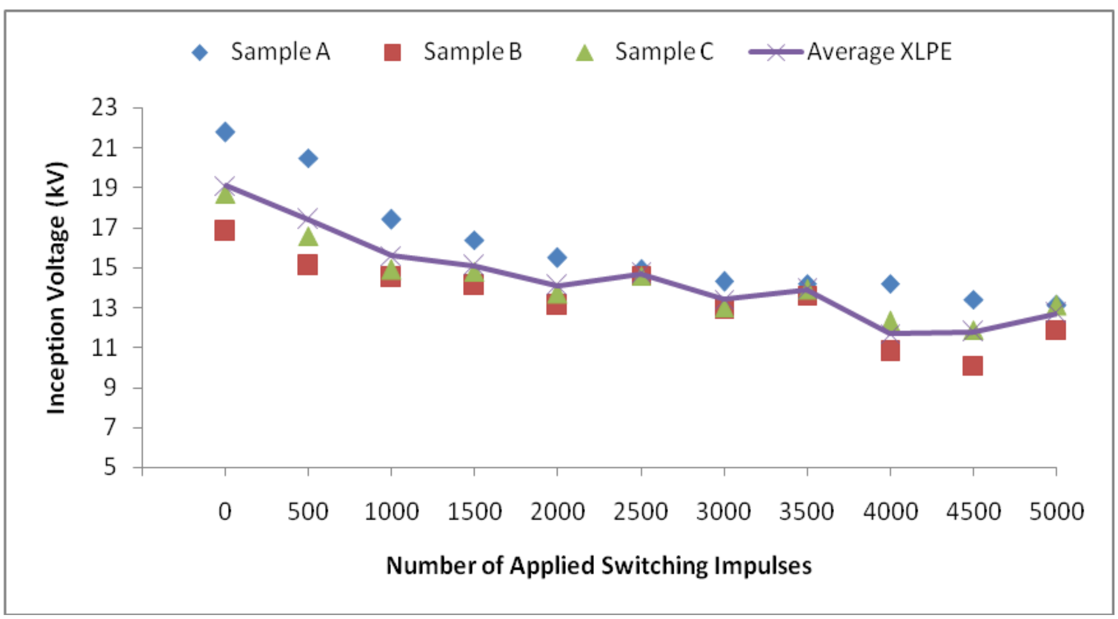


Figure 4.17 PD inception voltage of three XLPE cable samples for 5000 applied switching impulses

Table 4.16 PD inception voltage of EPR cables for 5000 applied switching impulses

Switching Impulse	Sample A V_i (kV)	Sample B V_i (kV)	Sample C V_i (kV)	Average V_i (kV)
0	21.4	19.9	15.3	18.8
500	21.1	18.9	13.4	17.8
1000	14.9	13.5	13	13.8
1500	16.1	13.5	14.5	14.7
2000	16.3	14.5	13.3	14.7
2500	16.7	15.6	14.7	15.7
3000	15.6	15.6	14.3	14.8
3500	17.4	15.4	14.3	15.7
4000	17.7	15.5	14.4	15.9
4500	16.7	14.8	14.1	15.2
5000	16.9	14.8	14.1	15.3

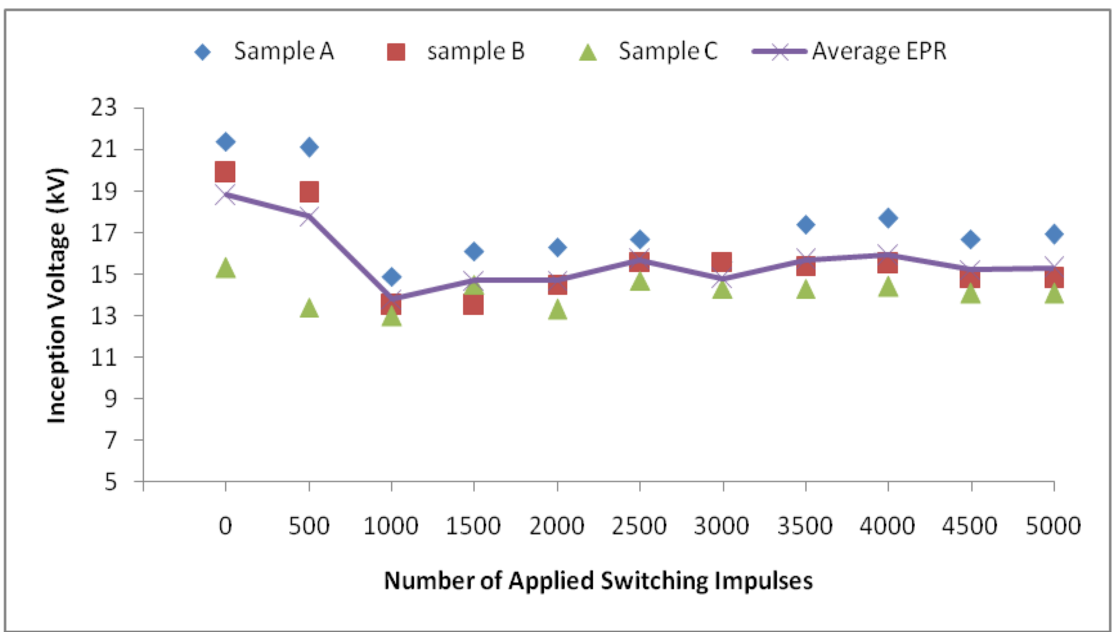


Figure 4.18 PD Inception voltage of three EPR cable samples for 5000 applied switching impulses

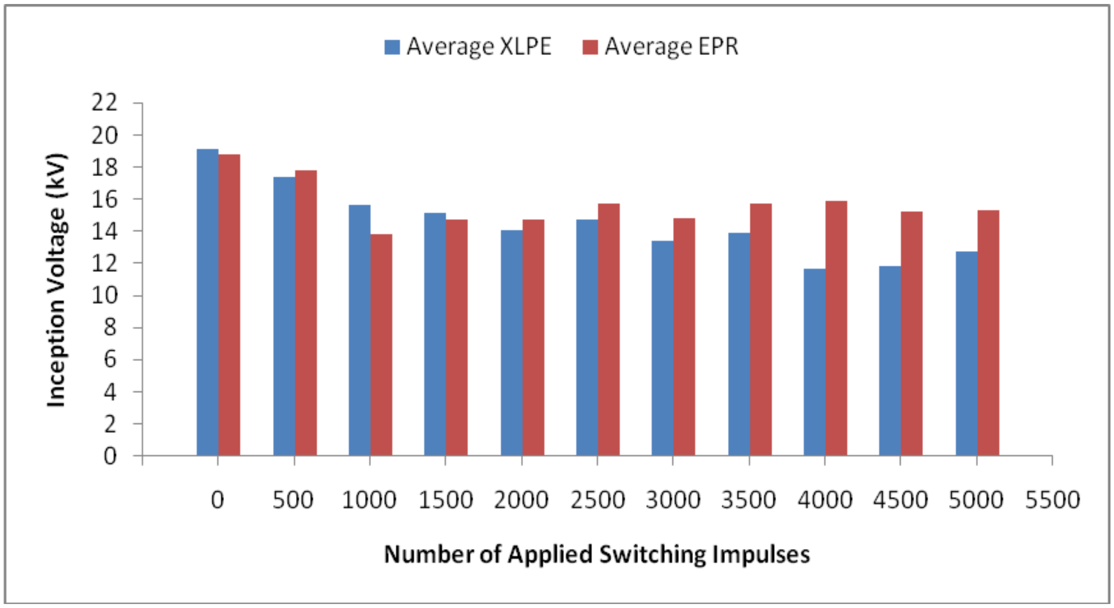


Figure 4.19 Average PD inception voltage of three XLPE and EPR cable samples for 5000 applied switching impulses

Table 4.17 PD extinction voltage of XLPE cables for 5000 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	19.6	15.8	16.5	17.3
500	19.2	14.5	16.4	16.7
1000	16.4	13	13.8	14.4
1500	16.2	13	13.7	14.3
2000	15.1	11.3	13.5	13.3
2500	14.1	13.7	13.9	13.9
3000	13.8	11.7	12.9	12.8
3500	13.7	12.3	12.9	13
4000	13.6	7.7	11.1	10.8
4500	12.6	8.9	10.9	10.8
5000	12.2	11.3	11.6	11.7

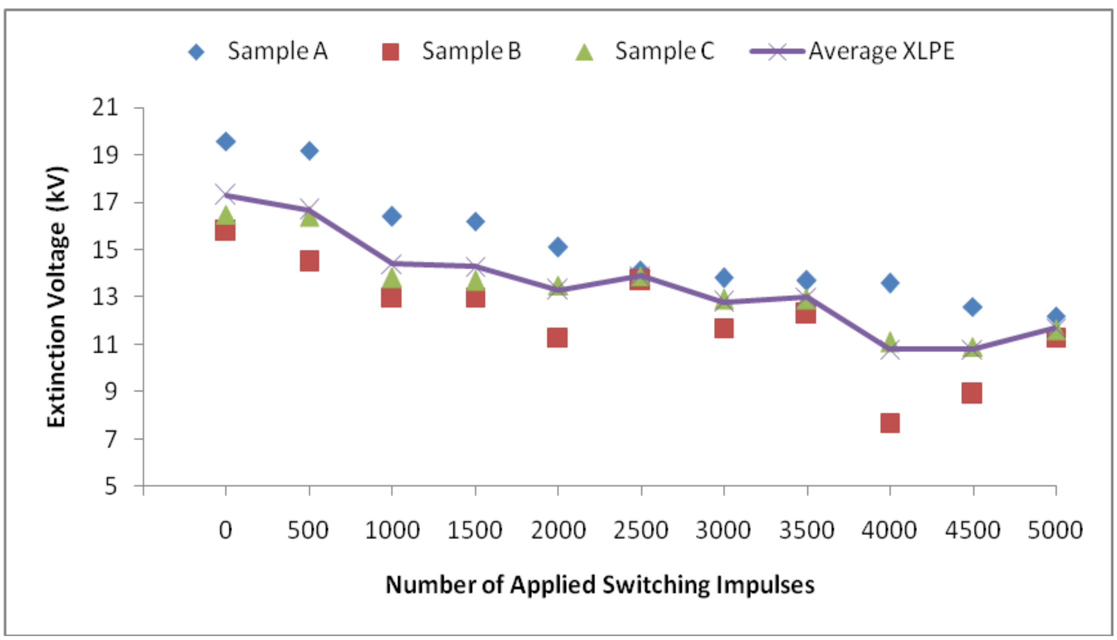


Figure 4.20 PD extinction voltage of three XLPE cable samples for 5000 applied switching impulses

Table 4.18 PD extinction voltage of EPR cables for 5000 applied switching impulses

Switching Impulse	Sample A V_e (kV)	Sample B V_e (kV)	Sample C V_e (kV)	Average V_e (kV)
0	19.9	18.3	14.9	17.1
500	19.7	18.1	11.1	16.3
1000	12.9	12.7	12.9	12.9
1500	14.4	12.8	13.7	13.6
2000	12.8	12.8	12.6	12.7
2500	14.3	14.6	12.9	13.9
3000	14.6	14.6	12.7	13.9
3500	16.8	14.8	13.7	15.1
4000	16.2	14.1	13.8	14.7
4500	15.8	13.9	13.2	14.3
5000	15.5	13.8	13.3	14.2

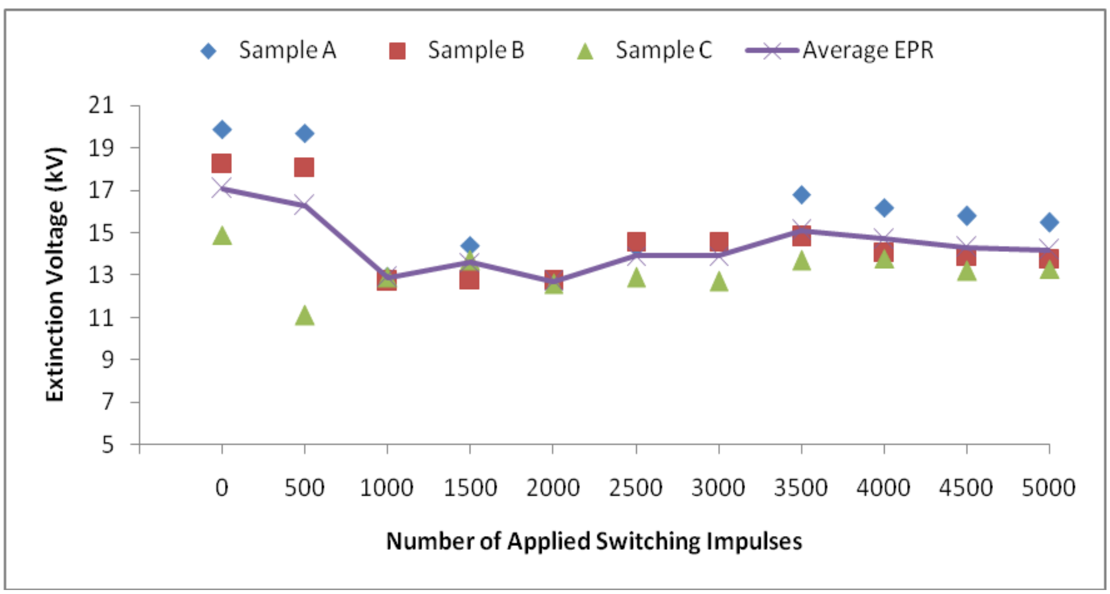


Figure 4.21 PD extinction voltage of three EPR cable samples for 5000 applied switching impulses

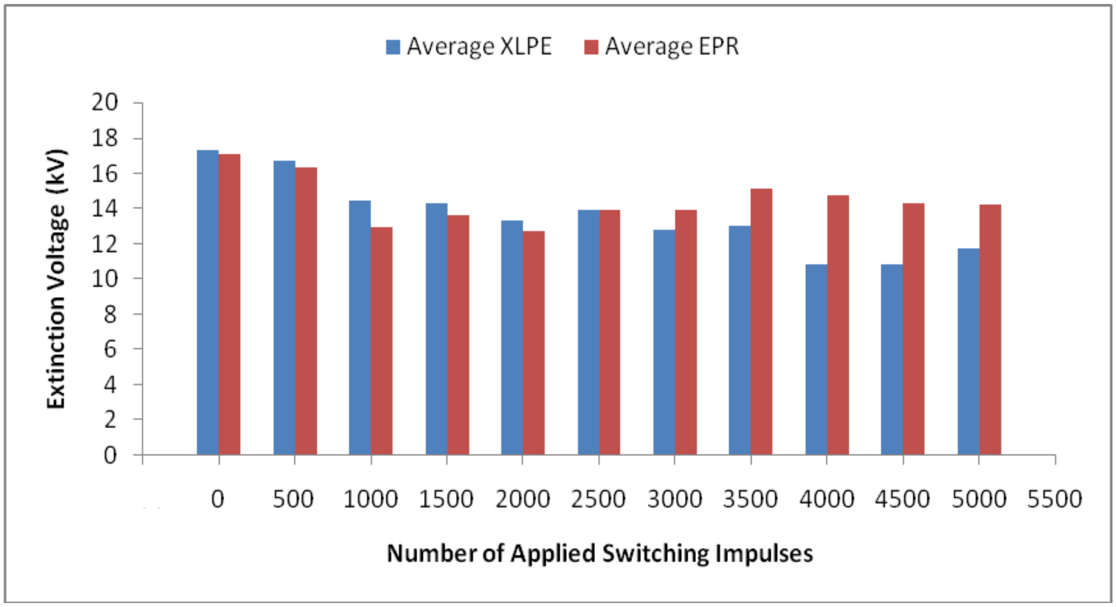


Figure 4.22 Average PD extinction voltage of three XLPE and EPR cable samples for 5000 applied switching impulses

Three samples, each of XLPE and EPR cables, were evaluated for 5000 switching impulses. For cable samples on which 5000 switching impulses are applied, partial discharge measurements are performed at every 500 impulses. The partial discharge inception voltage of three XLPE cable samples for 5000 switching impulses is presented in Table 4.15. Table 4.16 presents the partial discharge inception voltage of three EPR cable samples. Three cable samples are samples A, B, and C. The data presented in Tables 4.17 and 4.18 gives the partial discharge extinction voltage of three XLPE cable samples and three EPR cable samples for 5000 switching impulses. Figures 4.17, 4.18, and 4.19 present the trend of partial discharge inception voltage of XLPE samples, EPR samples, and average inception voltage of cable samples.

Partial discharge extinction voltage of XLPE cable samples, EPR cable samples, and average are presented in Figures 4.20, 4.21, and 4.22. The trend of average inception voltage measured for XLPE cable samples is from 19.1 kV to 12.7 kV whereas the trend of average inception voltage measured for EPR cable samples varies from 18.8 kV to 15.3 kV.

The average partial discharge inception voltage and extinction voltages of both XLPE and EPR cable samples decrease as more impulses were applied. It is observed in Figures 4.19 through 4.22. The measurement data of new cable samples showed that the XLPE cable samples have higher partial discharge inception voltage and extinction voltage than EPR cable samples. From Figures 4.19 and 4.22, it can be noted that after aging, the EPR cable samples maintain a higher inception and extinction voltages than that of XLPE cable samples. It indicates that EPR cables have better partial discharge performance than XLPE cables. The similar phenomenon is reported in paper [1]. From the measurements of all the different samples with specific number of switching impulses applied, it is observed that cable samples applied with 0, 100, 500 and 1000 switching impulses have no significant effect from partial discharge. It is only evidently observed that cable samples show partial discharge after 5000 switching impulses are applied.

4.1.1.6 Summary of Evaluation of Inception and Extinction Voltage on Cable Samples

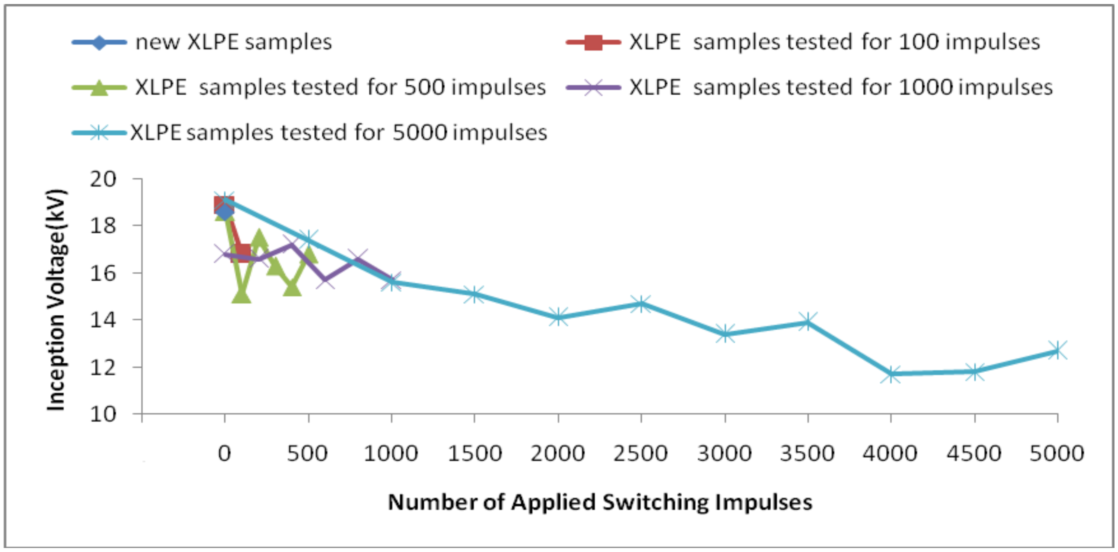


Figure 4.23 PD inception voltage of different XLPE cable samples

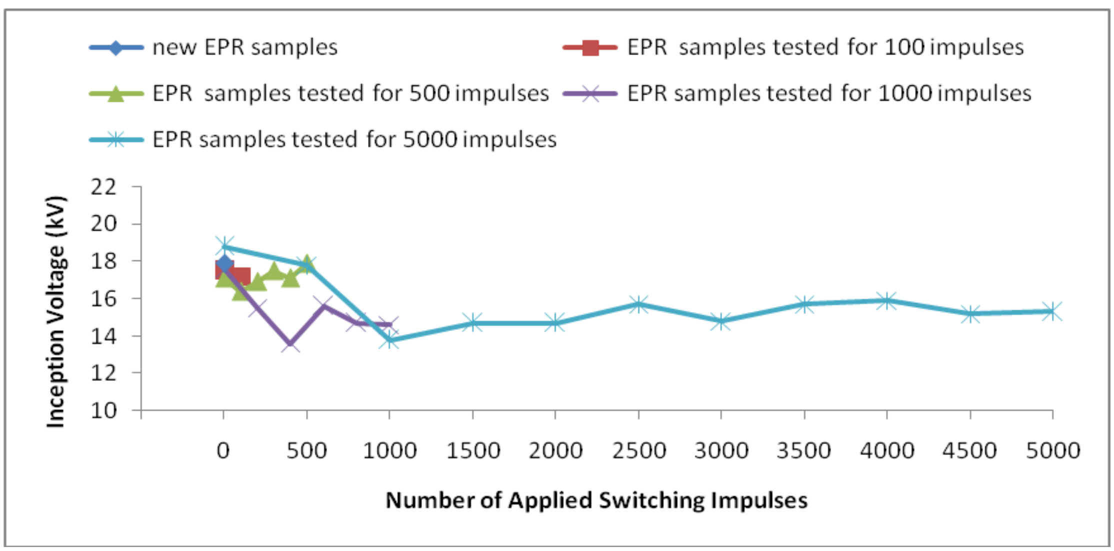


Figure 4.24 PD inception voltage of different EPR cable samples

Figures 4.23 and 4.24 present the partial discharge inception voltage of XLPE and EPR cable samples for different applied switching impulses. Figure 4.23 shows the inception voltage of new XLPE samples, XLPE samples tested for 100 impulses, XLPE samples tested for 500 impulses, XLPE samples tested for 1000 impulses, and XLPE samples tested for 5000 impulses. From the figure, it is seen that all cable samples have almost the same inception voltage at 0 impulse except the samples tested for 1000 applied impulses. The samples tested for 1000 impulses have a lower inception voltage at 0 impulse than other tested samples. It is also seen from the plotted graph that the samples tested up to 1000 impulses show variations in the inception voltage. The samples are prepared from the different sections of the cables. Some sections may have defects or cavity particles during manufacturing. This can be the reason for the variation in inception voltage. The samples tested for 500 impulses have lower inception voltage at 100 impulses but it again increases later. The similar phenomenon is observed for 1000 impulse samples. The samples tested for 1000 impulses shows the same trend as the samples tested for 5000 impulses when it reach to 1000 impulses. The samples tested for 5000 impulses are in decreasing trend as more impulses are applied. The decrease in inception voltage is expected due to formation of new cavities in insulation.

Figure 4.24 also shows the inception voltage of EPR cable samples for different applied impulses. The samples tested for 5000 impulses have relatively higher inception voltage than other tested samples at 0 impulse. Samples tested for 1000 impulses have lower inception voltage at 400 impulses and then increases again. The samples tested upto 1000 impulses show the same variation which was noted for XLPE samples. The decreasing trend in inception voltage is noted for tested 5000 impulse samples after several impulses are applied.

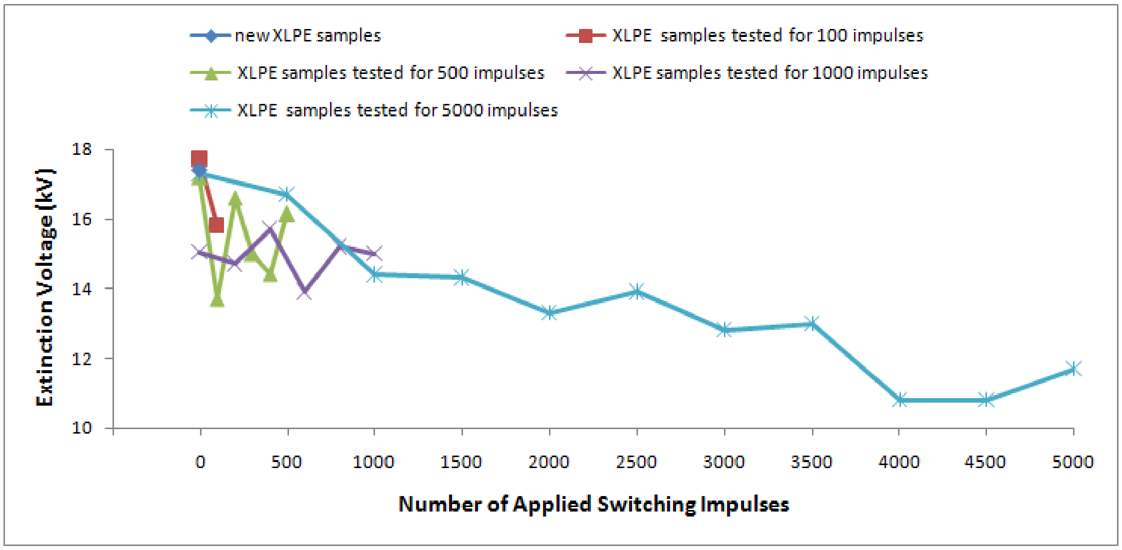


Figure 4.25 PD extinction voltage of different XLPE cable samples

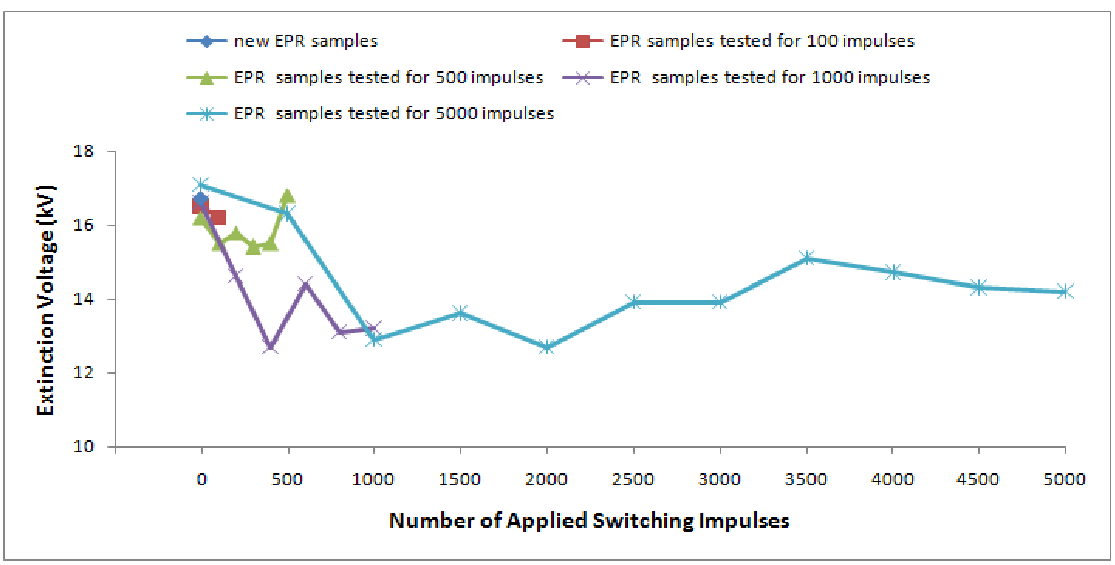


Figure 4.26 PD extinction voltage of different EPR cable samples

Figures 4.25 and 4.26 present the partial discharge extinction voltage measured for different XLPE and EPR cable samples. Figure 4.25 shows the extinction voltage of new XLPE samples, XLPE samples tested for 100 impulses, XLPE samples tested for 500 impulses, XLPE samples tested for 1000 impulses, and XLPE samples tested for 5000 impulses. From Figure 4.25, it is seen that extinction voltage of samples tested for 1000 impulses is lower than other tested samples at 0 impulse. The extinction voltage of these samples at 800 impulses is same to that of tested samples for 5000 impulses. The extinction of these samples has increased slightly at 1000 impulses. It is expected to decrease later. The samples tested for 500 impulses also show variation. It is noted that it has a higher extinction voltage at 500 impulses. These variations in extinction voltage for different tested samples are expected because they are prepared from different segments of the cable. Technical and measurement error can be the reason for this variation. The extinction voltage of samples tested for 5000 impulses is decreased for first 2000 impulses. It slightly increases and then decreases again.

The similar phenomenon is observed for EPR cable samples. The samples tested for 1000 impulses have shown fluctuations with its extinction voltage. The cable samples have lower voltage at 400 impulses. The cable samples tested for 500 impulses also show a variation in extinction voltage during measurement. Its value is almost the same for samples tested for 5000 applied impulses at 500 impulses. The extinction voltage of samples tested for 5000 applied impulses is decreased for first 1000 impulses and then increases again. Later, it again decreased. It is seen that the extinction voltage is always lower than inception voltage at applied specific impulses.

4.1.2 Partial Discharge Magnitude

The partial discharge (apparent charge) magnitudes were estimated in the 10 sec time frame at 18 kV ac. Tables 4.19 through 4.27 present the measured partial discharge apparent charge magnitude of the test samples when they are applied with 0 (new samples), 100, 500, 1000, and 5000 switching impulses. Similarly, for samples on which 500 switching impulses are applied, partial discharge magnitude is measured at every 100 impulses. For samples on which 1000 switching impulses are applied, partial discharge magnitude are recorded at every 200 switching impulses. For samples on which 5000 switching impulses are applied, partial discharge magnitude are measured at each 500 switching impulses.

4.1.2.1 Partial Discharge Magnitude for New Samples

Table 4.19 PD apparent charge of new XLPE and EPR cable samples at 18 kV, 60 Hz

Type of Cable Sample	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
XLPE	0	0	34	11.3
EPR	0	41	0	13.7

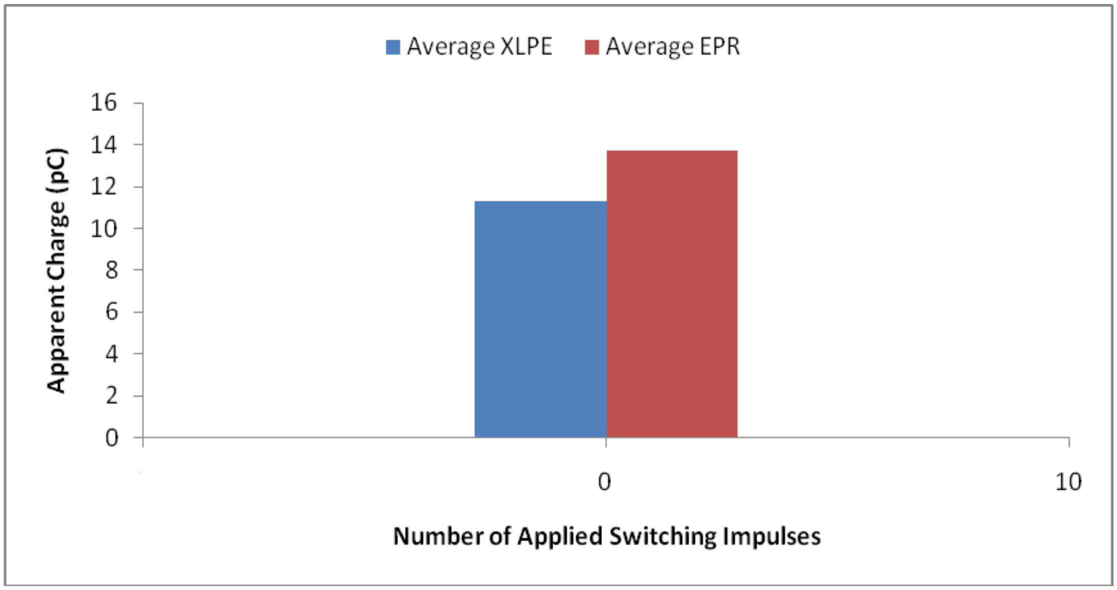


Figure 4.27 Average PD apparent charge of new XLPE and EPR cable samples at 18 kV, 60 Hz

4.1.2.2 Partial Discharge Magnitude for 100 Applied Impulse Samples

Table 4.20 PD apparent charge of XLPE cable samples for 100 applied switching impulses, at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	0	0	35	11.7
100	0	23	43	22

Table 4.21 PD apparent charge of EPR cable samples for 100 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	0	0	42	14
100	39	0	47	28.9

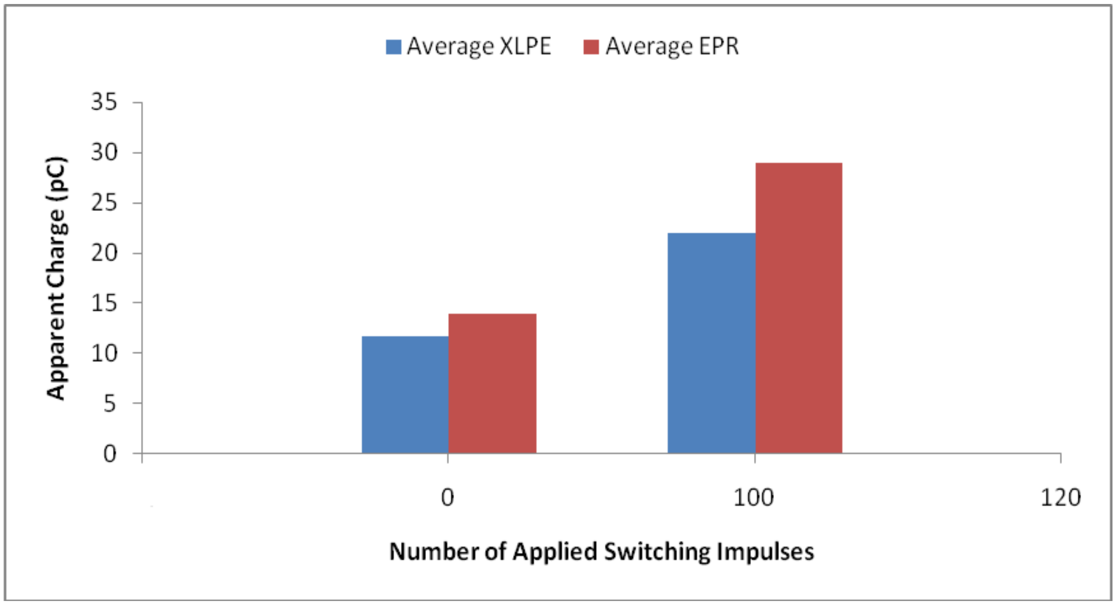


Figure 4.28 Average PD apparent charge of XLPE and EPR cable samples for 100 applied switching impulses at 18 kV, 60 Hz

The measurement results of new samples and 100 applied impulses on cable samples are presented in Tables 4.19 through 4.21. The apparent charge magnitude is measured in new cable samples (0 impulse). The average apparent charge measured in new XLPE and EPR cable samples are 11.3 pC and 13.7 pC. It is presented in Figure 4.27. From Figure 4.28, it is observed that the apparent charge of both XLPE and EPR cable samples show slight changes when applied with 100 impulses. The average apparent charge of XLPE and EPR cable samples for 100 impulses are 22 pC and 28.9 pC. There is a small increase in apparent charge as seen in a Figure 4.28.

4.1.2.3 Partial Discharge Magnitude for 500 Applied Impulse Samples

Table 4.22 PD apparent charge of XLPE cable samples for 500 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	0	15	25	13
100	16	77	31	41
200	0	21	28	16
300	0	88	98	62
400	0	82	113	65
500	0	86	127	71

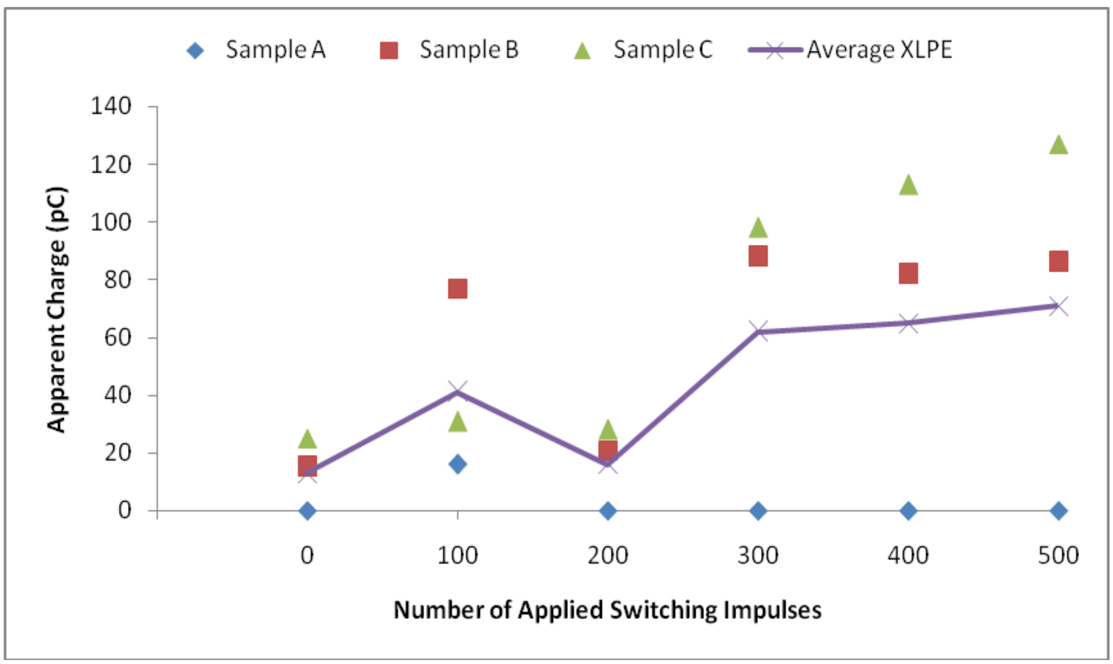


Figure 4.29 PD apparent charge of XLPE cable samples for 500 applied switching impulses at 18 kV, 60 Hz

Table 4.23 PD apparent charge of EPR cable samples for 500 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	17	22	31	23
100	42	28	38	36
200	33	15	65	38
300	0	19	54	24
400	53	0	87	47
500	0	0	95	32

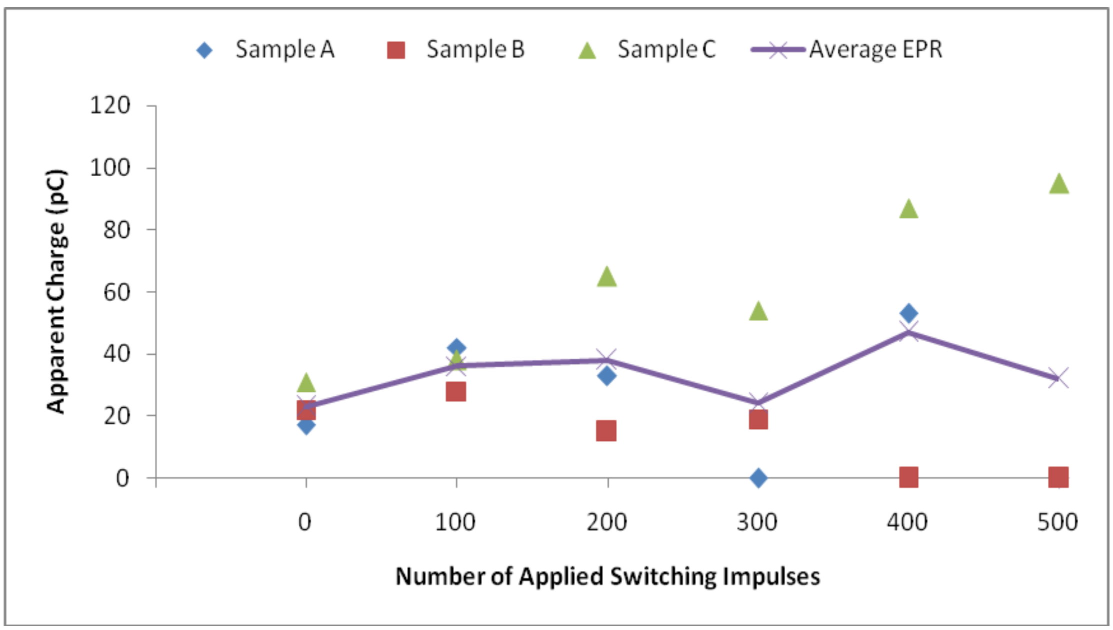


Figure 4.30 PD apparent charge of EPR cable samples for 500 applied switching impulses at 18 kV, 60 Hz

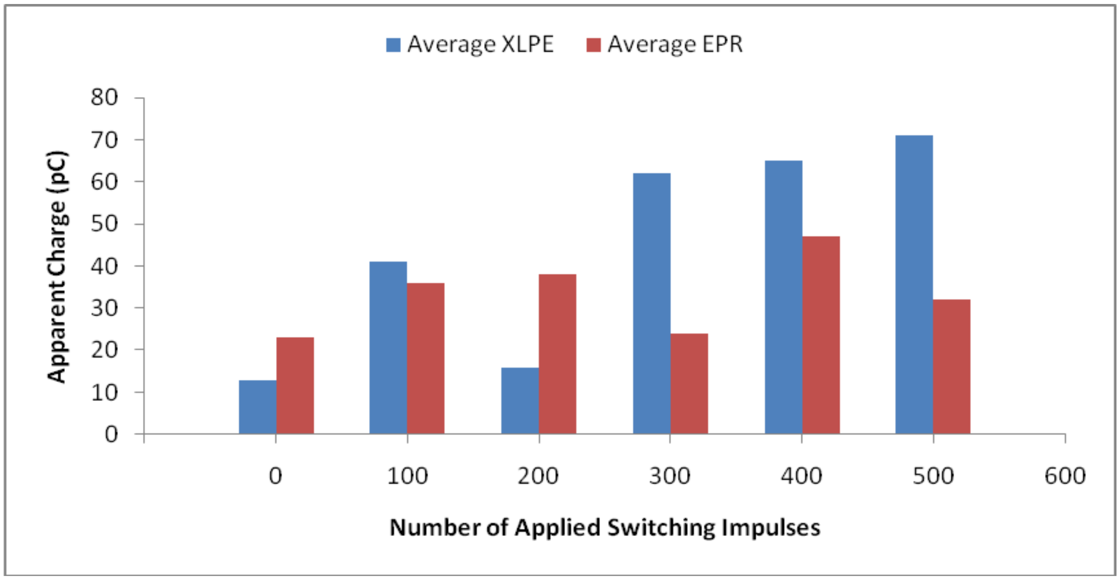


Figure 4.31 Average PD apparent charge of XLPE and EPR cable samples for 500 applied switching impulses at 18 kV, 60 Hz

Tables 4.22 and 4.23 present results of the partial discharge magnitude obtained from XLPE and EPR cable samples when 500 switching impulses are applied. The trend of average apparent charge magnitudes of XLPE cable samples recorded are in range from 13 pC to 71 pC. The trend of average apparent charge magnitudes of EPR cable samples measured are in range from 23 pC to 32 pC. In Figure 4.29, variation in apparent charge of XLPE samples can be seen. The apparent charge is low at 200 impulses and increases later again. From Figure 4.30, it is observed that average apparent charge shows small change for EPR cable samples whereas XLPE cable samples show the increasing trend of apparent charge. It shows that partial discharge is taking place in insulation. The average apparent charge of XLPE cable samples is higher than EPR cable samples for 500 impulses as shown in Figure 4.31.

4.1.2.4 Partial Discharge Magnitude for 1000 Applied Impulse Samples

Table 4.24 PD apparent charge of XLPE cable samples for 1000 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	16	19	18	18
200	26	22	22	28
400	0	31	32	21
600	0	44	38	27
800	37	33	35	35
1000	41	38	53	44

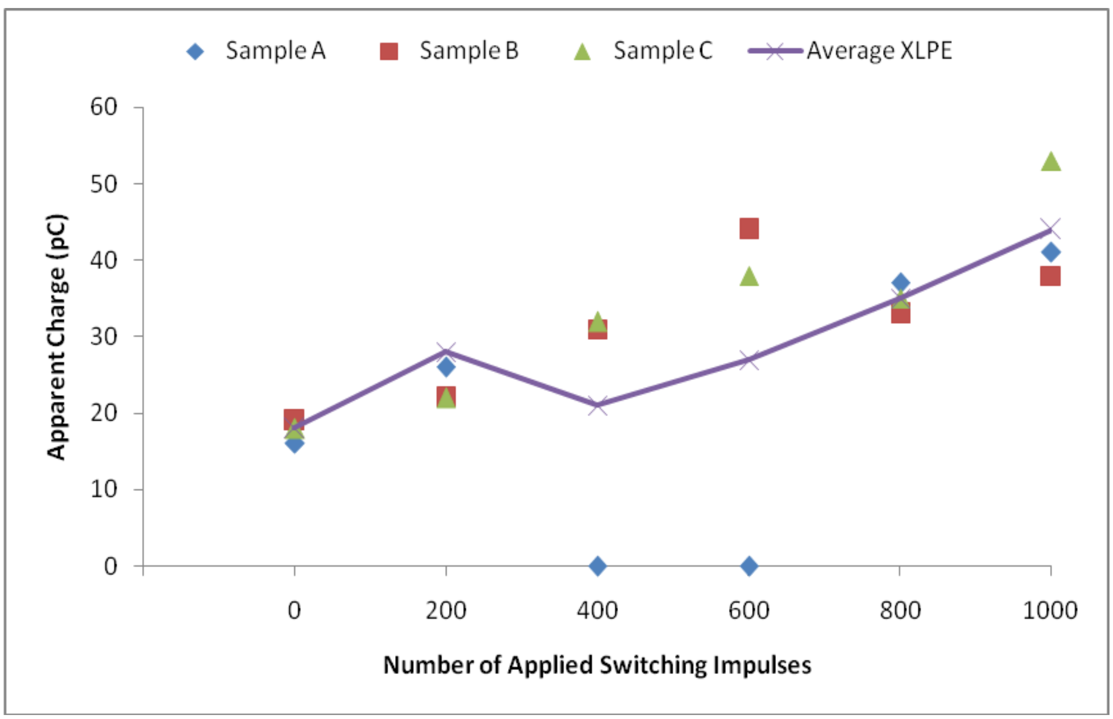


Figure 4.32 PD apparent charge of XLPE cable samples for 1000 applied switching impulses at 18 kV, 60 Hz

Table 4.25 PD apparent charge of EPR cable samples for 1000 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	16	23	0	13
200	69	43	38	50
400	63	50	72	62
600	64	58	61	61
800	65	36	48	50
1000	72	53	32	52

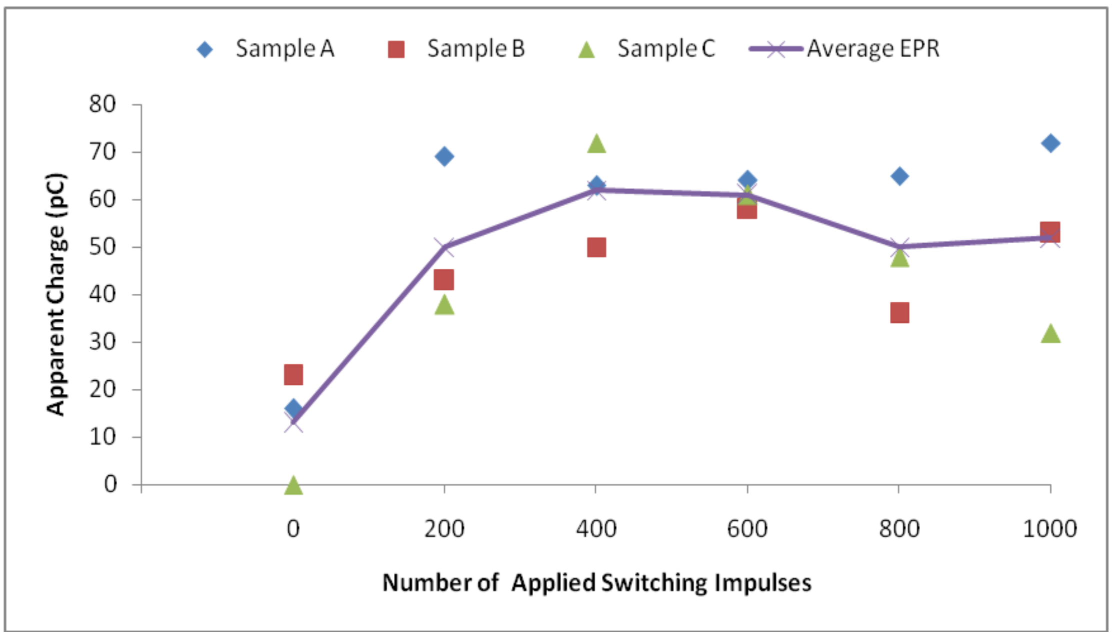


Figure 4.33 PD apparent charge of EPR cable samples for 1000 applied switching impulses at 18 kV, 60 Hz

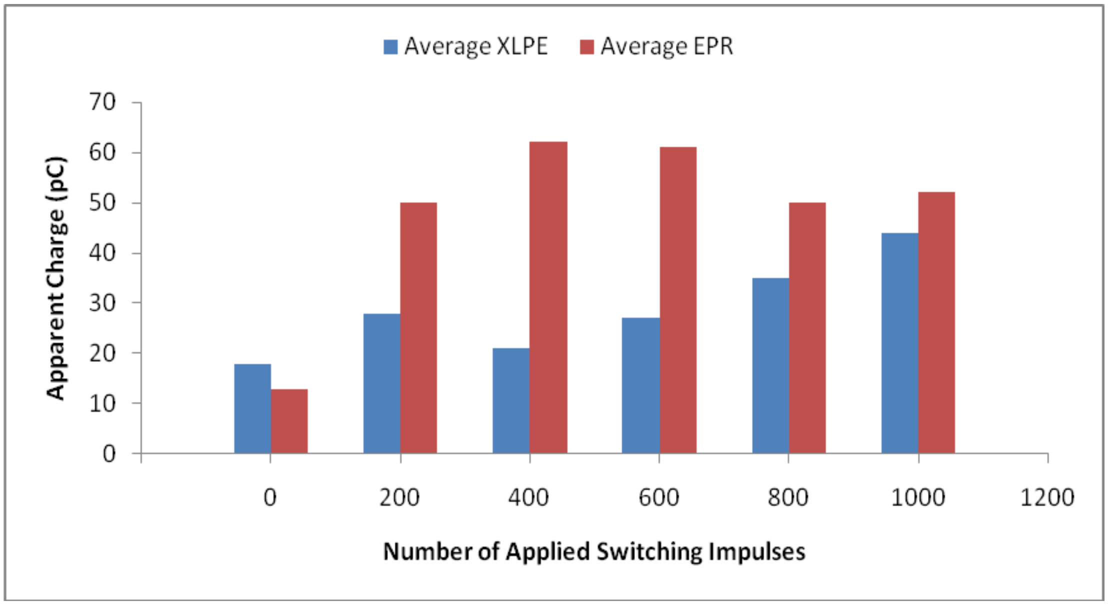


Figure 4.34 Average PD apparent charge of XLPE and EPR cable samples for 1000 applied switching impulses at 18 kV, 60 Hz

Tables 4.24 and 4.25 show the results obtained from the partial discharge measurement of XLPE and EPR cable samples when 1000 switching impulses are applied. In Figure 4.32, the average apparent charge magnitude measured for XLPE cable samples changes from 18 pC to 44 pC. From Figure 4.33, it can be observed that average apparent charge of EPR cable samples increases for the first 400 impulses applied and then decreases slightly. The trend of average apparent charge magnitude show variation from 13 pC to 52 pC. In XLPE cable samples, the average apparent charge is in upward trend but magnitude is still lower than EPR cable samples as shown in Figure 4.34. The average apparent charge of EPR cable samples is comparatively higher than XLPE cable samples as shown in Figure 4.34.

4.1.2.5 Partial Discharge Magnitude for 5000 Applied Impulse Samples

Table 4.26 PD apparent charge of XLPE cable samples for 5000 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	0	25	0	8
500	0	33	47	27
1000	15	25	53	31
1500	25	80	65	57
2000	26	45	73	48
2500	50	40	81	57
3000	102	155	95	117
3500	129	160	115	135
4000	123	175	147	148
4500	112	150	105	122
5000	147	165	137	150

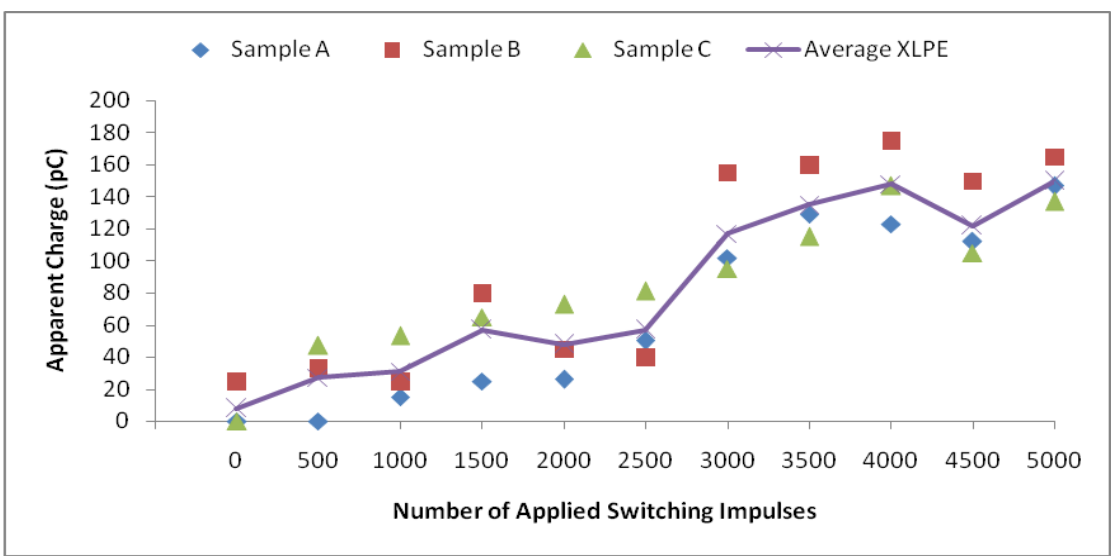


Figure 4.35 PD apparent charge of XLPE cable samples for 5000 applied switching impulses at 18 kV, 60 Hz

Table 4.27 PD apparent charge of EPR cable samples for 5000 applied switching impulses at 18 kV, 60 Hz

Switching impulse	Sample A PD (pC)	Sample B PD (pC)	Sample C PD (pC)	Average PD (pC)
0	0	0	32	11
500	0	0	47	16
1000	14	47	71	44
1500	37	45	46	43
2000	34	47	59	42
2500	48	81	94	74
3000	52	55	63	57
3500	34	47	57	46
4000	50	85	91	75
4500	62	99	107	89
5000	57	73	121	83

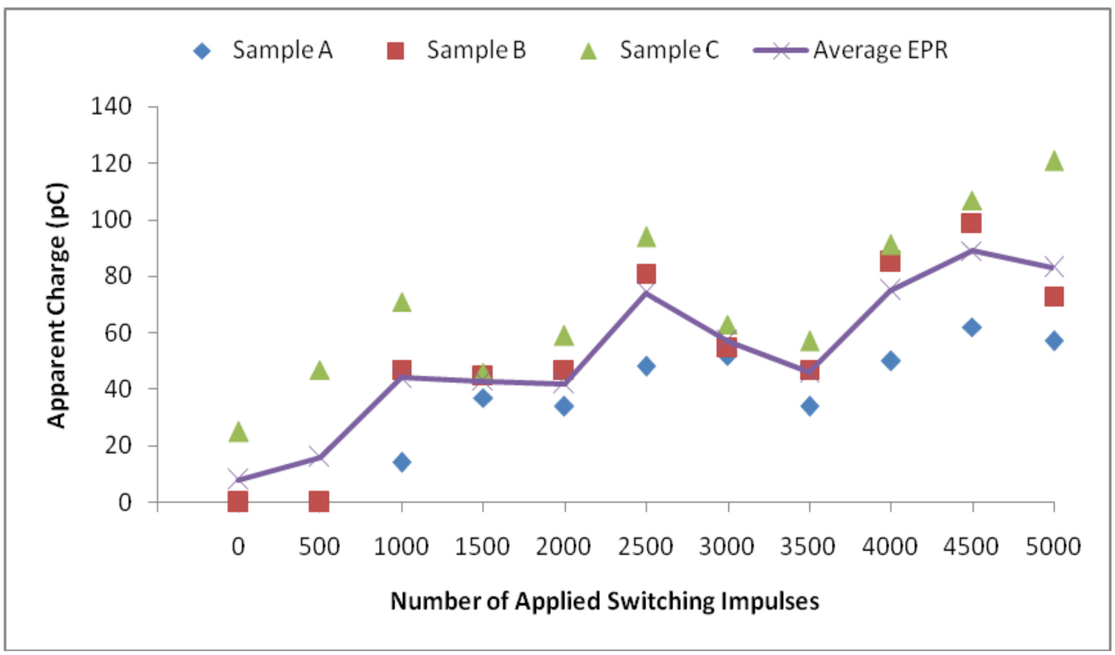


Figure 4.36 PD apparent charge of EPR cable samples for 5000 applied switching impulses at 18 kV, 60 Hz

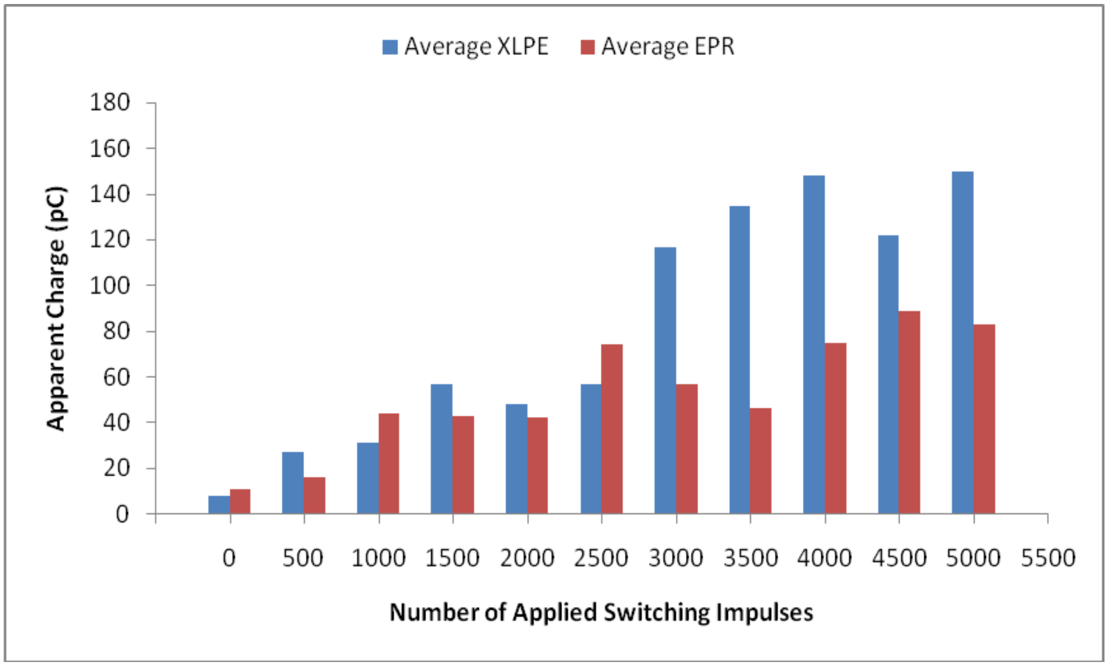


Figure 4.37 Average PD apparent charge of XLPE and EPR cable samples for 5000 applied switching impulses at 18 kV, 60 Hz

Tables 4.26 and 4.27 present the measurement data of partial discharge (apparent charge) magnitude for XLPE and EPR cable samples when cable samples were applied with 5000 switching impulses. Partial discharge magnitudes are measured on every 500 impulses applied on cable samples at 18 kV, 60 Hz. Table 4.26 presents the partial discharge magnitude measured for XLPE cable samples. The average apparent charge magnitudes of XLPE cable samples recorded during analysis show variation from 8 pC to 150 pC. Table 4.27 shows the apparent charge magnitude measured for EPR cable samples. The average apparent charge magnitudes recorded during analysis are in range from 11 pC to 83 pC. It can be observed that apparent charge increases slowly as more impulses are applied.

The average partial discharge apparent charge of XLPE cable samples is higher than that of EPR test samples. The apparent charge magnitude for XLPE cable samples show strong upward trend than EPR test samples. From Figure 4.37, the apparent charge of new XLPE cable samples is less than new EPR cable samples. The result from the measurement indicates that the aged EPR cables have better partial discharge performance than aged XLPE cables and partial discharge activities are more intense in the XLPE cables than EPR cables. The same trend is observed in paper [1].

It also signifies that degradation has taken place in cable insulation during 5000 switching impulses applied. The increase in apparent charge magnitude after aging cable samples with 5000 impulses are shown in three dimension plots in Figures 4.40 through 4.43. The increment of apparent charge in cables after 5000 impulses may be due to the formation of cavities. Figure 4.37 presents the average apparent charge measured for EPR and XLPE cable samples for the number of switching impulses applied.

4.1.2.6 Summary of Evaluation of Partial Discharge Magnitude on Cable Samples

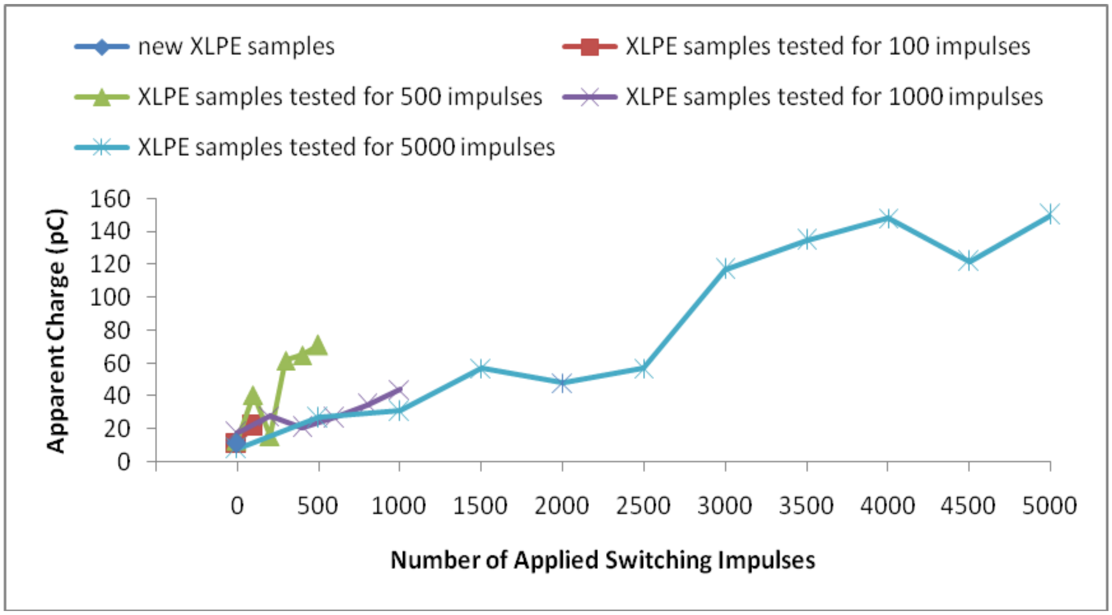


Figure 4.38 PD apparent charge of different XLPE cable samples

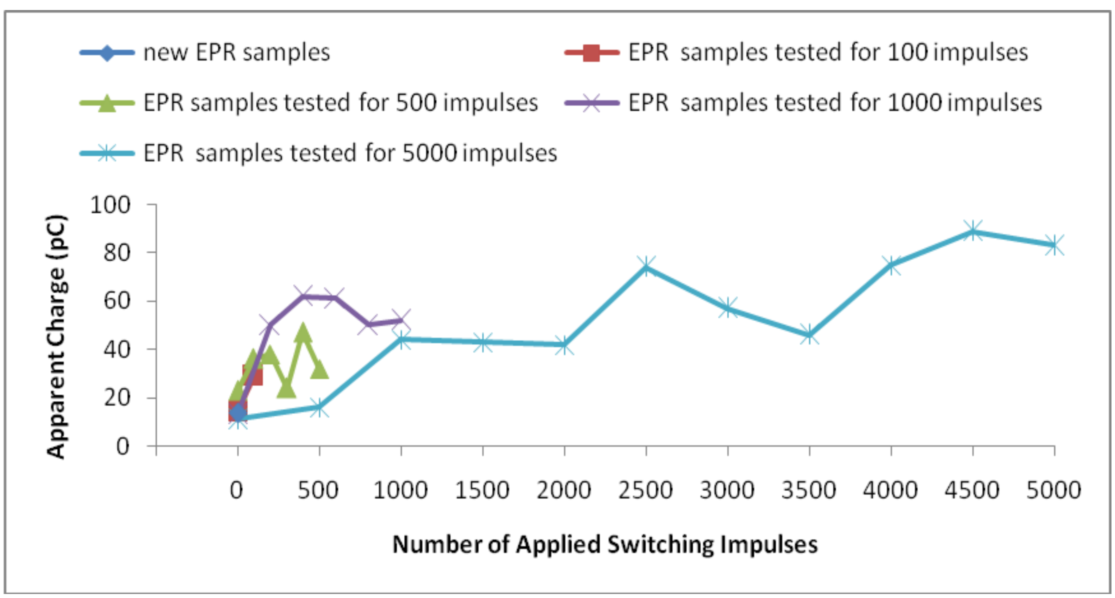


Figure 4.39 PD apparent charge of different EPR cable samples

Partial discharge magnitude measured for different XLPE and EPR cable samples for specific applied impulses are shown in Figures 4.38 and 4.39. In Figure 4.38, it is seen that all XLPE cable samples have nearly same partial discharge magnitude measured at 0 impulse. Later there is a difference in PD magnitude measured for cable samples. The partial discharge magnitude of XLPE cable samples for 500 applied impulses increases at first for 100 impulses and then decreases again. Partial discharge is increased again after 200 impulses and quite higher than other cable samples at that specific value. It may be due to the surface discharge that occurred during the measurement. Partial discharge measured of XLPE cable samples for 1000 applied impulses is in similar trend to that of XLPE cable samples for 5000 applied impulses. Partial discharge magnitude of XLPE cable samples for 5000 applied impulses is seen increased after many impulses applied. It shows that aging has occurred in cable insulation.

Figure 4.39 presents the partial discharge magnitude measured of new EPR cable samples and aged EPR cable samples at specific applied impulses. It is seen that partial discharge magnitude measured for new EPR samples has a slightly higher magnitude than other aged cable samples. The PD magnitude of EPR cable samples for 500 impulses increases and decreases during the measurement. The PD magnitudes for 1000 applied impulse cable samples have higher magnitude than other cable samples. It may be due to the formation of new cavities in insulation or surface discharge. It has decreased slightly after 600 impulses. The EPR cable samples tested for 5000 impulses also show variations in PD magnitude during measurements. The PD magnitude has been increased after several impulses applied and it shows that the aging has occurred in insulation.

4.1.3 Three Dimension Analysis of Partial Discharge

The measurement of partial discharge activity is shown in the three-dimension plot so that the aging phenomena can be observed during the aging process. The three dimension plot presents the phase, PD apparent charge, and PD pulse count in a 10 sec time frame at 18 kV, 60 Hz.

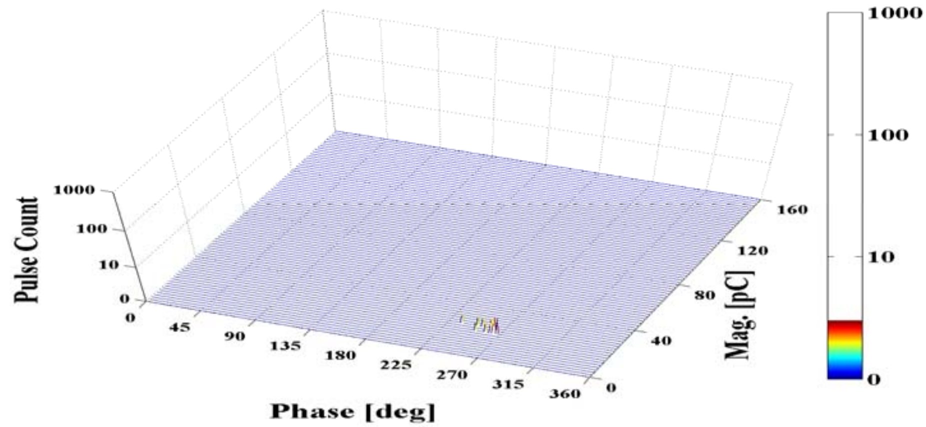


Figure 4.40 The three dimension PD of new XLPE cable sample at 18 kV, 60 Hz

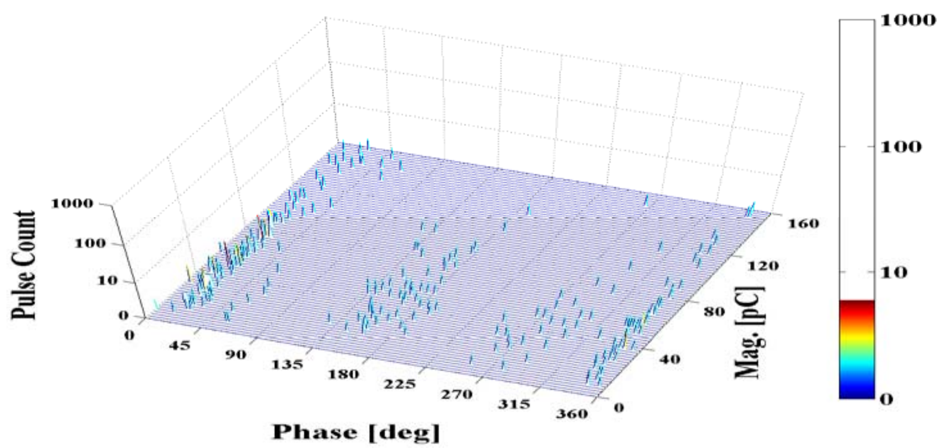


Figure 4.41 The three dimension PD of XLPE cable sample after 5000 impulses applied at 18 kV, 60 Hz

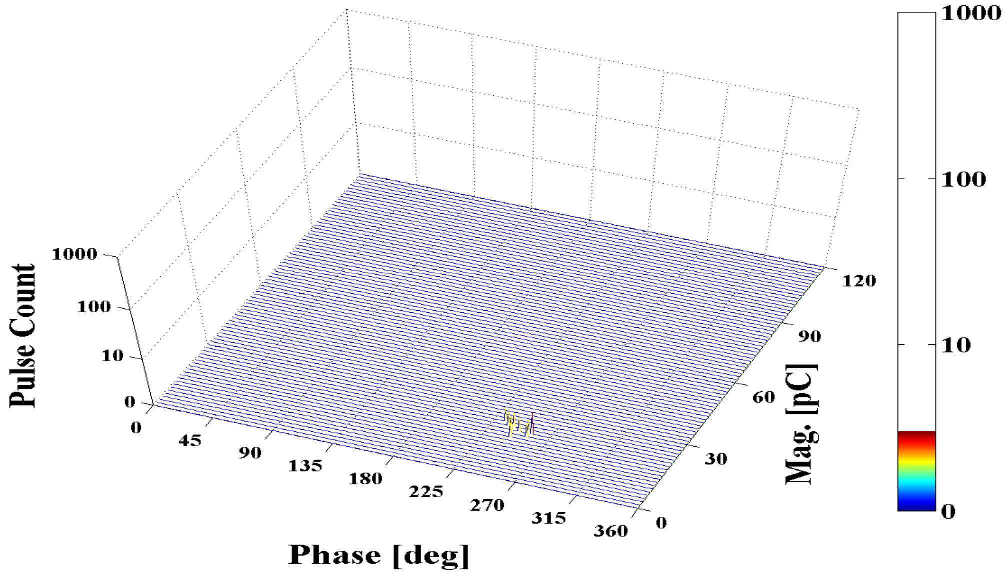


Figure 4.42 The three dimension PD of new EPR cable sample at 18 kV, 60 Hz

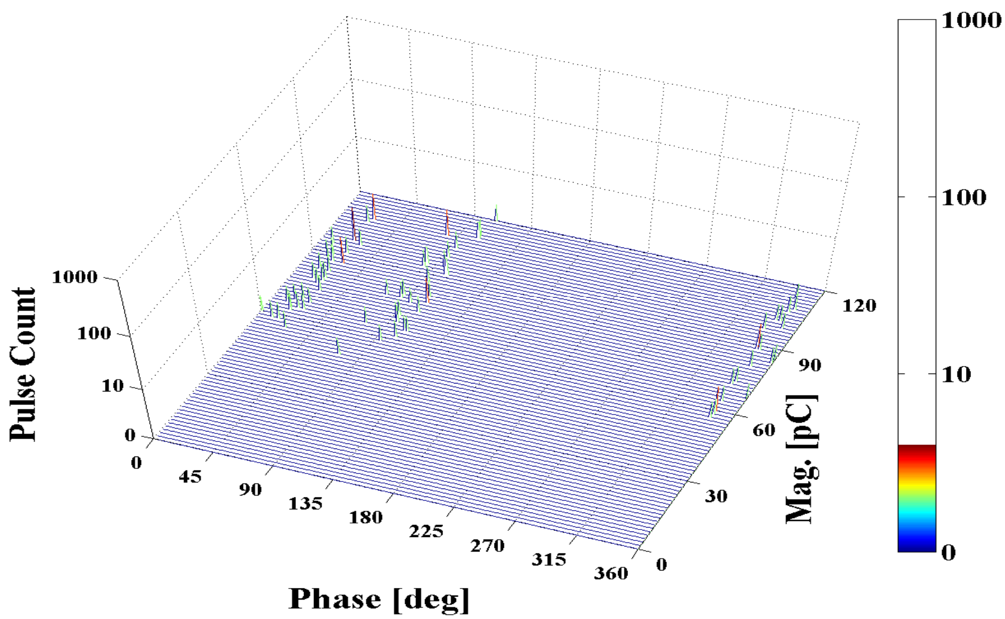


Figure 4.43 The three dimension PD of EPR cable sample after 5000 impulses applied at 18 kV, 60 Hz

Figures 4.40 and 4.41 present the measurement results of the partial discharge activity for XLPE cable samples before and after aging. From the plot, it can be observed that the pulse counts and partial discharge magnitude increase significantly after aging. Similarly, Figures 4.42 and 4.43 present the measurement results of the partial discharge activity for EPR cable samples before and after aging. There is an evident change in partial discharge magnitude after aging. The pulse count shows a slight change after aging that can be observed in three-dimension plot.

It is evident that shows that partial discharge activity has increased after aging and an indication that the degradation in insulation has taken place. When both XLPE and EPR test results are compared, it is observed that the partial discharge pulse count of EPR cable samples is much less than that of XLPE cable samples. The partial discharge magnitude of EPR cable samples is also lower than that of XLPE cable samples. The difference in the partial discharge pulse count and magnitude indicates that EPR cable samples are more resistant to the partial discharge than XLPE cable samples.

4.2 ac Breakdown Results

The ac breakdown measurement results of XLPE and EPR cable samples are presented in Tables 4.28 and 4.29. The ac breakdown voltage of cable samples was evaluated after applying specific number of switching impulses. The test determines the remaining dielectric strength of aged cable samples.

Table 4.28 ac breakdown voltage of XLPE cable samples

Material of Insulation	Sample A	Sample B	Sample C	Average
Switching Impulses	Breakdown Voltage (kV)	Breakdown Voltage (kV)	Breakdown Voltage (kV)	Breakdown Voltage (kV)
0	121.7	125.9	170.0	139.2
100	131.2	129.1	129.2	129.8
500	92.0	107.9	155.3	118.4
1000	126.7	129.1	154.2	136.8
5000	146.0	160.8	174.2	160.3

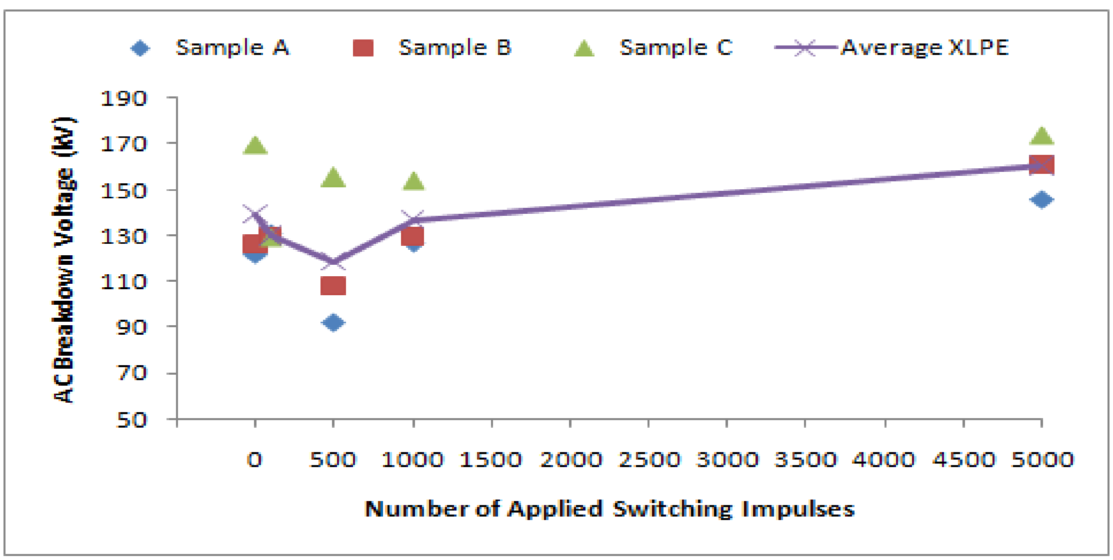


Figure 4.44 ac breakdown voltage of XLPE cable samples

Table 4.29 ac breakdown voltage of EPR cable samples

Material of Insulation	Sample A	Sample B	Sample C	Average
Switching Impulses	Breakdown Voltage (kV)	Breakdown Voltage (kV)	Breakdown Voltage (kV)	Breakdown Voltage (kV)
0	160.8	156.6	151.0	156.1
100	140.7	116.4	119.1	125.4
500	162.9	119.1	147.2	143.0
1000	124.8	129.1	174.2	142.7
5000	121.7	124.8	90.4	112.3

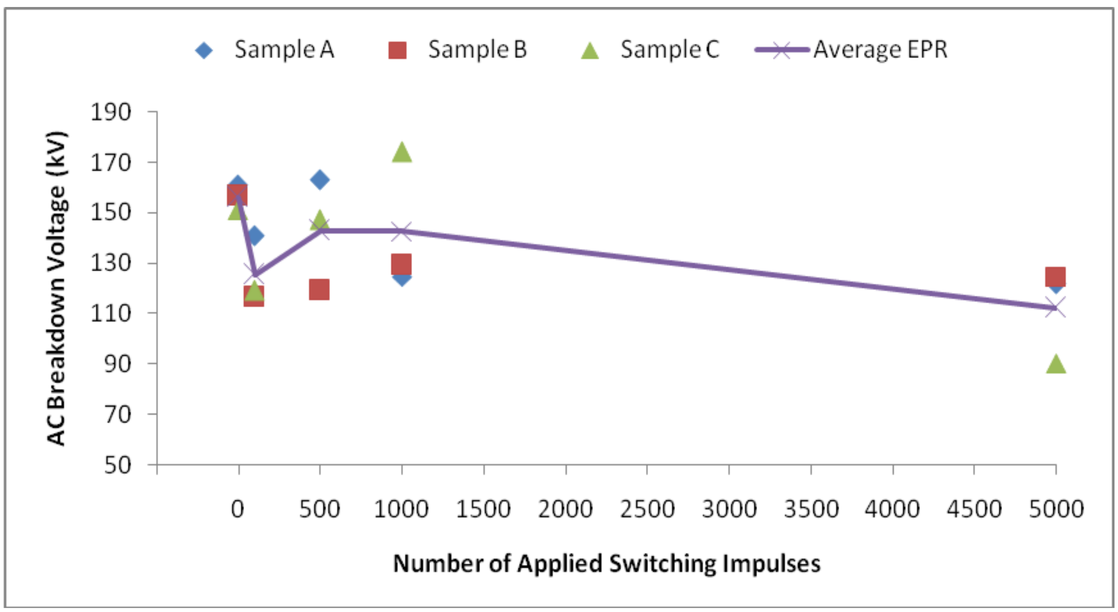


Figure 4.45 ac breakdown voltage of EPR cable samples

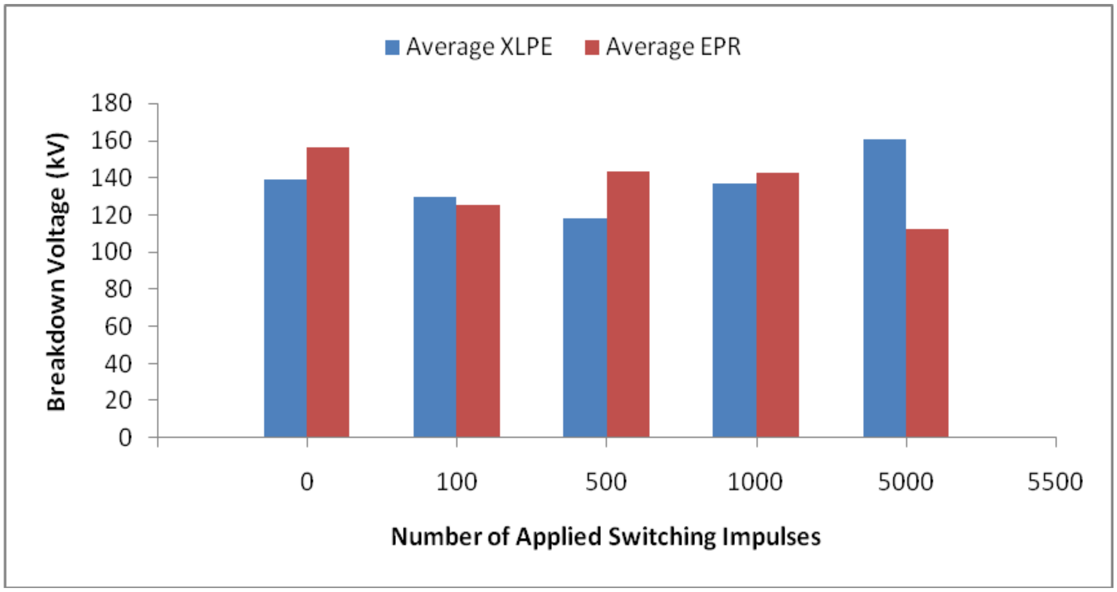


Figure 4.46 Average ac breakdown voltage of XLPE and EPR cable samples

Table 4.30 Average dielectric strength of XLPE and EPR cable samples

Material of Insulation	XLPE Samples	EPR Samples
Switching Impulses	Dielectric Strength (kV/mm)	Dielectric Strength (kV/mm)
0	25.3	28.4
100	23.6	22.8
500	21.5	26.0
1000	24.9	25.9
5000	29.1	20.4

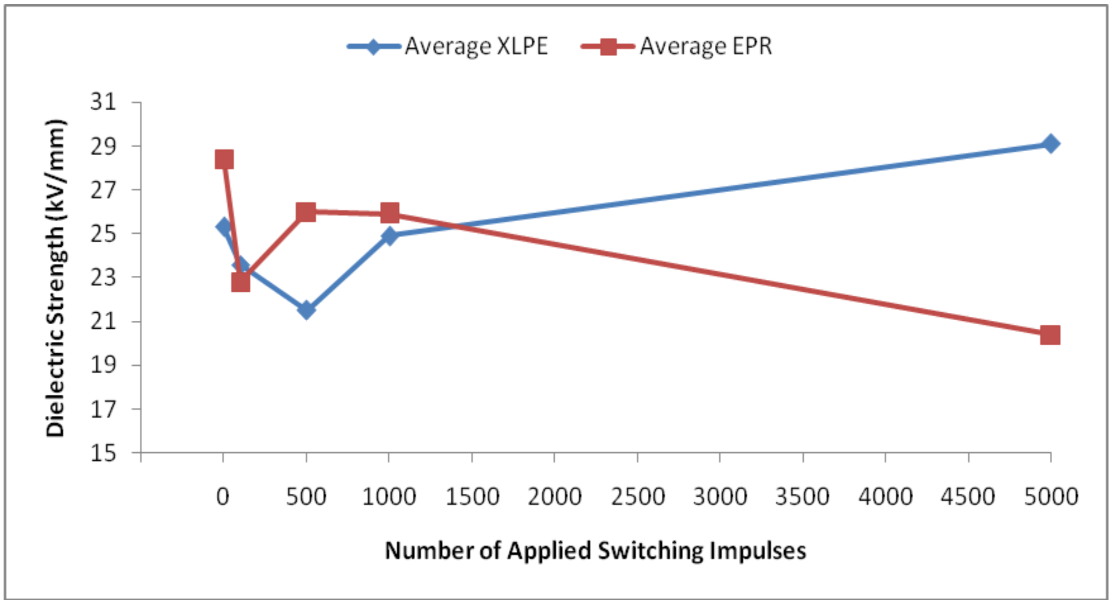


Figure 4.47 Average dielectric strength of XLPE and EPR cable samples

The test results show that the ac breakdown voltage has considerable scatter. The results of average ac breakdown voltage of XLPE cable samples are showing variation from 139.2 kV to 160.3 kV in Table 4.28. From Table 4.29, the results of average ac breakdown voltage measured in EPR cable samples show a decreasing trend from 156.1 kV to 112.3 kV. The average dielectric strength of XLPE and EPR cable samples are shown in Table 4.30. From the table, it is calculated that dielectric strength of new XLPE cable samples is between 22.1 kV/mm and 30.9 kV/mm whereas dielectric strength of new EPR cable samples is between 27.4 kV/mm and 29.2 kV/mm. After the cable samples were applied with 5000 switching impulses, the remaining dielectric strength of XLPE cable samples is between 26.5 kV/mm and 31.7 kV/mm while the remaining dielectric strength of EPR cable samples is between 16.4 kV/mm and 22.7 kV/mm.

From Figure 4.47, the dielectric strength of XLPE cable samples decreases sharply after the first 100 switching impulses are applied. Then the dielectric strength starts to increase as more impulses are applied. The EPR cable samples show the same decreasing trend for the first 100 switching impulses applied. In the interval between 100 and 500 impulses, the dielectric strength slightly increases. After 500 switching impulses are applied to the EPR cable samples, the ac breakdown voltage gradually decreases as more impulses applied.

The trend of XLPE cable samples observed in this experiment from Figure 4.47 is in agreement with the phenomenon reported in [30, 34], in which the dielectric strength of XLPE cables is determined after several years of aging in the field and accelerated aging in the laboratory. The ac breakdown voltage of XLPE cable sample decreases for first 500 applied impulses. The decrease of ac breakdown voltage is due to the increase of cavity numbers in insulation [32]. During the interval between 500 impulses and 5000 impuses, the ac breakdown voltage increases. This phenomenon is assumed to be attributed to the decomposition of cavities in insulation. It is expected that the ac breakdown voltage will decrease again after a large number of impulses are applied.

There is large scatter in results of EPR cable samples as shown in Figure 4.45. A very approximate linear relationship between dielectric strength and applied impulses can be observed. After 5000 impulses are applied, the remaining electrical strength of EPR cable sample is only 71.8% percent of the unaged cables. The decrease in ac breakdown voltage for XLPE and EPR cable samples for the first 100 impulses in the cables is generally assumed to be the effect of the new cavities formed in insulation due to the stress of switching impulses. The decrease in ac breakdown strength of cables, which were used in service, is reported by T. Nagata, and N. Shimizu [40]. They tested the several 33 kV cables that were in service for 20 years and found decrease in ac breakdown strength of used cables. The same phenomenon is observed for EPR cable samples in this experiment. During manufacturing of the insulation materials, some cavities are formed in the insulation. These cavities are irregular in shape and may have some sharp points. When energized by switching impulses, the electrical field around the sharp points of those cavities is so high that new cavities may be created as a result. The increase in cavities number decreases ac breakdown voltage.

The breakdown mechanism of XLPE and EPR materials has been studied in great depth. Publication [35, 39] provide general information of breakdown phenomenan in solid dielectric materials. Detailed information about the ac breakdown mechanism of XLPE materials can be found in publication [36]. In this experiment, both carbonized channels and pinholes have been observed on the cable insulation, where ac breakdown occurred [37]. Similar phenomena is observed in this study. Figures 4.48 and 4.49 presents the breakdown occurred in XLPE and EPR cable insulation when ac voltage was applied.

Figure 4.48 Insulation breakdown in XLPE cable sample due to applied ac voltage

Figure 4.49 Insulation breakdown in EPR cable sample due to applied ac voltage

CHAPTER V

CONCLUSION

Conclusion

This thesis discusses the aging phenomena and dielectric degradation of 15 kV XLPE and EPR cable due to electrical stress caused by switching impulses. This chapter discusses the ac breakdown results of both XLPE and EPR cables. Partial discharge parameters and analysis are used as a tool to determine the partial discharge activity in the cable insulation during the aging process.

In the thesis, the results show the effect of the switching impulse of 100 kV magnitudes on XLPE and EPR cables. The applied switching impulses cause the degradation of the both polymer cables. Partial discharge inception voltage, partial discharge extinction voltage, partial discharge pulse count, and partial discharge magnitude are the different parameters used to evaluate the degradation of the cable insulation. Three dimension (3D) analysis plots are used to show the deterioration in cable insulation. The ac breakdown results determine the remaining dielectric strength of both cables.

The following conclusions can be made based on the research that has been done:

a. After switching impulses are applied on 15 kV XLPE and EPR cables, both the cables show sign of degradation.

b. The partial discharge inception voltage and partial discharge extinction voltage, that are measured during the analysis, provides the most evident proof that deterioration of cable insulation has taken place.
c. XLPE cable samples show significant increase in partial discharge magnitude after aging.
d. EPR cable samples show a slight increase in partial discharge magnitude after aging.
e. The partial discharge inception and extinction voltage of EPR cable samples is higher than that of XLPE cable for aged cable.
f. From the partial discharge analysis, it is found that EPR cable provides more resistant to partial discharge activity than that of XLPE cable.
g. The ac breakdown voltage of EPR cable samples decreases significantly after 5000 impulses.
h. The ac breakdown voltage of XLPE cables decreases at first for the 500 switching impulses and then it increases again.
i. The ac breakdown voltage of XLPE cable is expected to decrease as more switching impulses are applied.

Future Work

From the research work conducted in XLPE and EPR cables, it is concluded that a large number of applied switching impulses will be needed for better understanding of the aging phenomenon [1]. The testing can be done with multi- stress to evaluate the cables in different conditions. The XLPE and EPR cables are susceptible to the treeing effect. The experiment can be conducted on moisture content or wet cables so that the effect of switching impulse on the cables during that condition can be evaluated and breakdown strength can be determined from ac breakdown test.

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