DIELECTRIC RESPONSE ANALYSIS OF SOLID INSULATING MATERIAL USED IN HIGH VOLTAGE EQUIPMENT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ELECTRICAL ENGINEERING
2016

By

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The foregoing thesis is hereby approved as a credible study of an engineering subject, carried out and presented in a manner satisfactory to warrant its acceptance as pre-requisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for which it has been submitted.

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I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of the Master in Electrical Engineering studies.

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Acknowledgements

I would like to take this opportunity to humbly express my gratitude for the innumerable gesture of help, cooperation and inspiration that I have received from my teachers, friends and well wishers during this course.

I feel honored to express my profound regard and deep sense of gratitude to my guide Dr. Sovan Dalai and Dr. Biswendu Chatterjee, Electrical Engineering Department, Jadavpur University, Kolkata, for allowing me to do my work in this exciting field. They have been the people to instill in me a sense of commitment, dedication and optimism. I am highly obliged and grateful for their excellent guidance, endless encouragement, unique cooperation extended to me, right from the time of onset of this colossal task till its successful completion of my work.

I would also wish to express my sincere gratitude to Prof. Abhijit Mukherjee, Kesab Bhattacharya, and Prof. Sivaji Chakravorti, Dept. of Electrical Engg., Jadavpur University for their keen interest and active support in this work.

I would like to thank Prof. Swapan Kumar Goswami, Head of the Department, Electrical Engineering, Jadavpur University for providing the necessary facilities for carrying out this thesis.

I would like to give a special thanks to Mr. Arpan Kumar Pradhan, Mr. Riddhi Ghosh and Mr. Nasirul Haque, Mr. Soumya Chattrjee and Mr. Suhas Deb for their spontaneous support and inspiration in carrying out this work.

I would like to thank all my classmates, colleagues Niladri Ray Choudhury & Arnab Baug and juniors for their help and endless effort to complete this work during M.E. course.

Words would be trite to express the extent of dependency, love and fortitude towards my parents and younger brother, without their love and encouragement it would have been impossible to complete this work. Last but not the least; I thank almighty God for all his blessing.

Amrendra Kumar

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CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTIONS

The modern power network is a complex system that consists of a variety of electrical equipments such as power transformers, circuit breakers, potential transformers, current transformers, high voltage transmission lines and cables, etc. Failure of any of this equipment may lead to interruptions in the power supply which further results in substantial loss of money and time. Hence, to ensure the reliability and quality of a power system, it must be ensured that outages on account of equipment failure are minimized. Equipment failure may be caused due to a number of factors such as end-of-life, environmental stresses, etc. However, a major part of outages in a power network is caused as a result of insulation failure.

A variety of different insulation systems may be encountered in a power network. Insulation systems may be solid (overhead insulators, cables), liquid (transformer oil) and gaseous (SF_6 in circuit breakers and air in overhead transmission lines). While a lot of research has been carried out over the years to study the aging and deterioration of liquid and gaseous dielectrics and various models exist to correlate aging and insulation failure, the behavior of solid dielectrics are not that well understood. For this reason, this thesis explores some areas related to condition monitoring of solid insulation, which has not been previously studied.

1.2 SOLID INSULATING MATERIAL

Insulating material plays an important role in high voltage equipment and high voltage power supply system. Solid insulation or dielectric material is mainly used in high voltage cables, outdoor insulators (like pin/disc insulators), Dry type Transformer etc. so, we can say that the insulation plays an important role in reliable and efficient operation of the power system.

Several type of insulating material exists, each with distinct physical, chemical, mechanical and electrical properties. Depending on various applications, insulating materials have to comply with most diverse requirements. Apart from Electrical properties, the other properties of significance are mechanical, thermal, physical and chemical properties, the ability of materials to lend them to required treatment when used in the manufacture of necessary products, and also the cost and availability.

Here, a brief discussion concerning various solid insulating material mainly organic polymers is presented.

1.2.1 POLYETHYLENE (PE)

The simplest ethylene (C_2H_4) is a gaseous substance at normal temperature. The structure of the molecule of the ethylene polymer, called polyethylene or polythene, which is a solid substance, has the shape of a chain.

Polyethylene (PE) is subdivided on the basis of their polymerization processes. When the polymerization of ethylene is done at a pressure of up to 300 MPa and a temperature of about 200^0C, oxygen is introduced in small quantities into the reactor, which acts as an initiator of the reaction. The material produced with this method is called high-pressure polyethylene (HPPE). There is also a technique to obtain low-pressure polyethylene (LPPE) in which polymerization proceeds at a low pressure of 0.3 to 0.6 MPa and a temperature of approximately 80^0C. The molecular structure of Ethylene and the Polyethylene is shown in the Figure 1.1 and Figure 1.2

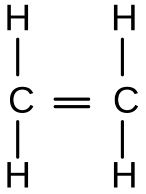


Figure 1.1. Molecular structure of ethylene

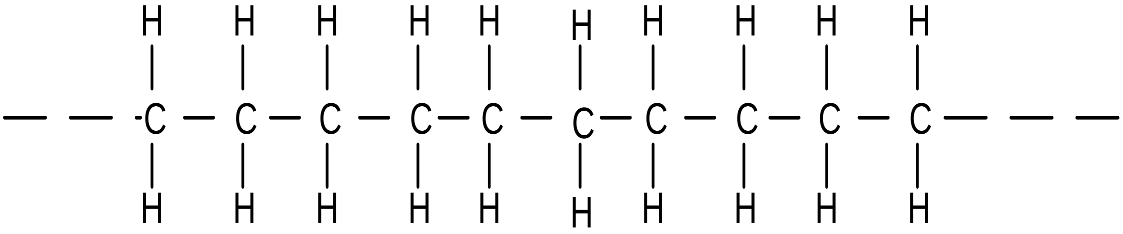


Figure 1.2 Molecular structure of polyethylene

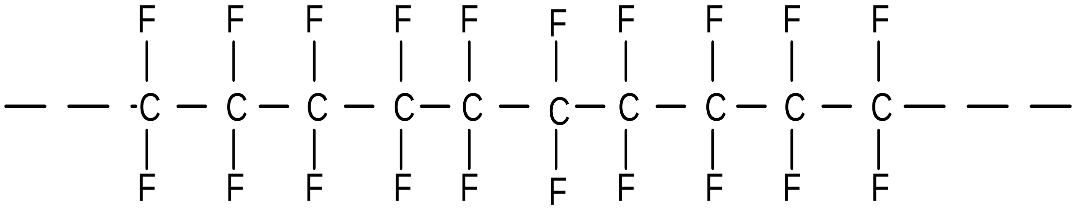
When polythene comes in contact with heat for short time, its physical strength is decayed. But when it is exposed for long time, it gets oxidized in presence of light and air. Thermal ageing of polyethylene can be retarded by introducing antioxidants, specifically some aromatic substances having amino groups –NH- disposed between benzene rings.

Various types of polyethylene find wide use in the insulation systems of high frequency, telephone and power cables etc. It should be kept in mind that the procedure of reprocessing the HPPE into products is appreciably simpler than for other types of polyethylene.

The thermal persistence of polyethylene can be increase by exposing it to ionizing radiation, which causes a partial cross-linking of the chains in polyethylene molecules and thereby brings about the formation of a space structure. Under short-term exposure to a temperature of up to 200^0C, an irradiated polyethylene item still retains significant mechanical strength sufficient for the item to maintain its shape. The prolonged thermal endurance of irradiated HPPE, estimated in terms of limiting temperature that do not cause thermal ageing, can be as high as 105^0C, while for the irradiated LPPE this temperature limit is even higher. It may be mentioned here that similar temperature limit for non-irradiated polyethylene is not greater than 90^0C [1].

1.2.2 POLYTETRAFLUOROETHYLENE (PTFE)

Polytetrafluoroethylene is obtained from the polymerization of tetrafluoroethylene $F_2C=CF_2$ (i.e., ethylene in which all the four hydrogen atoms are replaced by fluorine atoms) and has the following molecular structure:



$$-\,-\,\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\underset{\underset{F}{|}}{\overset{\overset{F}{|}}{C}}-\,-\,-$$

Figure 1.3 Molecular structure of Polytetrafluoroethylene

Polytetrafluoroethylene is a non-polar substance owing to the symmetric structure of its molecules. This material is commonly known as Teflon. Teflon exhibits an unusually enhanced thermal endurance (of the order of 250^0C) that is attributed to a high bonding energy of the C-F links. It is exceptionally stable to chemical agents. Moreover, it is completely non-flammable, absolutely non-hygroscopic and non-wettable, be it water or other liquids. As far as electrical insulating properties are concerned, Teflon ranks among the best dielectrics ever known in practice. Its permittivity within the frequency range of 50 to 10^{10} Hz is 1.9 to 2.2, and volume resistivity is about 10^{16} Ω.m. As for the cold resistance, Teflon retains its flexibility at temperatures below -80^0C [2]-[4].

Teflon can be prepared as a plastic mass suitable for the production of molded items, sheets, flexible films, cable insulation etc. The unique properties of Teflon make it indispensable for special applications, for example, in the conditions of simultaneous actions of high and low temperatures on insulation, or chemically active media, moisture and so on. However, the complex production process and thus the high cost of Teflon impede its wide usage.

1.2.3 POLYPROPYLENE (PP)

Commercial polypropylene homopolymers is a synthetic, high molecular mass, semi crystalline solid polymer of propene having melting point around 160^0C -165^0C(320-329^0F) [5,6]. Propylene $CH_3CH = CH_2$ is produced with ethylene in large quantities at low cost from the cracking of oil and other hydrocarbon feed stocks. It can also be made by propane dehydrogenation. The molecular structures of propene are shown in the Figure 1.4.

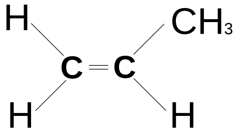
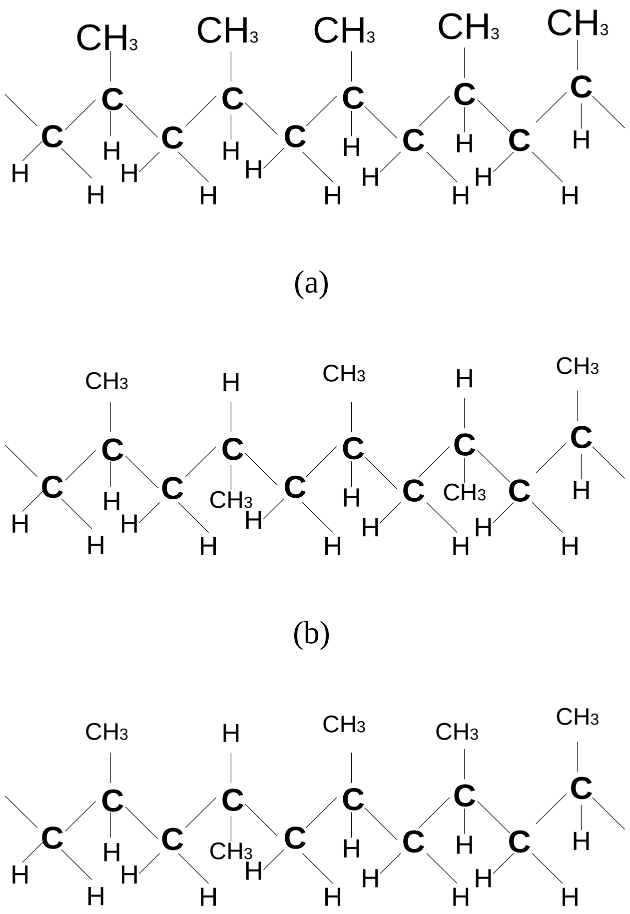


Figure 1.4 Molecular structure of polypropylene

The polymerization of propylene can yield the three basic types of polypropylene materials-isotactic, syndiotatic and atactic which differ from the orientation of the methyl groups (CH_3) along the polymer chain shown in the Figure 1.5.



(a)

(b)

(c)

Figure 1.5. Idealized Molecular structure of Polypropylene Materials. (a) Isotactic; methyl group always on same side of chain. (b) Syndiotatic; Methyl group position alternating (c) Atactic; Methyl groups randomly distributed [7]-[9].

Purely isotactic form can be manufactured by either Ziegler-Natta or metallocene catalyst process. Both the isotactic and syndiotatic form of polypropylene have relatively high melting, high degree of crystalline solids, resulting in superior properties, whereas atactic polypropylene is an amorphous frequently sticky material [10]. Its application range from food container to high performance, high frequency and low loss capacitor, Electrical insulation, Medical equipment. It is non toxic in nature, that’s why it is used in electrical and non –electrical quantity to provide addition level of safety [11].

1.2.4 POLY METHYL METHACRYLATE (PMMA)

Poly methyl methacrylate or poly methyl-2 methyl propenate is a hard transparent polymer, with high optical clarity, high reflective index and good resistance to the effect of light and aging. It is a polymer of methyl methacrylate, with chemical formula$(C_5H_8O_2)_n$. It is available on the market in both plate and sheet from under the name of Acrylite, Perspex, Lucite etc. it is commonly called acrylic glass or simply acrylic.

Poly methyl methacrylate is produced by free radical polymerization of methyl-methacrylate or suspension polymerization [12-13].molecular structure of methyl-methacrylate and poly methyl-methacrylate are shown in the Figure 1.6 and Figure 1.7.

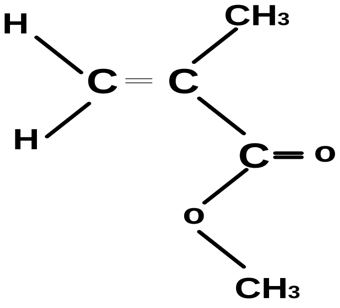


Figure 1.6. Molecular Structure of Methyl-Methacrylate

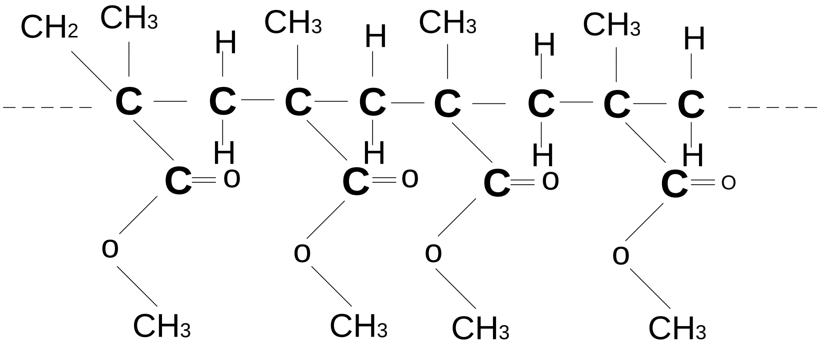
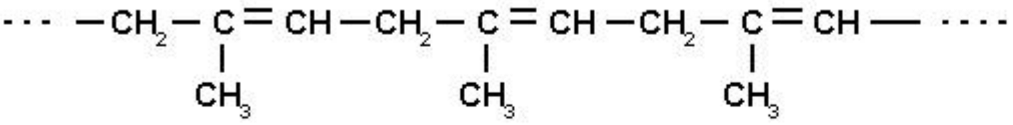


Figure 1.7.Molcular Structure of poly methyl-methacrylate

PMMA is a liner thermoplastic polymer. PMMA has high mechanical strength, high Young’s modulus and low elongation at break. It is one of the hardest thermoplastics and is also highly scratch resistant. It exhibits low moisture and water absorbing capacity, due to which products made have good dimensional stability. Both of these characteristics increase as the temperature rises. The thermal stability of standard PMMA is only65^0C. Heat-stabilized types can withstand temperatures of up to100^0C. PMMA can withstand temperatures as low as-70^0C. Its resistance to temperature changes is very good. The low water absorption capacity of PMMA makes it very suitable for electrical engineering purposes. Its dielectric properties are very good. Its resistivity depends on the ambient temperature and relative humidity. The dielectric constant, as well as the loss tangent, depends on the temperature, the relative humidity of air and the frequency [14-15].

1.2.5 NATURAL RUBBER

Natural rubber is derived from special plants, called rubber-bearing plants. By its chemical composition, natural rubber is a polymeric hydrocarbon with the composition $(C_5H_8)_n$ and the structure is characterized by the presence of double bonds:



$$\cdots\ -CH_2-\underset{\underset{\textstyle CH_3}{|}}{C}=CH-CH_2-\underset{\underset{\textstyle CH_3}{|}}{C}=CH-CH_2-\underset{\underset{\textstyle CH_3}{|}}{C}=CH-\ \cdots$$

Figure1.8 Molecular Structure of Natural Rubber

Natural rubber softens and becomes tacky when heated up to 50^0C, while at low temperature it turns brittle and it dissolves in hydrocarbons. Because of these factors, natural rubber cannot be used as electrical insulation. To make it suitable for electrical insulation systems, natural rubber is vulcanized with sulphur and heat to break apart the double bonds in chain molecules and to cross-link the chains with –S- atoms to form a space structure. Vulcanization of natural rubber improves its thermal and cold endurance, increases its mechanical strength and resistance to solvents. Depending on the amount of sulphur added to natural rubber during its vulcanization, the process yields various products: with a sulphur content of 1 to 3% it gives a soft rubber of high stretchability and elasticity, but when as much as 35% sulphur is added the product obtained is hard rubber, called *ebonite* that shows superior impact stress endurance[16,17].

Ozone that appears due to partial discharge in air voids or due to discharges in surrounding air is most injurious to rubber. It sharply accelerates ageing of rubber parts. Moreover, the residues of free (chemically unbound) sulphur contained in rubber can have detrimental effect on copper in contact with rubber, especially at elevated temperature. This is why it is inadmissible to use common rubber insulation directly on copper conductor. But aluminum conductors can be coated with rubber directly.

1.3FACTORS AFFECTING INSULATING MATERIAL PROPERTIES

The performance of the solid insulation can be affected by environmental condition within which it is used. However, many of this parameter is also impacted by the internal operating conditions of the solid insulation. Temperature has predominanant effect on the behavior of solid insulation .humidity also plays important role in deteriorating the performance of solid insulation.

1.3.1 TEMPERATURE

Different parameters such as voltage (operating and ripple), current (operating, ripple, and leakage), capacitance, impedance, dissipation factor, and dielectric absorption are affected by temperature. High temperature has disastrous effect on the characteristic of the solid insulation. Generally higher the operating temperature, lower is the insulation resistance value of the dielectric materials. For each type of insulation there will be highest temperature beyond which the dielectric will become useless as insulation because resistivity and dielectric strength will be too low. The performance of the dielectric becomes better at lower temperatures. Dielectric absorption increases with increase of operating temperature. Similarly the leakage current increases with increase in temperature.

The maximum operating temperature of an insulation of a material is that temperature at which the insulation can be continuously operated within its limits. If the operating temperature exceeds the maximum temperature for a long period of time the insulation resistance value becomes so low as to make the insulation use less. While selecting the insulation of any equipment for electric engineering adequate care should be taken to see that operating temperature remains below the highest permissible temperature.

The rise in temperature of insulation of the material may be due to the rise in ambient temperature and also due to higher absorption of energy due to polarization effect and lowering of leakage resistance. While selecting and designing an insulation of material for high voltage operation, adequate attention should be paid to this factor. If necessary, proper thermal cooling arrangement should be used to keep the operating temperature low and maintain the proper characteristic of insulation

1.3.2 HUMIDITY

Higher humidity can lead to failure of the insulation. Excessive humidity in the environment will degrade the performance of the insulation. It is well known that the humidity reduces the usefulness of oil paper insulation system. However, for polymer insulation the effect of humidity is not as pronounced as compared to the oil-paper insulation, because of lower absorption of the moisture by the polymer insulation. Nevertheless, surface resistivity of polymer insulation may drop sharply when in contact with moist environment.

1.4 INSULATION LIFE

Insulation of high voltage equipment is made up of various materials that will exhibit certain electrical behavior when exposed to external stimuli. The combination of materials that make up some insulation might not be stable over time. Insulation characteristics can change during storage as well as during operation. The behavior of insulation over time or its anticipated life is dependent upon the materials of composition, storage conditions, and its operating parameters. The manufacturer supplies high voltage equipment with a rated life based upon specific parameters. Because the life of insulation depends upon various conditions, the shelf life or storage life, the service life, and their relationships should be understood by the user.

1.4.1 RATED LIFE

The rated life of insulation of equipment is the anticipated period of time that insulation of a equipment has been designed to operate, based upon application and operating conditions. The manufacturer will typically quote this life based on accelerated testing or field experience, depending upon available data. Typically, the manufacturer will supply a device with a certain expected life based upon placing it in service soon after manufacture (that is, within two years of manufacture) and operating it within specified limits. The rated life will be different for different types of insulation and applications. Although the manufacturer provides the rated life, it is the responsibility of the user to understand the effects of its application on the rated life. The rated life provides a reference point when no other data are available regarding insulation behavior. The rated life of insulation also depends on the quality of the construction and the materials used to make up the insulation of the system. There are two quality levels typically assigned to insulation of the equipment: general purpose and premium. Typically, the rated life of premium insulation is greater than that of a general purpose insulation of the equipment.

1.4.2 SHELF LIFE

Self Life is the span of time or Period of time on insulation of a dielectric material will retain its effective usability when just kept stored (or stocked) without any use. For each and every material there is the shelf life after which material becomes useless. This is mainly due to the changes in the internal structure of the dielectric material over a period of time.

While manufacturing an insulating material, care should be taken to ensure that insulation with expired shelf life are not used. Even a manufactured item (such as capacitor or insulating materials) should not be used after expiry of the shelf life of any one of its component

1.4.3 SERVICE LIFE

Service life is the anticipated life that a component, equipment or system should provide before significant deterioration in operational characteristics or total failure occurs in proportion to rated life. This term is often referred to as “useful life.” The useful life of a component, equipment or system, however, is more akin to characteristic variations than to total failure of a component. Depending upon operability requirements, characteristic variations do not necessarily indicate equipment failure or loss of operability.

The anticipated service life of an insulation of the equipment must be based on several factors such as date of manufacture, storage conditions, operating parameters, and environment. The service life of an insulation of equipment can be prolonged by operating it below its specified ratings. The three key characteristics that affect insulation service life are:

- Applied voltage
- Ripple current
- Ambient temperature

The service life of an insulation of the equipment is typically provided by the manufacturer or can be calculated based on the circuit application requirements (for example, voltage rating).The useful life of insulation should be related to the change in performance characteristics. The change in insulation characteristics is primarily due to changes in its dielectric properties.

A useful life can be assigned to insulation of the system by establishing levels at which maintenance actions will be taken, based upon measurable characteristics. These actions will also depend upon whether one is concerned with discrete components (for example, single capacitors) or assemblies (for example, power supplies or circuit cards).

1.5 FAILURE OF INSULATION

An AC power system is a complex network of many components such as synchronous generators, power transformers, transmission lines, distribution network and loads. Serious failures in a power system owing to insulation breakdown cause considerable financial loss due to power outage and cost of replacement or repair [18]. Temperature (ambient and operational) is the principal stress that prompts changes in insulation operating parameters. These changes can be gradual or catastrophic depending on temperature levels.

The rated life or design life of insulation is specified by the manufacturer. The service life can differ from the rated life due to degradation during storage or due to degradation caused by misapplication

The insulation failure of high voltage system or equipment depends on predominantly two factors: (i) environmental factor (ii) electrical factor,

Environmental factors include temperature, humidity, atmospheric pressure, and vibration. Electrical factors include operating voltage, ripple current, and charge-discharge duty cycle. Among these factors, temperature (ambient temperature and internal heating due to ripple current) is the most critical to the life of insulation of the equipment. Conditions such as vibration, shock, and humidity have less effect on insulation life.

The type of age-related failure that a particular insulation of the system exhibits, as well as the time it takes for a failure to occur, depends on its design, application, and environment. Under ideal conditions, the failure rate of insulation of the system tends to follow some form of a traditional bathtub curve [19- 20][21]. It can be divided in three failure mode shown in the Figure. 1.9.

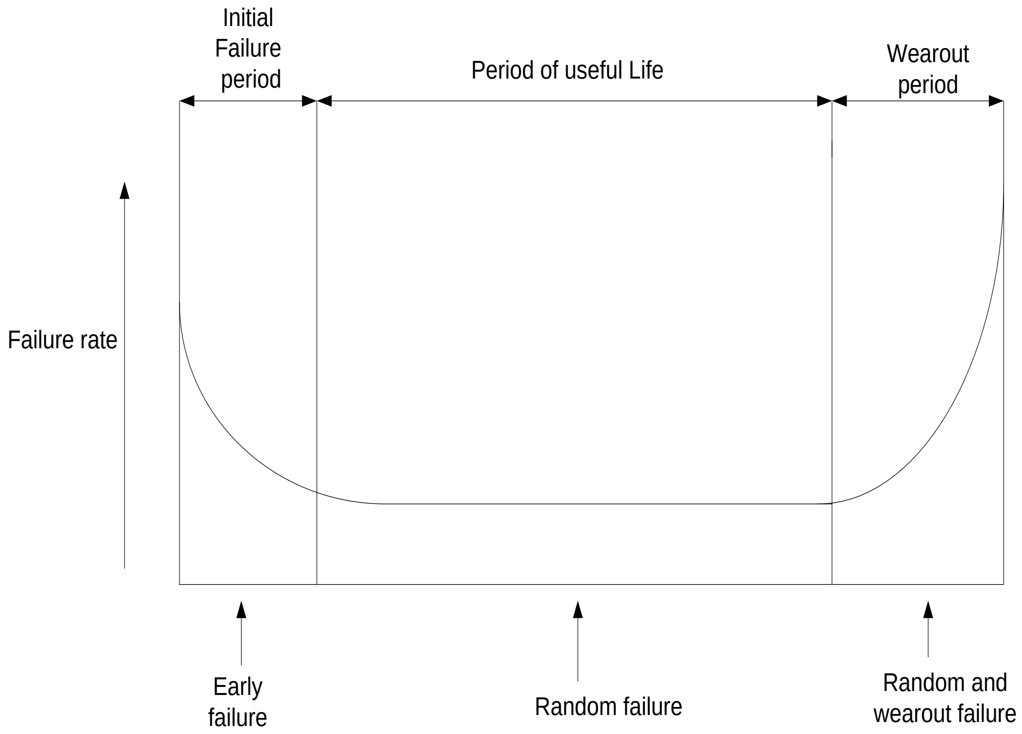


Figure 1.9 Typical Failure Rate curve

1.5.1 Early Failure of Insulation

These occur during the first year of energization and typically caused by deficiencies in design, structure, manufacturing processes, or severe misapplication.

- Short circuits caused by foil impurities
- Defects, such as burrs
- Breaks or tears in the foil
- Breaks or tears in the separator paper

The manufacturing process has improved considerably, and new insulation are properly screened and tested as part of production, with defective insulation being rejected prior to shipment. For this reason, most early failures are more likely to be caused by misapplication. Typical misapplication examples include extreme ambient conditions, exceeding rated voltage, reverse voltage, or excessive ripple current.

1.5.2 PERIOD OF USEFUL LIFE

After an equipment or power system is installed and operating within its rated parameters, the failure rate tends to be low for several years. Random failures should rarely occur for many years of operation, unless application conditions are severe. Short circuits are the most common failure mode during the period of useful life, caused by random breakdown of the dielectric materials under operating stress. Short circuits can also be caused by excessive stress in which voltage, temperature, or ripple current exceed specified ratings. Excessive temperature, high voltage, or reverse voltage can also promote dielectric breakdown. Some users have noted that open circuits are more common than short circuits in their power supply applications. Open circuits can be caused by failure of the internal circuits joining insulation terminals to the foil. Mechanical connections can develop an oxide film at the contact interface, increasing contact resistance and eventually causing an open circuit. Defective weld connections can also fail. Excessive mechanical stress, such as high vibration, can accelerate this type of failure.

The failure of a insulation can be defined as either total failure (that is, short circuit or open circuit) or significant changes in parametric values that significantly affect circuit operation.

Insulation degradation and failure are related to changes in insulation characteristics. The operating life of insulation is determined by its operating voltage, ripple current, and operating temperature.

1.5.3 WEAROUT PERIOD

This type is the result of material wear out. Normally, the wear out mode becomes predominant only after 20 years of operation. This normal wear out period is followed by an increasing failure rate.

Failures in wear out period occurs due to

- Thermal fatigue
- Change in operating parameters
- Component damage

1.6 SCOPE OF THE THESIS

In this thesis, a measurement system controlled by the software known as LabVIEW is used to investigate the polarization and depolarization current measurement as well as recovery voltage measurements of different high voltage insulating materials. The aim of this thesis is to utilize the polarization and depolarization current measurements to study the condition of the high voltage insulating materials. Firstly, Different types of High Voltage insulating materials are collected and gathered in High Tension Laboratory, Jadavpur University. After that, Electrodes made of brass with diameter of 5 cm are used in experiments. The samples are placed in between the electrodes. By using the developed dielectric measurements system polarization and depolarization currents are recorded to assess the insulation condition of the insulating materials.

1.7 CONTRIBUTION OF THE THESIS

- The PDC measurement system is developed in the High Tension Laboratory of Jadavpur University has been made to study the insulation condition of high voltage insulating materials.
- Dielectric dissipation factor ($tan\delta$) for different insulating materials at different frequency has been measured.
- Observed the effect of temperature on PDC measurement of solid insulating materials

1.8 OUTLINE OF THE THESIS

Chapter 1: provides the introduction and scope of the thesis. The chapter describes preliminary concepts related to high voltage insulating materials, factor affecting the properties of the insulating materials and failure of insulation of the high voltage equipment. Finally scope of the study of Dielectric Response Analysis of Solid Insulating Materials used in High Voltage Equipment.

Chapter 2: Describes the different methods of condition monitoring of the solid insulating materials.

Chapter 3: Describes the general information about Polarization and depolarization Current measurement and also describes the modeling of polarization and depolarization current.

Chapter 4: Describes the experimental setup and experimental procedure for measurement of polarization and depolarization current, dielectric dissipation factor $tan\delta$ measurement.

Chapter 5: Describes the result of the experiment and analysis that were done on the basis of experimental result.

Chapter 6: Contains the conclusions of the thesis. Future scope of work is also presented.

CHAPTER 2

CONDITION MONITORING OF SOLID INSULATING MATERIALS

CHAPTER 2

CONDITION MONITORING OF SOLID INSULATING MATERIALS

2.1 INTRODUCTION

As previously mentioned, insulating material plays an important role in high voltage equipment and high voltage power supply system. In power supply various electrical equipments are connected like transformers, circuit breakers, high voltage cables etc, and they are very expensive to replace when the problem occurs. Therefore, condition monitoring is required to extended life of the insulation beyond its designed life. Degradation of insulation could be dealt with by replacing the aged insulation by the new insulating materials or by proper maintains through the condition monitoring.

As this thesis is basically focused on solid insulating materials, it is important to review the available methods for insulation monitoring involving solid dielectrics. These solid dielectrics, i.e. LDPE, XLPE,HDPE etc. are mostly used in cables, which is a very essential component of the overall power system. In this chapter some condition monitoring methods for solid dielectric based high voltage insulation systems are discussed.

2.2 TENSILE STRENGTH MEASUREMENT

With aging the tensile strength of insulating materials decrease. An aged insulation is more vulnerable to insulation failure under high electric stress then fresh insulation. Therefore, tensile strength measurements of insulating materials can be a good indicator of insulation condition. Tensile strength measurement is performed at high voltage to find out the reliability of the insulation. Voltage source greater than the rated voltage is applied to the insulation. The motive of this measurement is to see how the insulation reacts to that voltage at the specified time, whether it will withstand it or breakdown.

The mechanical strength is usually measured by its tensile strength. The insulation will deteriorate seriously when the insulation material has lost his mechanical strength.

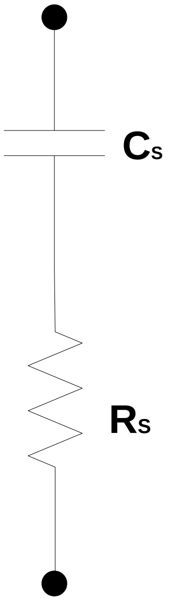
The tensile strength of the insulation is the most sensitive measure of degree of aging [22].

Tensile strength of the insulating material is often regarded as the braking strength per unit cross-section area of the insulation. It is able to measure the strength of the insulating material and provide indication of the suitability of the insulation used. Therefore; this technique can be used by manufacturers and users to check on the design.

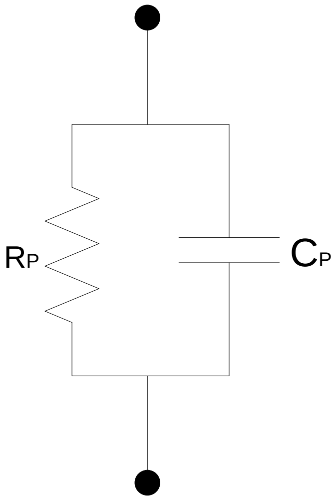
2.3 DISSIPATION FACTOR

One of the important Measurements of the quality of the insulation is the dielectric loss of the insulation. Variation of the dielectric loss can provide useful information caused of aging of the insulating material. A high dielectric loss will result in the thermal breakdown of the insulation at low voltage. It would be easier to understand the dissipation factor by using modeling of the insulation.

A simplified model of an insulation system can be represented by a capacitance and resistance either series or parallel shown in the Figure 2.1. This is the concept employed in the use of power factor testing of insulation systems [23]. Dielectric loss can be determined using loss angle δ the phasor diagram of loss angle is shown in the Figure 2.2. The loss angle can be measured using the Schering Bridge.



C_S-Capacitance in series
R_S-resistance in series



Cp-Capacitance in parallel
Rp-Resistance in parallel

Figure 2.1 Modeling of the solid insulating material

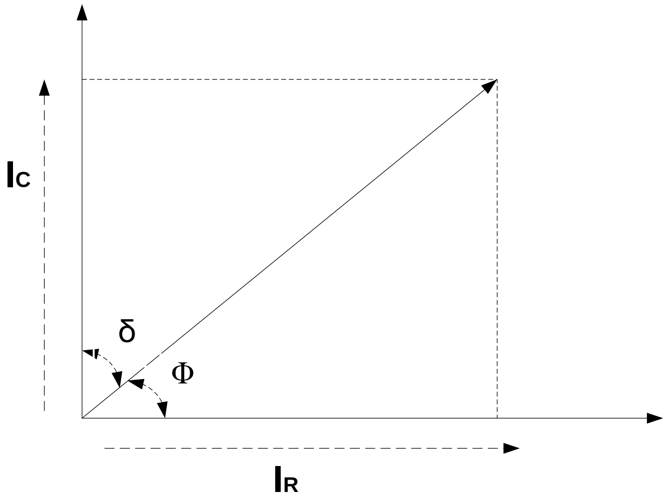


Figure 2.2 Phasor Diagram for Showing the Loss Angle 'δ'

In high voltage application, insulating material should possess low dissipation factor, as the dielectric loss is directly prepositional to the loss angle and voltage squared. High dissipation factor would causes the energy loss in the dielectric is very rapidly with voltage and this cause thermal unstable condition. The dissipation factor is increases when the temperature is increases. It also increases with frequency at low moisture content and decreases with high moisture content. The dissipation factor increases as the degradation proceeded at low frequencies.

2.4 PARTIAL DISCHARGES

Partial discharge monitoring is an effective on-line predictive maintenance test for high voltage distribution equipment. Partial discharge theory involves an analysis of materials, electrical fields, arching characteristic, frequency response, etc [24].

Partial discharge is a localized electrical discharge that only partially bridge the insulation between conductors and which may or may not occurs adjacent to a conductor. The term partial discharge include a wide group of discharge phenomena :(i) internal discharge occurring in the in voids or cavities within solid dielectric; (ii) surface discharges appearing at the boundary of different insulating materials; (iii) continuous impact of discharges in solid dielectrics forming discharge channels (treeing) ;(iv) corona discharges occurring in gaseous dielectric in the persons of in homogeneous fields.

The difference in permittivity of the gases and the surrounding solid insulation will cause the electrical stress to be very high in gas cavity. As a result, partial discharges may occur at the interface of insulating materials within a dielectric. The PD measurements are utilized mainly to identify defects in insulation systems that are subjected to high electrical stress. The magnitude of partial discharges is an indication to the extent of erosion in the insulation system [25].

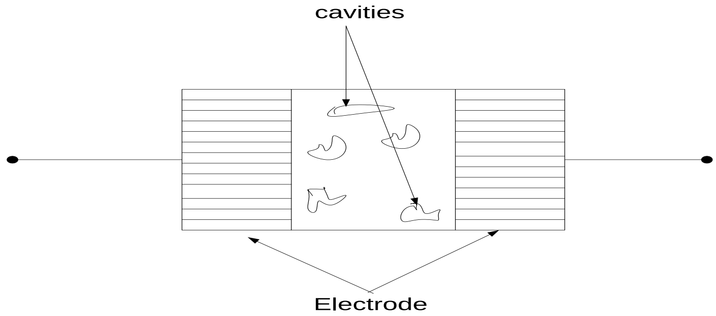


Figure.2.3. Solid Insulation as a Dielectric

Thus partial discharge can be used to analyze the degradation of High Voltage insulating materials. Environmental condition such as temperature, pressure, water content, previous electrification and the dielectric properties of the immersion fluid could influence the magnitude and the occurrence of partial discharges [22].

2.5 DIELECTRIC RESPONSE MEASUREMENTS

Dielectric response measurement is a non-invasive electrical technique is widely used for condition assessment of high voltage equipment, high voltage cable, winding of rotating machine, and high voltage insulation. Dialectical response depends on the condition of the insulating material, the geometry of the active part of the solid insulation. Dielectric response measurement is done in frequency and time domain. Capacitance and tan-δ are measured for characterizing insulation systems [26].

Dielectric properties of insulation are strongly influenced by ageing. Therefore, dielectric measurements can be utilized to assess the insulation conditions. The condition of the dielectric and its degradation due to thermal aging can be obtained by studying the rate and process of polarization.

Main dielectric responses are

- Polarization and Depolarization Current (PDC) Measurement
- Recovery Voltage Measurement (RVM)
- Decay Voltage Measurement

This thesis mainly concentrates on investigating the insulation condition using polarization and depolarization current measurement and Dissipation factor measurement.

2.6 POLARIZATION AND DEPOLARIZATION CURRENT MEASUREMENTS

A dielectric material becomes polarized when exposed to an electric field. Polarization is proportional to the intensity of the electric field and polarization process can be observed by measuring the current.

Polarization current is obtained when the system is exposed to a step voltage [27]-[30]. A reverse polarity current known as the depolarization current is obtained if the step voltage is removed and the dielectric is short-circuited. These two currents can be used to determine the response function and the conductivity of the dielectric material.

The PDC measurement gives general information about the state of insulation condition. This technique is proved to be a useful testing method in investigation of ageing phenomena. Both the polarization and depolarization tests are performed for the same period of times. Theory behind PDC measurement will be further discussed in Chapter 3 of this thesis.

2.7 RECOVERY VOLTAGE MEASUREMENT (RVM)

The principle behind the recovery voltage measurement (RVM) is to charge the insulation with a steady voltage (V_{dc}) for a specified time, t_c, and then short-circuit for a specified time, t_d, (where $t_c > t_d$) [31]-[34]. The voltage is then measured across the insulating material under open circuit condition. Due to insufficient discharge time, the residual energy within the dipoles is re-distributed and geometric capacitor during energy re-distribution is known as recovery voltage. The residual charge in the dielectric is present due to the fact that the discharging time in this type of measurement is less than that required to completely discharge the sample. The circuit for recovery voltage measurement has been shown in the Figure 2.4.

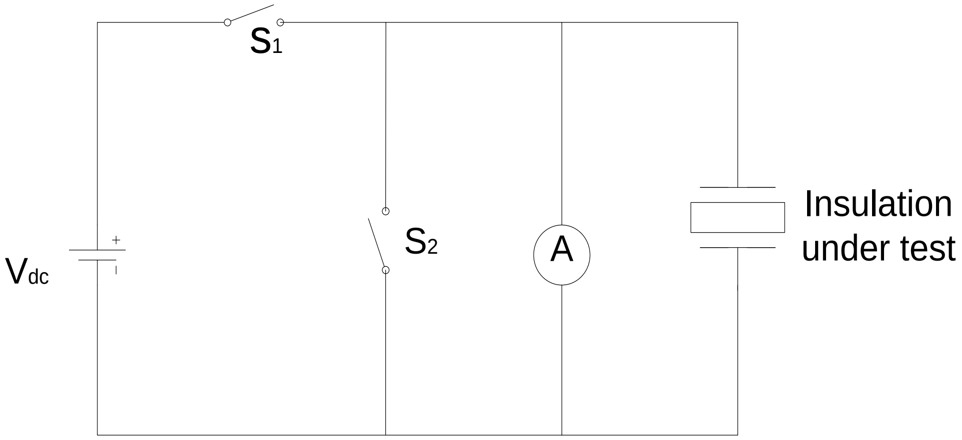


Figure 2.4: Circuit of Recovery Voltage Measurement

The circuit in Figure 2.4 can represent the measurement of recovery voltage. In this circuit the test object is represented by the capacitance C. The determination of recovery voltage consists of the following steps [35].

- The test object is charged by a DC voltage of $\boldsymbol{V}_{dc}$ during a time t_c (charging time) by closing switch S1
- The test object is isolated from the voltage source by opening S1 and short-circuited by closing S2 for a time of t_d (discharging time).
- S2 is then opened and the so-called recovery voltage appears across the electrodes, to be measured by the voltmeter.

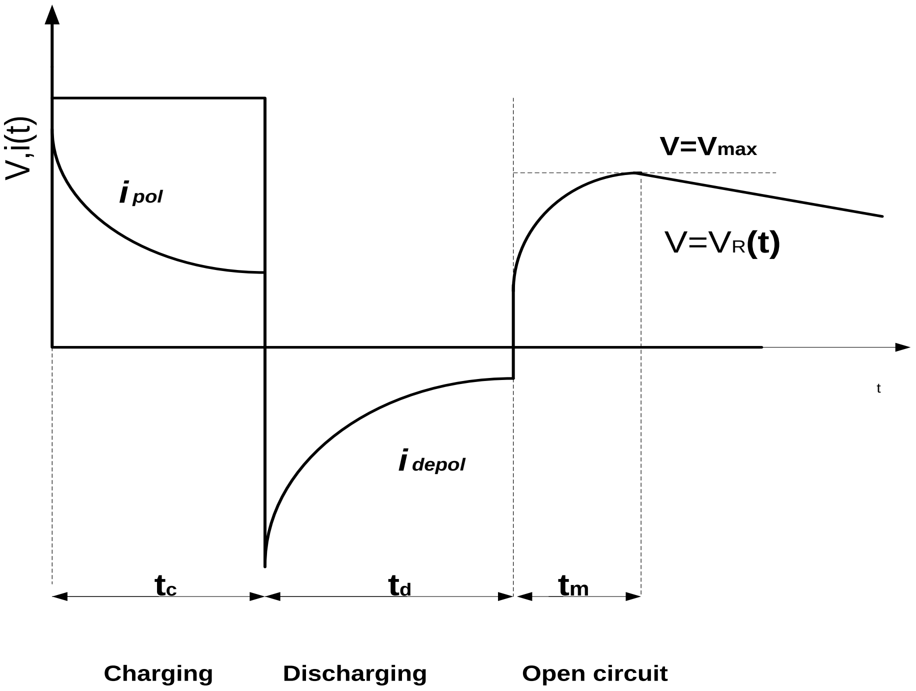


Figure 2.5: Typical nature of Recovery Voltage

This test cycle is performed many times with different charging and discharging times. The ratio of tc/td is kept constant (usually tc/td =2). This recovery voltage will display a maximum for each test cycle. The charging and discharging current and the recovery voltage data are recorded for every test cycle [36]. This data is then used to form an RVM spectrum. The RVM spectrum is a plot of the maximum recovery voltages obtained from the RV measurements versus the corresponding charging time [37]. The charging time at which the maximum recovery voltage is measured is called the central time constant. The typical voltage developed across the geometric capacitance has been shown in Figure 2.5. It should be mentioned here that the ratio of t_c and t_d is typically kept 2 for recovery voltage measurement.

2.8 DECAY VOLTAGE MEASUREMENT

After long period of charging of insulation, the DC source is disconnected from the insulation. The decay voltage is measured as the charge in the electrodes discharges. Figure 2.6 shows the decay voltage curve after a long charging time.

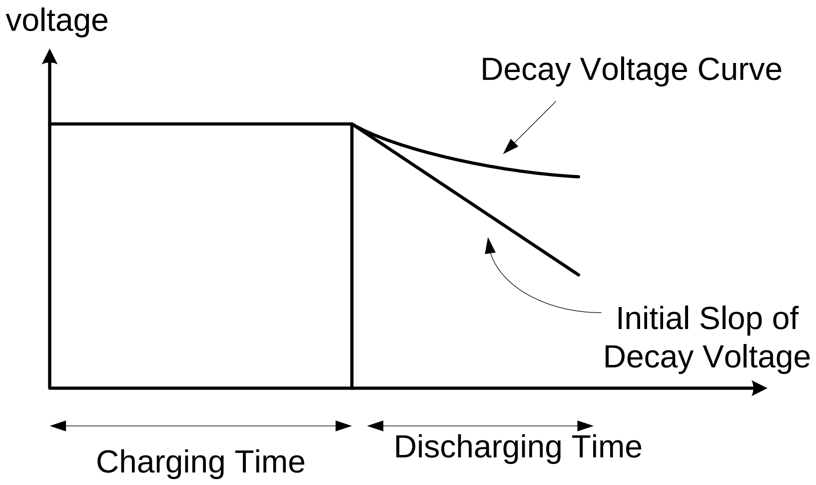


Figure 2.6 Decay voltages Curve after charging

Since moisture mainly affects the conductivity of the insulation material, which is found to be directly proportional to the steepness of the initial slope of the decay voltage curve, the decay voltage slope can be utilized to study the moisture content of the insulation system [38].

CHAPTER 3

DIELECTRIC RESPONSE MEASUREMENT

BY

POLARIZATION AND DEPOLARIZATION CURRENT

CHAPTER 3

DIELECTRIC RESPONSE MEASUREMENT BY POLARIZATION AND DEPOLARIZATION CURRENT

3.1 INTRODUCTION

The main objective of this thesis is to investigate the result of polarization and depolarization current, and tan delta measurements of different types of insulating materials to monitor their conditions. When a high voltage insulating material is in service or kept in store, it's insulation system degrades due to the different effect such as the environmental effect and electrical effect.

A brief description of polarization and depolarization current has already been discussed in the previous chapter. In this chapter, the theoretical model of basic polarization and depolarization processes are discussed. The application of Debye model for proper modeling of a dielectric material and its development from polarization-depolarization current measurements is also discussed.

3.2 POLARIZATION AND DEPOLARIZATION CURRENT (PDC) MEASUREMENT

Every kind of insulation material consist, at an atomic level, of negative and positive charge balancing each other on the microscopic as well as on more macroscopic scales(if no unipolar charge was deposited within the material before by well known charging effect). Macroscopically, some localized bipolar space charged may be present, but even then, an overall charged is naturally exists. A dielectric material polarized when exposed to an electric field [39]-[43]. The different dipolar groups is present in the different portion of the insulating material, try to align in the direction of the applied electric field and the polarization process starts within the dielectric medium. Due to this polarization of dipoles, an equivalent current flow through the dielectric medium, this is known as polarization current. A reverse polarity current known as the depolarization current is obtained if the step voltage is removed and the insulating material is short-circuited. These two currents can be used to determine the response function and the conductivity of the dielectric material.

Two components of leakage current exist in a dielectric: conduction current and polarization current. The conduction current is due to effective series resistance (ESR) associated to the dielectric material whereas the polarization current is due to the property of dipoles to align in the direction of the field. In a constant electric field, the resultant of this dipole alignment is an additional charge on the electrodes of the dielectric, compared to the charge that would be seen if the electrodes were Vacuum-insulated [44]. The polarization process can be described best as a process of energy storage in the form of various time constants and can only exist in the presence of an external field. When the field is removed, the dipoles relax and then recovery to the original state [35, 45]. Polarization is proportional to the intensity of the electric field and polarization process can be observed by measuring the current.

Polarization and depolarization current gives the general information about the condition of the insulation. This technique is proved to be a useful testing method in predicting the development of ageing phenomena.

3.2.1 Basic Theory of the Dielectric Response Measurement

The basic theory of dielectric response as it pertains to the analysis described in this Thesis has been developed in [24], [46-48].

On application of an electric field, the polarization processes being within the dielectric medium. For an isotropic and homogeneous medium, the polarization$P(t)$, holds a relationship with the applied electric field $E(t)$, as represented by equation (3.1) [49]-[50].

$$P(t) = \chi(t)\varepsilon_0 E(t) \tag{3.1}$$

Where $\chi(t)$ and ε_0 represent the electrical susceptibility of the materials and permittivity of free space, respectively. As the dielectric material is microscopically liner, isotropic and homogeneous, the electric flux density,$D(t)$, within the insulating medium can be expressed as given by equation (3.2)[51]-[55]

$$D(t) = \varepsilon_0 E(t) + P(t) = \varepsilon_0 (1 + \chi(t)) E(t) \tag{3.2}$$

The polarization processes,$P(t)$, within the dielectric medium is the combined effect of all the polarization mechanisms. Among these polarization processes, the electronic and ionic polarizations are very fast processes and can be considered as instantaneous polarization, P_∞. Since the dielectric medium cannot store infinite electrical energy, the polarization at longer times is finite $P(t \to \infty) = P_s$. When a step voltage,V_{dc}, is applied to a charge free media, the resultant polarization vector,$P(t)$ maintains an asymptotic increasing profile as shown in Figure 3.1

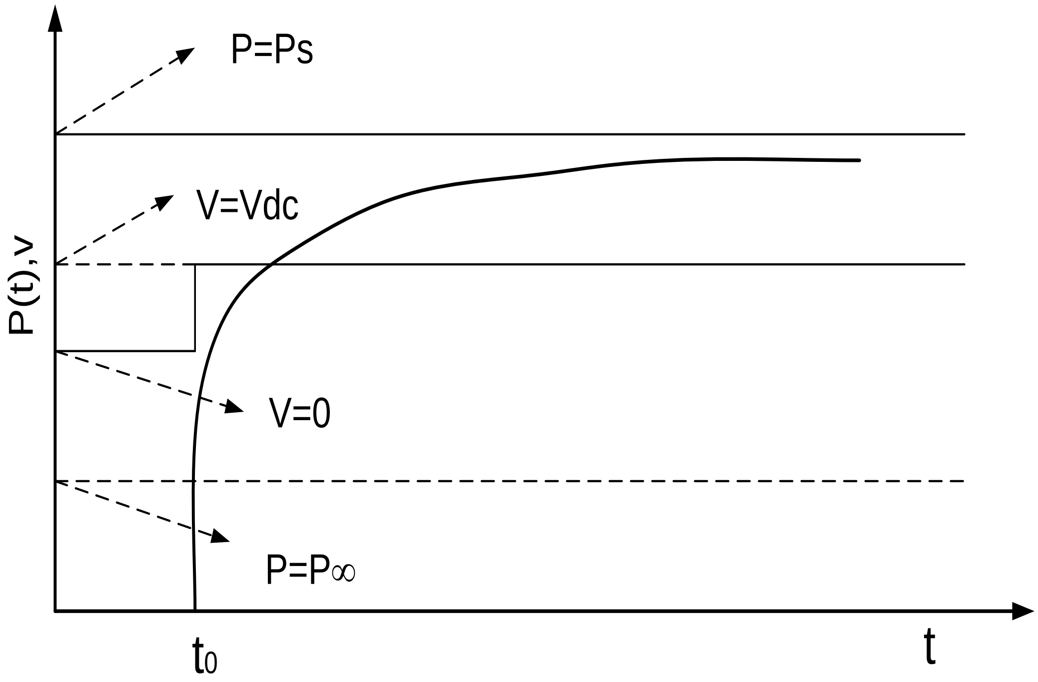


Figure 3.1: Time dependence of polarization under step voltage,V_{dc} at $t = t_0$

it can be observed from figure 3.1 that the polarization process within the dielectric medium can be expressed by equation (3.3)

$$P(t) = (P_s - P_\infty)g(t - t_0) + P_\infty \delta(t - t_0) \tag{3.3}$$

Where $\delta(t - t_0)$the Dirac delta functions and $g(t - t_0)$ is a monotonically increasing function with time (t) that satisfied the following conditions.

$$g(t - t_0) \geq 0, \frac{dg(t - t_0)}{dt} \geq 0 \quad for\ all\ t_0 < t < \infty \tag{3.4}$$

and according to the electrical energy criteria

$$g(t - t_0) = \begin{Bmatrix} 0\ When\ t \leq t_0 \\ 1 When\ t \to \infty \end{Bmatrix} \tag{3.5}$$

Using equation (3.3) and the asymptotic behavior of susceptibility, total polarization process due to any electric field at any time instant can be expressed as equation (3.6)

$$P(t) = \varepsilon_0 \left[\chi_s + (\chi_s - \chi_\infty) g(t - t_0) \right] E(t) \tag{3.6}$$

χ_∞ And χ_s in the equation (3.6) are the susceptibility of the dielectric material at $t = 0$ and $t > 0$, respectively. As susceptibility of dielectric materials is related to its permittivity, total polarization in the dielectric medium can be represented by equation (3.7)

$$P(t) = \varepsilon_0 \left[(\varepsilon_\infty - 1) + (\varepsilon_s - \varepsilon_\infty) g(t - t_0) \right] E(t) \tag{3.7}$$

If should be mentioned here if the electric field history is known (i.e.$E(t) for\ \infty < t < 0$), then the increase of polarization (dP) process due to the increment of the electric field (dE) result in

$$dP(t) = \varepsilon_0(\varepsilon_\infty - 1)dE(t) + \varepsilon_0(\varepsilon_s - \varepsilon_\infty)\int_{-\infty}^{t} g(t-\tau)dE(\tau) \tag{3.8}$$

Hence, the total polarization at time t in the dielectric material due to all increment of rewritten as in equation (3.9)

$$P(t) = \varepsilon_0(\varepsilon_\infty - 1)E(t) + \varepsilon_0(\varepsilon_s - \varepsilon_\infty)\int_{-\infty}^{t} g(t-\tau)\frac{dE(\tau)}{dt}d\tau \tag{3.9}$$

After some mathematical calculation, equation (3.9) can finally be represented as equation (3.10) [56]

$$P(t) = \varepsilon_0(\varepsilon_\infty - 1)E(t) + \varepsilon_0\int_{-\infty}^{t} f(t-\tau)E(t)d\tau \tag{3.10}$$

Where, monotonic decreasing function $f(t-\tau) = (\varepsilon_s - \varepsilon_\infty)\frac{dg(t-\tau)}{dt}$ represents the dielectric response function. Therefore under an electrical field, $E(t)$ total current density, $J(t)$ in the dielectric medium can be expressed by the equation (3.11)

$$J(t) = \sigma_0 E(t) + \varepsilon_0\varepsilon_\infty\frac{\partial E(t)}{\partial t} + \frac{\partial P(t)}{\partial t} \tag{3.11}$$

Where, σ_0 is the dc conductivity of the dielectric medium and $\varepsilon_0$is the permittivity of the free space. For a homogeneous material, the field strength, $E(t)$can be considered to generated by an excitation voltage,$V(t)$ then the total current,$i(t)$ flowing through a dielectric medium with geometric capacitance,C_0 (measured capacitance at or near power frequency ,divided by relative permittivity)can be written as [57]-[58].

$$i(t) = C_0 \left[\frac{\sigma_0}{\varepsilon_0} V(t) + \varepsilon_\infty \frac{dV(t)}{dt} + \frac{d}{dt} \int_{-\infty}^{t} f(t-\tau) V(\tau) d\tau \right] \tag{3.12}$$

In equation (3.12), part-I represent the conduction current flowing through the dielectric material whereas part-II and part –III represent the displacement and polarization current, respectively. It should be mentioned here that equation (3.13) is valid for a single dielectric medium as well as an arrangement of several dielectric material in series or in parallel.

It can be observed from equation (3.12) that the excitation voltage, V (t), can be steady or time varying.

3.2.2 POLARIZATION AND DEPOLARIZATION CURRENT

In the polarization and Depolarization current (PDC) measurement, a steady excitation voltage is applied to the insulation under test [59]-[60]. The dipoles in the insulation try to align in the direction of the applied field and the polarization process starts [39]. During polarization, monotonically decreasing current i_{pol} flows through the insulating media as shown in Figure 3.2

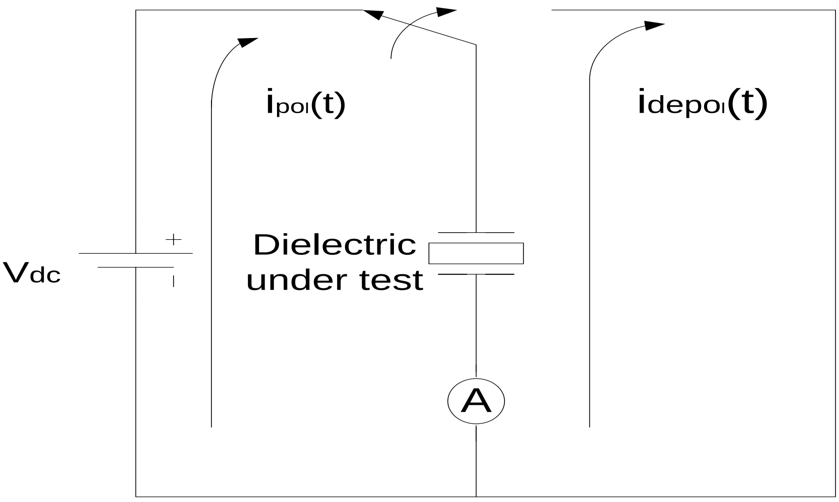


Figure 3.2: Basic Experimental arrangement for the PDC Measurement

These polarization processes are completed when all the dipoles are oriented in the direction of the applied field. Once the polarization process is completed, the polarization current become zero and conduction current flow through the medium. The magnitude of the conduction current depends on the insulation resistance of the dielectric media. During depolarization current is short-circuited. The dipoles start to return to their original state and the stored energy during polarization being to release. This phenomenon result is monotonically decreasing depolarization current,i_{depol} to flow in the opposite direction. The typical nature of polarization and depolarization current has been shown in Figure 3.3 [32]-[34], [61]

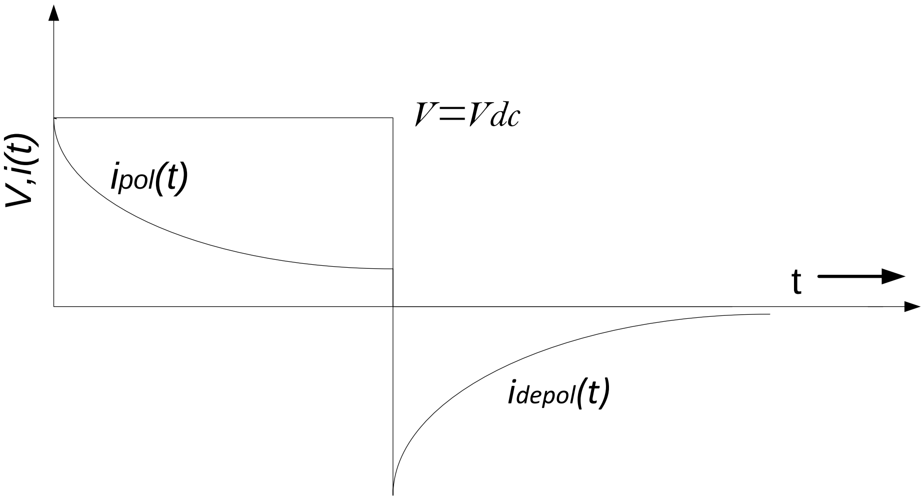


Figure 3.3: Typical nature of polarization and depolarization current

If a steady voltage V_{dc} is applied to the insulation under test, the polarization current flowing through the insulation under test (as shown in the figure 3.2) can be obtained from the equation (3.12) by replacing the $V(t)$ by V_{dc}

$$i_{pol}(t) = C_0 V_{dc}\left[\frac{\sigma_0}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t)\right] for\ 0 < t < t_c \qquad (3.13)$$

In the equation (3.13), t_c represent the time span during which the field is applied to the test sample. After t_c, the excitation voltage source is removed and the test object is short-circuited. It may be observed that the displacement current $(\varepsilon_\infty \delta(t))$ has Zero contribution to the polarization current,i_{pol} except at $t = 0$. Therefore, the resultant current is mainly composed of two components: conduction current which is contributed by conductivity σ_0 and $f(t)$ which is the dielectric response function. Hence the dielectric response functions,$f(t)$, can be modeled from the polarization current provided that the conduction current is known.

At the end of t_C, the voltage source is removed and the test object is short circuited. The dipoles in the insulation start relax and release the stored energy to return the original state [39], [40], [62]. The depolarization current i_{depol}, starts to flow through the insulating material due to the re-orientation of the dipole. This depolarization current can be expressed as given in the equation (3.14)

$$i_{depol}(t) = -C_0 V_{dc}\left[f(t) - f(t - t_C)\right]\ for\ 0 < t < \infty \qquad (3.14)$$

It has already been mentioned that the dielectric response function $f(t)$ is monotonically decreasing function. Therefore, for a sufficiently long charging time, t_c the magnitude of $f(t - t_c)$ is very low with the respect to $f(t)$ and can be neglected [63]. Hence, the depolarization current in equation (3.14) can be re-written as equation (3.15).

$$i_{depol}(t) = -C_0 V_{dc} f(t) \ \ for \ 0 < t < \infty \tag{3.15}$$

It may be observe from equation (3.15) that once the depolarization current of a dielectric material is measured, its dielectric response function can be obtained from it.

3.2.3 DIELECTRIC RESPONSE FUNCTION ESTIMATION

Available literature shown [64]–[67] that, dielectric response function can be modeled using the general purpose response function$f(t)$. For insulation system, the "general response function" can be expressed in parametric form as

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m} \tag{3.16}$$

With A, t_0>0,   m>n>0 and m>1.

In order to estimate the dielectric response function $f(t)$ from a depolarization current measurement it is assumed that the dielectric response function is a continuously decreasing function in time, then if the polarization period is sufficiently long, so that$f(t + t_c) \approx 0$, the Dielectric response function $f(t)$ is proportional to the depolarization current. Thus from equation (3.14)

$$f(t) = \frac{-i_d}{C_0 U_0} \tag{3.17}$$

The parameters of $f(t)$ are obtained from a non-linear least square fit into (3.17).

3.3 DIELECTRIC RESPONSE FUNCTION ESTIMATION FROM DEBYE MODEL

3.3.1 DEBYE MODEL

The application of equivalent circuit model is a well known approach for understanding electrical properties of capacitive or in general dielectric material. In such approach the dielectric is often modeled as a simple series or parallel RC circuit, from which certain parameters i.e. dielectric loss, dielectric dissipation factor, capacitive and resistive current are evaluated. These parameters are used to get an idea about the insulation condition of the material of interest.

There are certain limitations related to such simple RC Model. The main problem with this approach is that it does not reflect the complexity of the dielectric. Such approach yields accurate results only when the dielectric specimen under study is homogeneous. However, due to aging and thermal processes, considerable amount of in-homogeneity can be induced in an otherwise homogeneous insulation structure. Considering this limitation several researchers [68]-[72] have purposed a number of equivalent circuit which are extinction to the simple RC model, most of these equivalent circuit where dependent upon the intrinsic structure of the insulation geometry.

Debye model in this aspect posses an upper hand the since that it treats the whole complicated insulation geometry as a black box, the structure of Debye model is based on relaxation characteristic of the dipole groups forms different $Ri\,Ci$ branch with two separates branches dedicated only two geometry resistance R and geometry Capacitance C0 respectively. A general structure of Debye model is presented below in Figure 3.4.

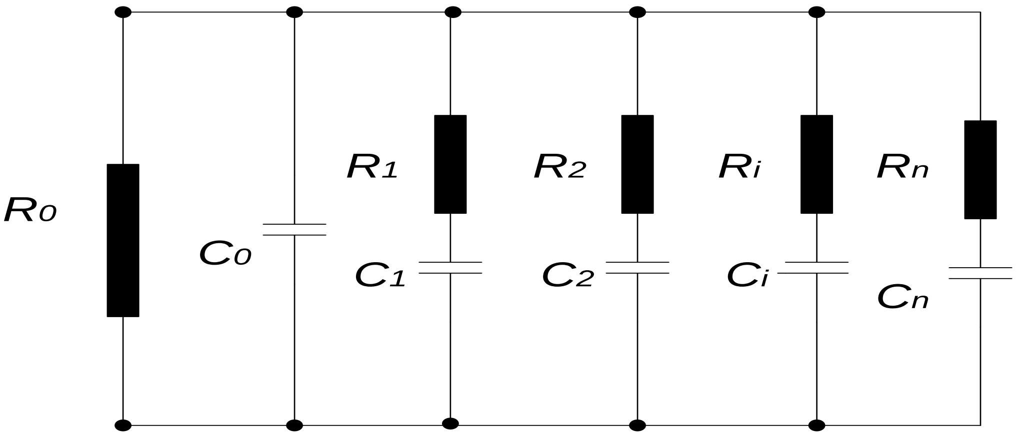


Figure 3.4 Structure of Debye Model

Due to present of electrical field polarization current flows due to dipoles try to align to the dipole relaxes and return to the original state this relaxation time deferrers from one dipole group to another which result in different depolarization current with different time constant using this concept the parallel $RiCi$ branches of a Debye model is constructed with each parallel branch representing the different time constant $\tau_i = R_iC_i$ for different dipoles groups apart from polarization and depolarization current conduction current also flows which is represented by geometric capacitance and geometric resistance of the insulation system[73].

3.4 ANALYSIS OF PDC MEASURMENTS

3.4.1 CALCULATION OF DEBYE MODEL PARAMETERS VALUE FROM DEPOLARIZATION CURRENT

The calculations of Debye model circuit parameter are presented as flows. Geometric capacitance C_0 is calculated at power frequency using conventional measurement technique for rest of the parameter profile of polarization and depolarization current is required. The Geometric resistance R_0 is calculated as the difference of polarization and depolarization current at larger value of the time. For different R_iC_i branches only depolarization current is analyze. Deferent polar groups within the insulating system with have different relaxation time hence different time constant given as$\tau_i = R_iC_i$. The different time constant also arise due to even aging phenomenon or uneven heating effect hence different part of the insulation may have different time constant its give rise to different R_iC_i branches. The value of the branch parameter $R_i \, and \, C_i$

along with time constant τ_i can be calculated by fitting the depolarization current into the equation given as

$$i_d = \sum_{i=1}^{n} \left(A_i . e^{\left(\frac{-t}{\tau_i} \right)} \right) \tag{3.18}$$

Where

$$A_i = U_0 \frac{1.e^{\left(\frac{-t_p}{\tau_i} \right)}}{R_i} \tag{3.19}$$

The first task in the modeling work is to identify the τi and $A i$ corresponding to different branches. The process starts with the largest time constant branch. The depolarization current at longer times can be assumed to be due only largest time constant branch, with the influences of the rest of the smaller time constant branches dying down well before that time. Hence, the final part of the depolarization current is used to find out the values of τi and $A i$ corresponding to the largest time constant branch using an exponential curve fitting technique. Once the exponential component with the largest time constant is identified, it is then subtracted from the original depolarization current to go to the next level. In this level, like before, the final part of the resultant current curve is influenced by the second largest time constant only, with the next smaller time-constant branches practically going to zero well before that time. Following the same exponential curve-fitting procedure, the values of and corresponding to the second largest time-constant branch are found out. Proceeding in the same way—all the other time-constant branches are identified. Once the values of τ_i and $A_i$corresponding to different time constant branches are found, the values of Ri and Ci can be easily separated and the equivalent model can be constructed [74].

3.4.2 POLARIZATION CURRENT CALCULATION FROM DEBYE MODEL

The values of parameters of Debye model are calculated from depolarization current as discussed above. Once the values are calculated, the polarization currents are calculated by applying the following equation.

$$i_p(t) = \sum \frac{U_o \exp\left(\frac{-t}{R_i}\right)}{R_i} \quad , i = 1,2,3,4 \ldots \ldots \ldots n \qquad (3.20)$$

In this way, branch parameters can be calculated from polarization current and depolarization current measurements. The values of these branch parameters are very sensitive to overall insulation condition. The experimental results are discussed in chapter 5 of this thesis, and modeling and analysis are also presented.

CHAPTER 4

THE EXPERIMENTAL SETUP AND EXPERIMENTAL PROCEDURE

CHAPTER 4

THE EXPERIMENTAL SETUP AND EXPERIMENTAL PROCEDURE

4.1 INTRODUCTION

As discussed in the previous chapter, to carry out measurements of polarization and depolarization current in solid insulating materials an experimental set-up has been developed in **High Voltage Laboratory, Jadavpur University**. The developed set-up is capable of generating short time voltage pulses with varying pulse width as well as varying frequency, so that it can be adjusted according to the application requirements. The details of the experimental set-up are described in the following section.

4.2 EXPERIMENTAL SETUP FOR PDC MEASUREMENT

Figure 4.1shows the overall block diagram for the aforesaid measurement of polarization and depolarization current (PDC) in solid insulating material.

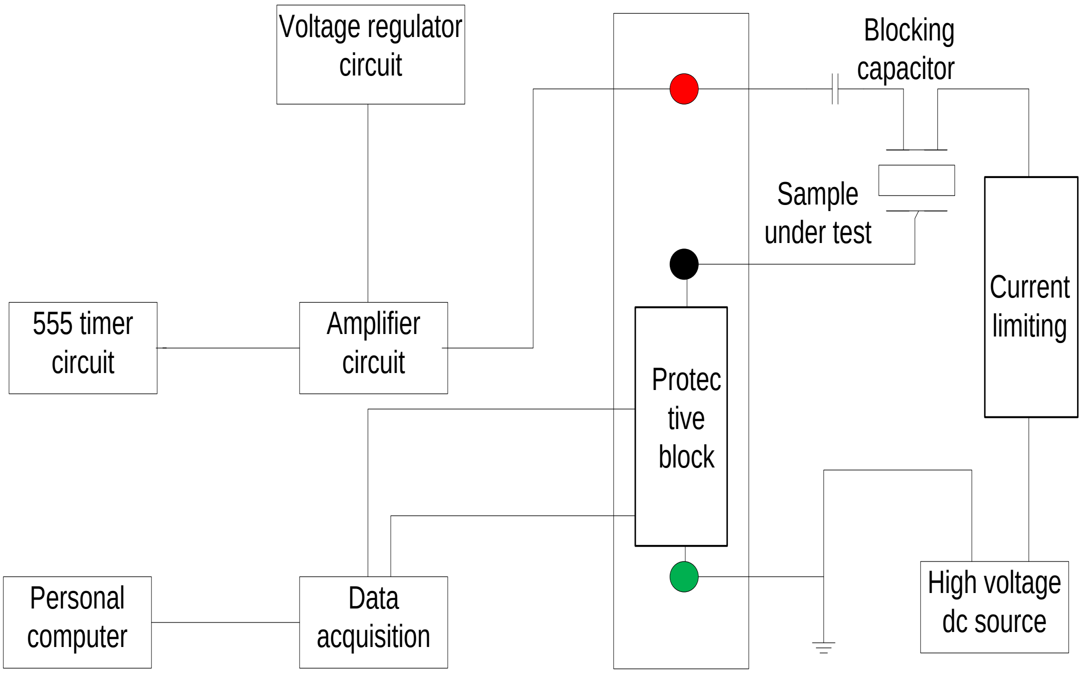


Figure 4.1 Block diagram of the experimental setup for measurement of PDC on solid insulating material.

A critical part of the experimental setup is the excitation source which feeds the sample. The source needs to polarize and depolarize the sample and at the same time, stress the sample upto high voltage, so that the phenomena that are active with the high voltage system, is reflected in the response current. This source is discussed in the next section.

4.3. THE EXCITATION SOURCE

The excitation source consists of various small sub- modules that have been enumerated below:

1) Timer

2) Voltage regulation

3) Amplifier

4) High voltage dc source

The individual sub modules have been described in subsequent sub sections.

4.3.1 TIMER

In the above circuit, the timer is used for the generation of the square pulse. The schematic of the circuit shown in Figure 4.2 and its corresponding photograph is shown in Figure 4.3

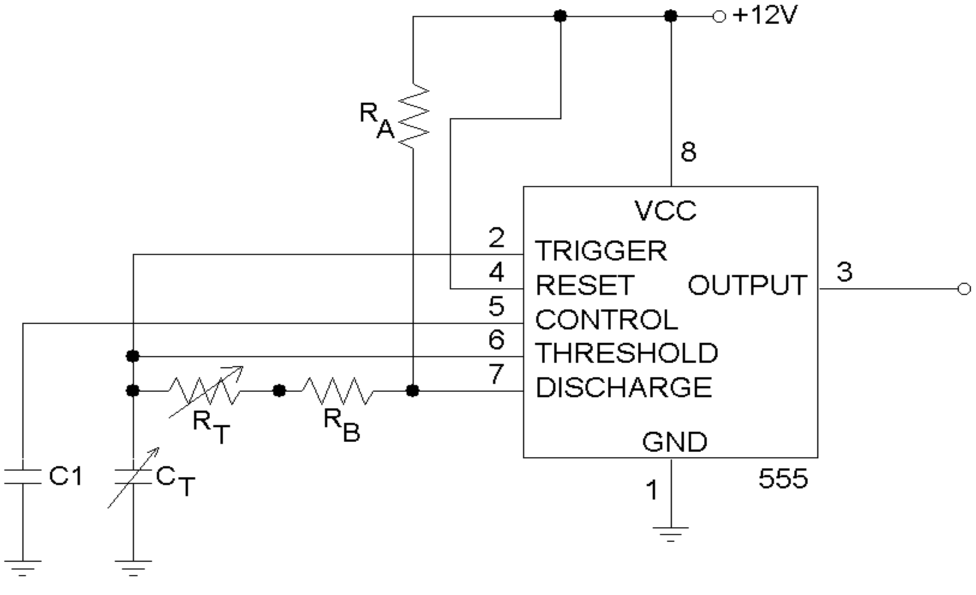


Figure 4.2 Schematic for generation of the timed square pulse.

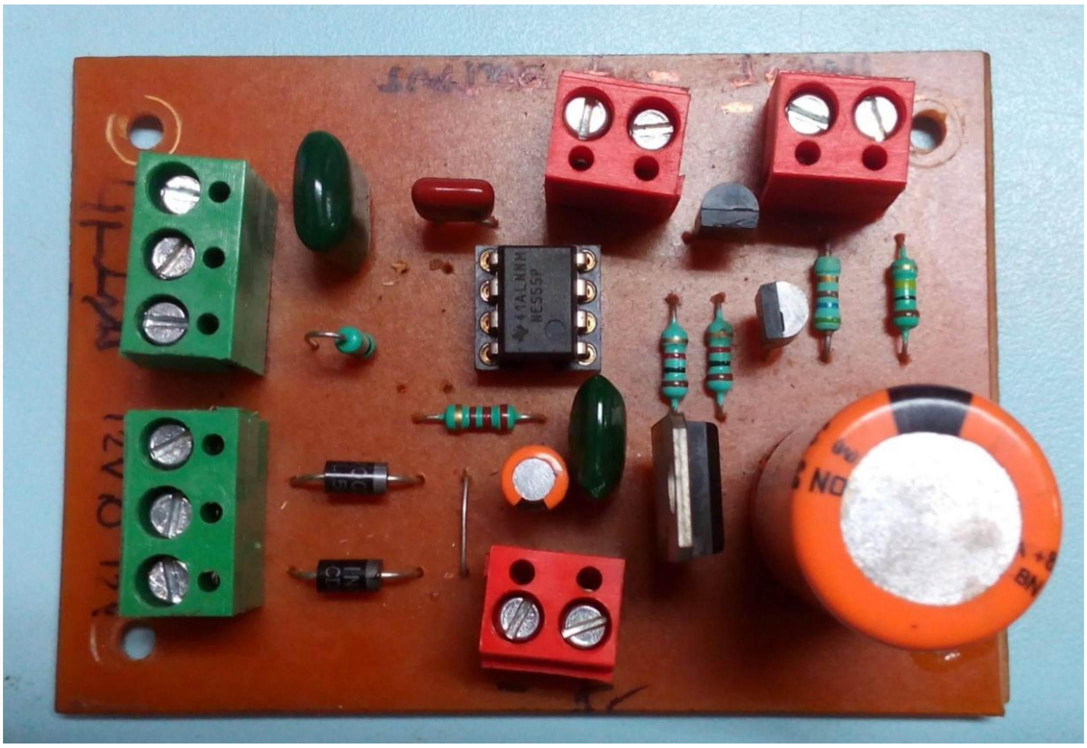


Figure 4.3 **Photograph of the Timer Module.**

For generation of square pulse, a 555 timer circuit is operated in astable multivibrator mode. Pin 2 and the pin 6 are shorted and the pin 4 and pin 8 are connected to +Vcc. Pin 5 is grounded through the 0.01µF (C_1) capacitor. The timing resistor R_B and the timing capacitor C_T are connected externally to the circuit via terminal block to facilitate the timing adjustments through external controls. The resistor R_A is connected between the pin 7 and pin 8; the resistor R_B is connected between the pin 6 and pin 7; the capacitance C_T is connected between the pin 6 and ground in the circuit. Thus, the circuit is in the self triggering mode and runs as an Astable multivibrator. Assume the capacitor C_T is initially discharged. The output is high. Capacitor C_T will charge up through the series combination of R_A and R_B and the Voltage Vc across it will rise exponentially toward Vcc with the time constant $C_T \times (R_A+R_B)$. As soon as the voltage rises beyond the threshold level, i.e., 2/3rd of Vcc, the output goes low and the capacitor is discharged through the resistor R_B. Thus the circuit will oscillate and the square waveform is produced at the output. The frequency of oscillation can be determined as follows:

It can be considered that the capacitor is charged and discharged between Vcc/3 and 2/3 of Vcc. In the astable mode, the frequency is independent of the supply voltage.

The time during which the output is high is given by

$$t_h = 0.69(R_A + R_B)C_T \tag{4.1}$$

And the time duration of which the output is low is

$$t_l = 0.69(R_B)C_T \tag{4.2}$$

Therefore, the time period of the wave form is

$$T = t_h + t_l$$

$$T = 0.69(R_A + 2R_B)C_T$$

$$F = \frac{1}{T} = \frac{1}{0.69(R_A + 2R_B)C_T} \tag{4.3}$$

The duty cycle of the output square wave can be found from equation (4.1) and equation (4.2)

$$\text{Duty cycle} = \frac{th}{th + tl} = \frac{R_A + R_B}{R_A + 2R_B} \tag{4.4}$$

Now, one interesting fact is that, the duty cycle reaches 50% if, from the above equations, it can be considered that R_A is much less that R_B. Thus in practice, the value of R_A is kept fixed and the value of R_B is changed externally which may be 100 times the value of R_A. Obviously, as R_B is increased, the duty cycle will approach more towards 50%. In this way, an approximate square wave pulse is produced at the output whose frequency can be changed by adjusting R_B and C_T. For practical purposes, if a wide frequency range is to be considered, the coarse control consists of a switching arrangement which changes the value of timing capacitor C_T by adding more capacitors in parallel, and the finer control is obtained by putting a variable resistor in place of R_B.

4.3.2 Voltage regulator

In Figure 4.1, a transistor series voltage regulator circuit is used for controlling the amplitude of voltage at the output terminal. Analog regulator is used because the circuit is simple and smooth variation of a wide range from 2V to 30V can be achieved easily with the help of an external control knob. The schematic and actual photograph of the series voltage regulator shown in Figure 4.4 and Figure 4.5 respectively.

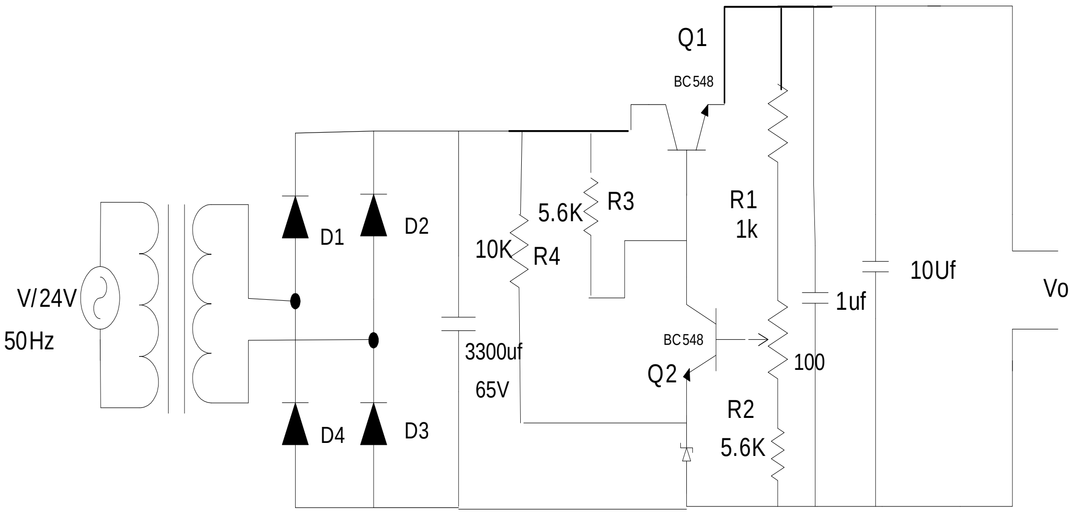


Figure 4.4. Diagram of transistor controlled series voltage regulator circuit

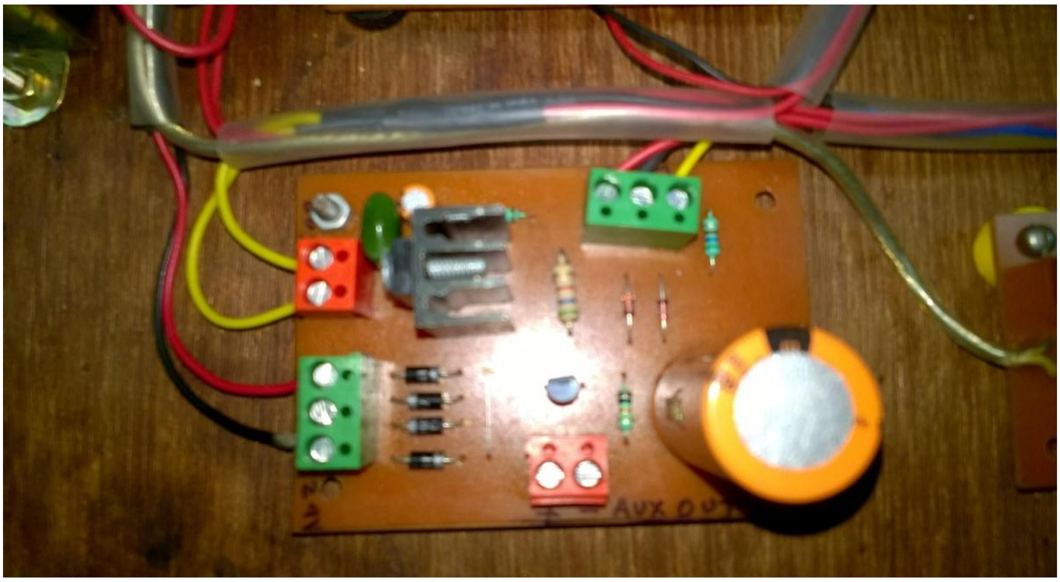


Figure 4.5. Photograph of controlled series voltage regulator circuit.

The regulated power supply consists of an ordinary unregulated power supply in conjunction with a voltage regulating device. The output of the unregulated power supply is fed to the control unit which produces the regulated output. The output voltage remains almost constant almost irrespective of the load current. The circuit is quite similar to that of a single transistor series voltage regulator except that an additional transistor Q_2 is inserted in the circuit. The emitter terminal of this transistor Q_2 is connected to the negative terminal of input supply through a Zener diode. The base of this additional transistor is connected to the variable tap of a potentiometer. This voltage regulator employs the principle of negative feedback to hold the output voltage almost constant despite variations in supply voltage and /or load current. The zener diode and the resistor R4 (10kΩ) act as the voltage reference source. The voltage divider consisting of resistors R1 (1kΩ) and R2 (5.6kΩ) samples the output voltage and delivers a negative feedback voltage to the base of transistor Q_2 and this feedback voltage controls the collector current of transistor Q_2.

Now, let us assume that the output voltage increases due to lowering of load current. This will cause an increase in voltage across the 5.6kΩ as it a part of the output circuit. Thus, more voltage is fed to the base of the transistor Q_2, producing the large collector current. This in turn, shunts the base current in Q_1. So, the collector current of Q_1 decreases. Thus the output voltage remains constant. In the case of decreased output voltage, the reverse phenomena takes place so that, again, the output voltage remains constant.

The voltage divider provides the feedback voltage at the base of the transistor Q_2.

$$\text{Feedback fraction } m = \frac{V_f}{V_{out}} = \frac{R2}{R2 + R1} \tag{4.5}$$

$$\text{Closed loop voltage gain, } \quad A_{CL} = \frac{1}{m} = \frac{R1 + R2}{R2} = 1 + \frac{R1}{R2}$$

$$\begin{aligned} V_f &= V_Z + V_{BE} \\ mV_{out} &= V_Z + V_{BE} \\ V_{out} &= \frac{V_Z + V_{BE}}{m} \\ V_{out} &= A_{cl}(V_Z + V_{BE}) \end{aligned}$$

Therefore, the regulated output voltage is equal to closed-loop voltage gain times the sum of zener voltage and base-emitter voltage of the transistor Q_2. If a change in the amplitude of the output voltage is required, a change is done to the closed loop voltage gain by changing the value of the resistance R1 and R2.

4.3.3 Amplifier

In the experimental setup, an amplifier circuit is used for amplification of the square wave pulse. The schematic and actual photograph of the amplifier circuit is shown in the Figure 4.6 and Figure 4.7, respectively.

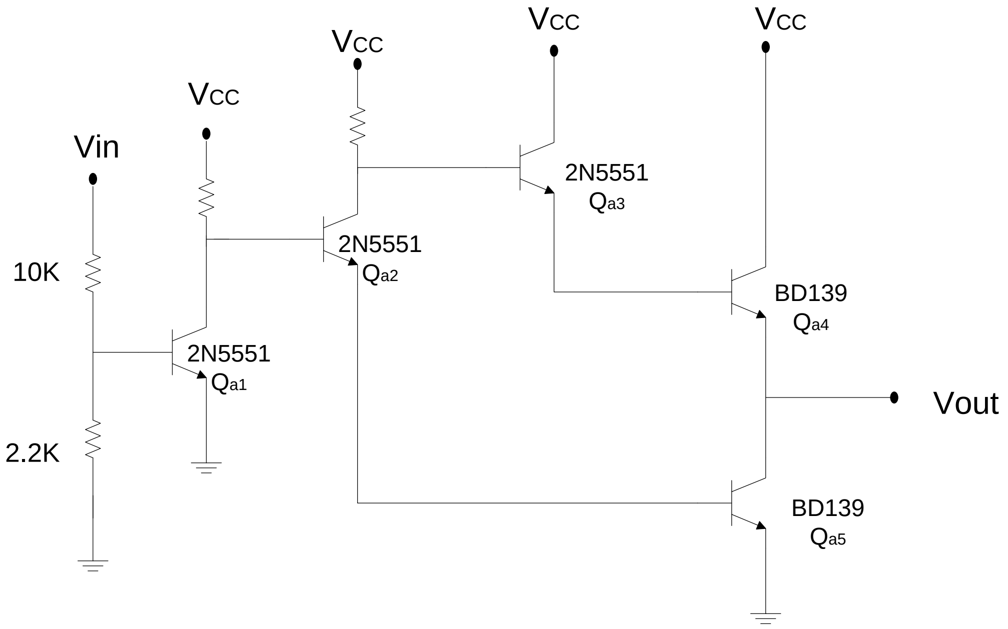


Figure 4.6. Schematic of the amplifier circuit.

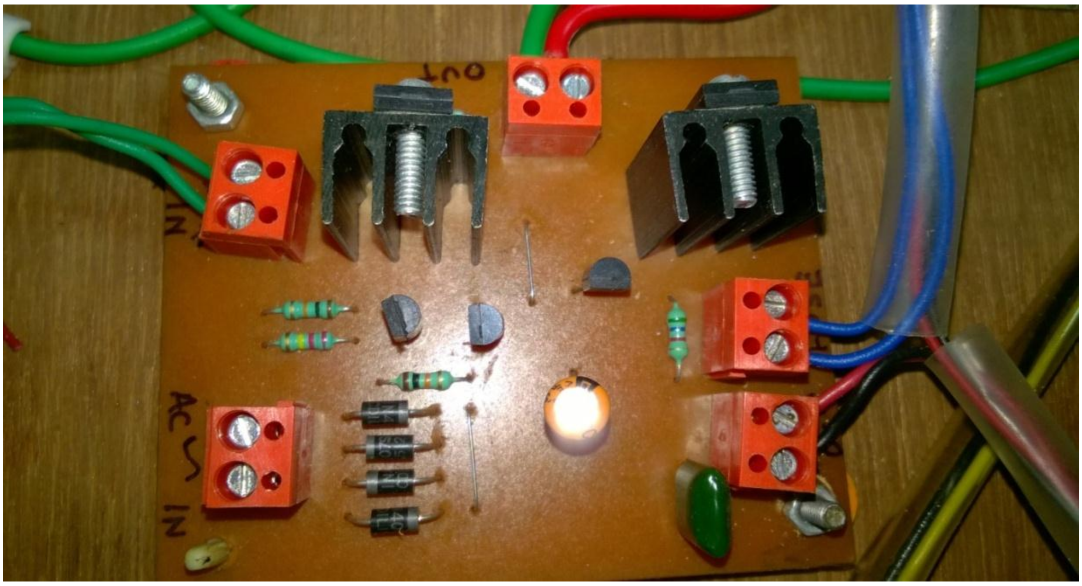


Figure 4.7. Photograph of the amplifier Circuit

Since the output is square wave, normal analog amplifier is not used here to avoid power loss and heat dissipation. Instead, an output transistor pair $Q_{a4} - Q_{a5}$ in totem pole configuration is used which, truly speaking, switches the output by getting the signal from the output of the 555 timer. The actual voltage control at the output is obtained by feeding this circuit from the 0-30V variable voltage source as explained in section 4.3.2. Thus, the output varies according to the input supply voltage from a range of 2-30V. Here the timings are same as that of the 555 timer output as the switching of the output transistors are in synchronism with the timer.

4.3.4 High Voltage Dc Source

To investigate the polarization-depolarization phenomena under high voltage applications, a high voltage dc source was also used in addition with the developed pulse voltage source. The high voltage dc source used is made by Aplabs, and is capable of providing voltage upto 3kV. A dc blocking capacitor was used to separate the high voltage dc source from the pulsating voltage source and data acquisition system.

4.4 Overall Experimental Setup

As already depicted in Figure 4.1 the sample is fed from the excitation source that has been elaborately discussed in section 4.1. A voltage source that is specified in section 4.3.4 is fed to the sample under test. A dc blocking capacitor helps to feed the sample with the square wave excitation source which is already at an elevated voltage. The sample is kept in an environmental controlled oven in which the temperature and the humidity can be adjusted.

The response current is captured through a 16 bit data acquisition system Model X 5133 from National Instruments. This device is capable of capturing the analog signal and converts it to 16 bit equivalent digital data that can be stored in the computer. The captured data is depicted in the chapters that show the results.

4.4.1 Experimental Method for Polarization and Depolarization current Measurement

After the set up is ready, the insulation samples are connected to the set up. The insulating samples are made of different materials (LDPE, XLPE, HDPE, Teflon, PMMA, Rubber) and are bought commercially in sheet sizes. After that, the sheets were cut down to 4×4 cm size. Electrodes made of brass with diameter of 5 cm were used in experiments. The samples were placed in between the electrodes. Now the excitation source was kept on and 30 volt pulses were applied on the sample. The high voltage dc source, as already mentioned, was separated from the excitation source through a dc blocking capacitor. The system is fully automatic and can be controlled by a PC using LABVIEW instruction. The polarization current data are taken for 4ms. After that, the set up is shifted to depolarization mode and depolarization current data are taken for another 4ms. After testing is completed, the polarization and depolarization current measurements are put into folders in the PC automatically. The photograph of the overall experimental setup for Polarization and Depolarization current Measurement is shown in the Figure 4.8

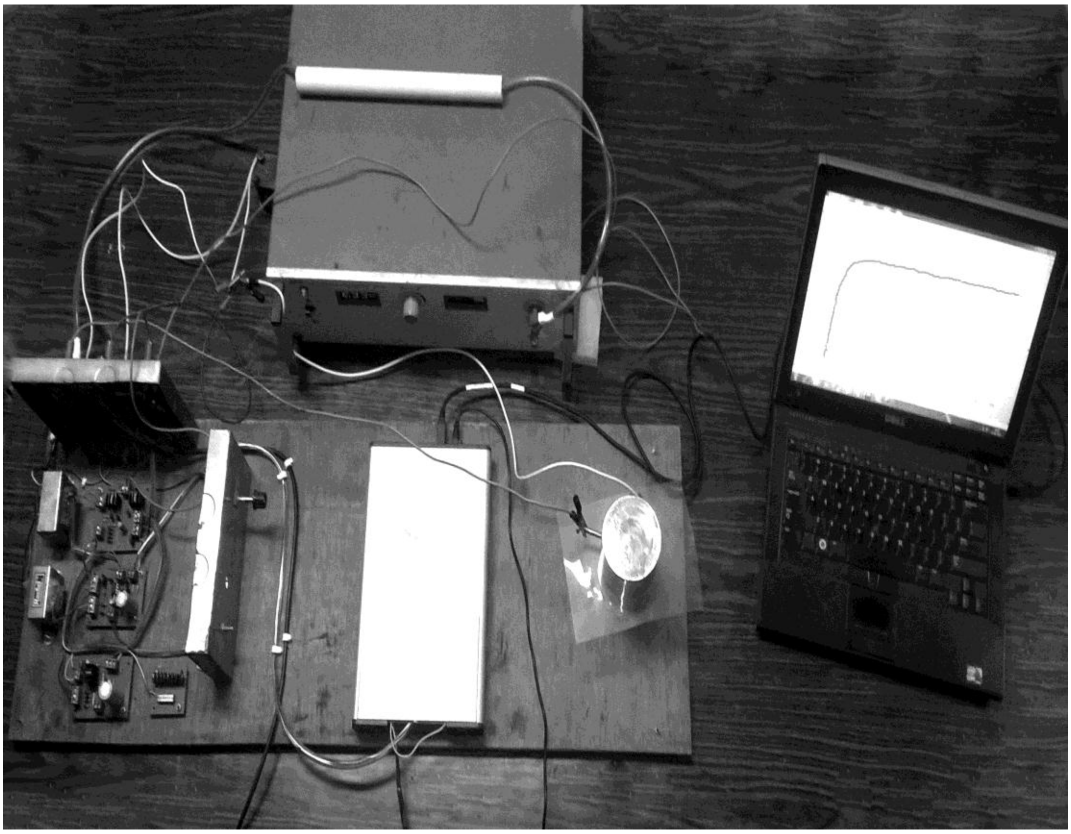


Figure 4.8. The photograph of the Overall experimental setup for Polarization and Depolarization current Measurement

4.4.2 Experimental Method for Dielectric Dissipation factor ($tan\delta$) Measurement

In general the tan delta measurement is executed by conventional Schering bridge method. However, this kind of method of measurement in not practical for the field measurement. Therefore, digital measurement devices which provide mobile use and convenience in field studies are developed for tan delta measurements. In this work, measurement of the Dielectric dissipation factor ($tan\delta$) can be measured using the tan delta and capacitance measurements unit which is designed and manufactured by ISA Advanced test of Diagnosis System of the model STS with TDS 5000. The measurement device shown in Figure 4.9 which consist of the two units out of which one is the high voltage unit and second is the control unit. The high voltage unit can generate a maximum output of 12 kV, 300 mA at frequencies from 15 Hz-400 Hz which is boosted up TDS 5000.

Figure 4.9 TDS 5000 tan delta and capacitance measurement device

This device has two measuring probes. One of them is high voltage probe whereby high voltage is applied to the insulating material and another one is the measuring probe whereby measurement data is collected. The specification and operating range of measurement device shown in the table 4.1.

Table 4.1: The specification and operating range of measurement device

Terminal	Voltage/frequency	Output current	Maximum output duration
High voltage output	12V-12kV	300	>2 min
	15Hz -400Hz	100	>60 min

The experimental setup for tan delta and capacitance measurement is shown in Figure 4.10 and measurement setup for tan delta & capacitance in High Voltage Lab in Jadavpur University shown in Figure 4.11.

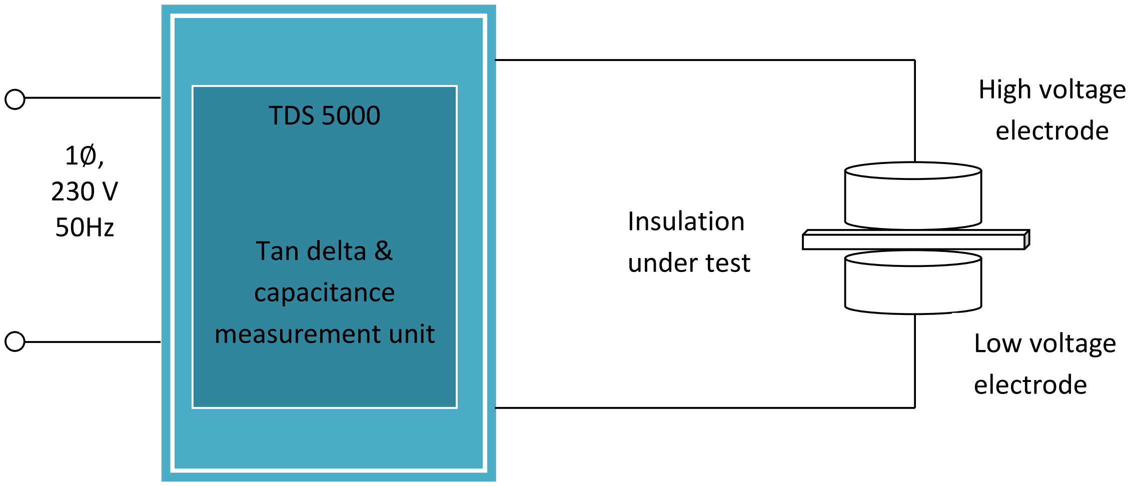


Figure 4.10 Experimental setup for $tan\ \delta$ &capacitance measurement

Figure 4.11.measurement setup for tan delta & capacitance in High Voltage Lab

CHAPTER 5

RESULT AND DISCUSSION

Chapter 5

RESULTS & DISCUSSIONS

5.1 Introduction

In this chapter, Dielectric Response method and Dissipation factor Measurement results of different type of solid insulating materials are described. The first section of the chapter is focused on Dielectric Response Measurement method, which has been implemented on each insulating sample through polarization-depolarization current (PDC) measurements. From depolarization current data, number of branches and the value of the parameters of each branch of Debye model corresponding to each insulating material are calculated. Effect of temperature on the depolarization characteristics has also been studied. Then, in later part of the chapter, dissipation factor measurements for different insulating materials are described. Overall, it was observed, both PDC and dissipation factor are dependent on material properties.

5.2 Analysis of Polarization and Depolarization Current

From PDC measurement polarization and depolarization current curves are obtained as discussed in section 2.6.The depolarization current curve of each high voltage insulating material has been given hereafter. The sample dimensions used in this analysis are given in Table. 5.1

Table 5.1: Sample and electrode dimension used in analysis

Sample	Sample dimension
LDPE	4cm X 4cm X 3mm
hdpe	4cm X 4cm X 2mm
PP	4cm X 4cm X 2mm
PTFE	4cm X 4cm X 2mm
rubber	4cm X 4cm X 2mm
PMMA	4cm X 4cm X 2mm
Electrode	Diameter 50 mm

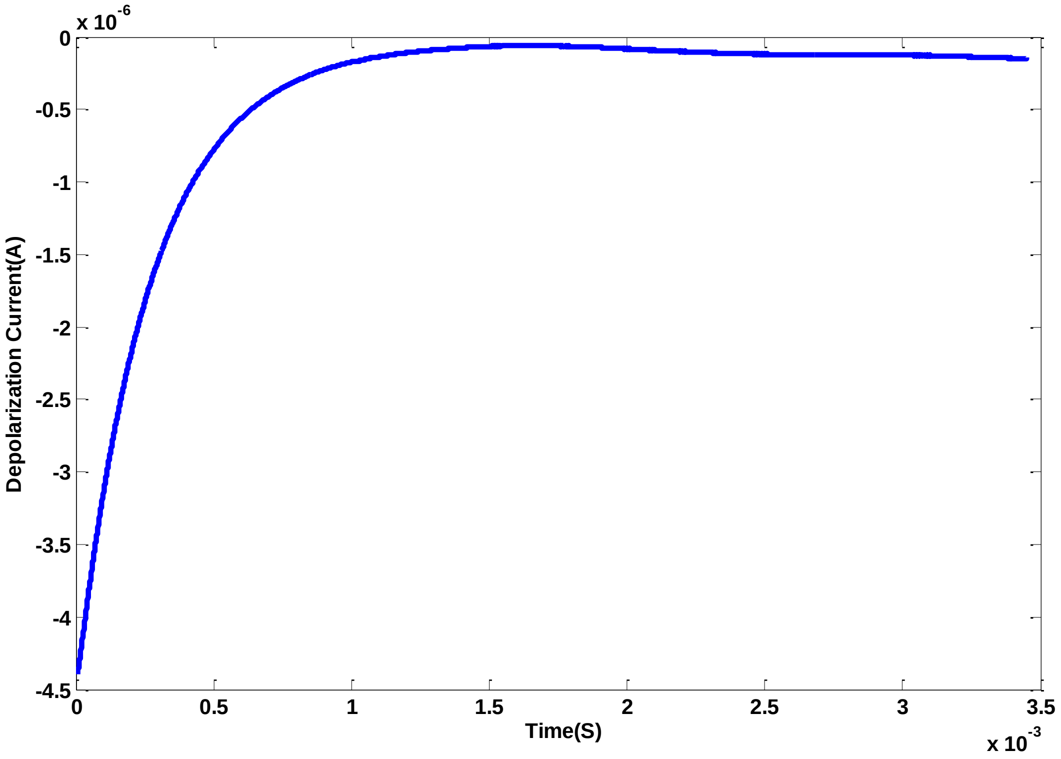


Figure 5.1 Depolarization Current Characteristic of HDPE insulating material.

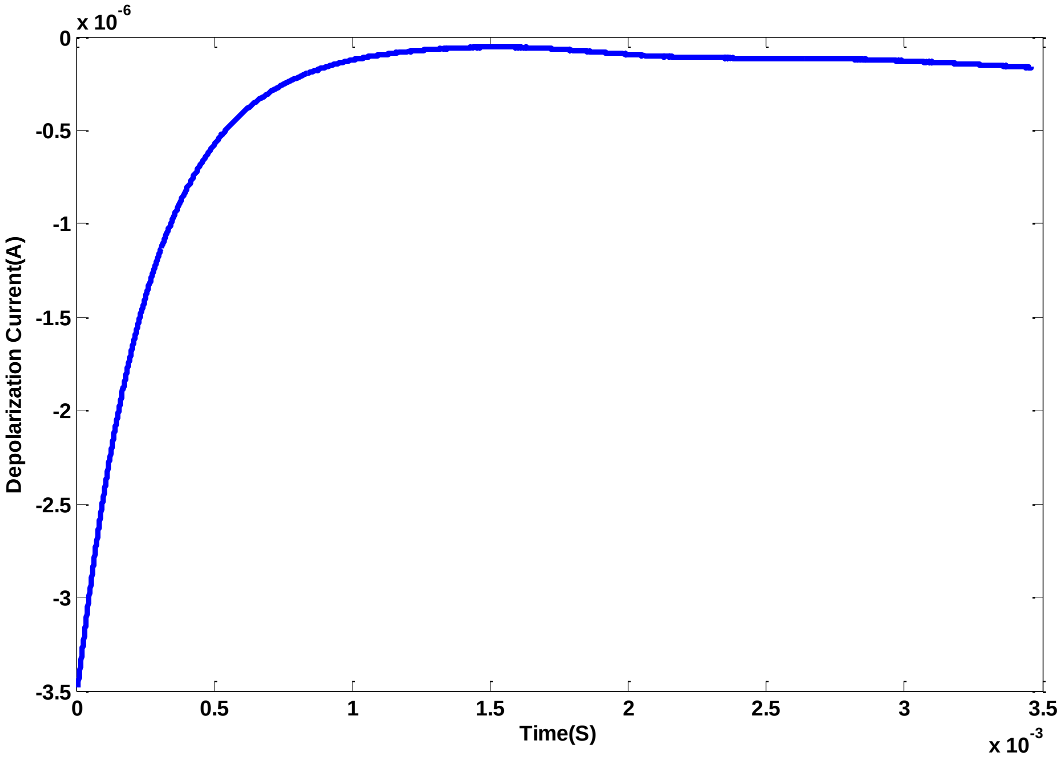


Figure 5.2 Depolarization Current Characteristic of LDPE insulating material.

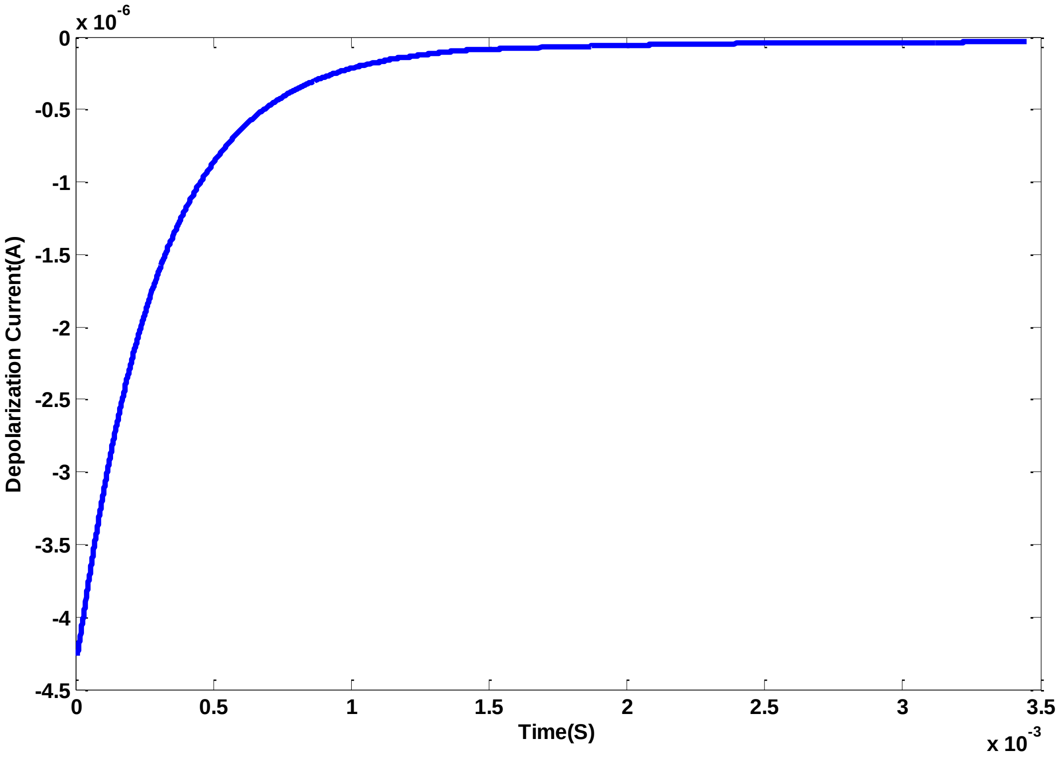


Figure 5.3 Depolarization Current Characteristic of PMMA insulating material.

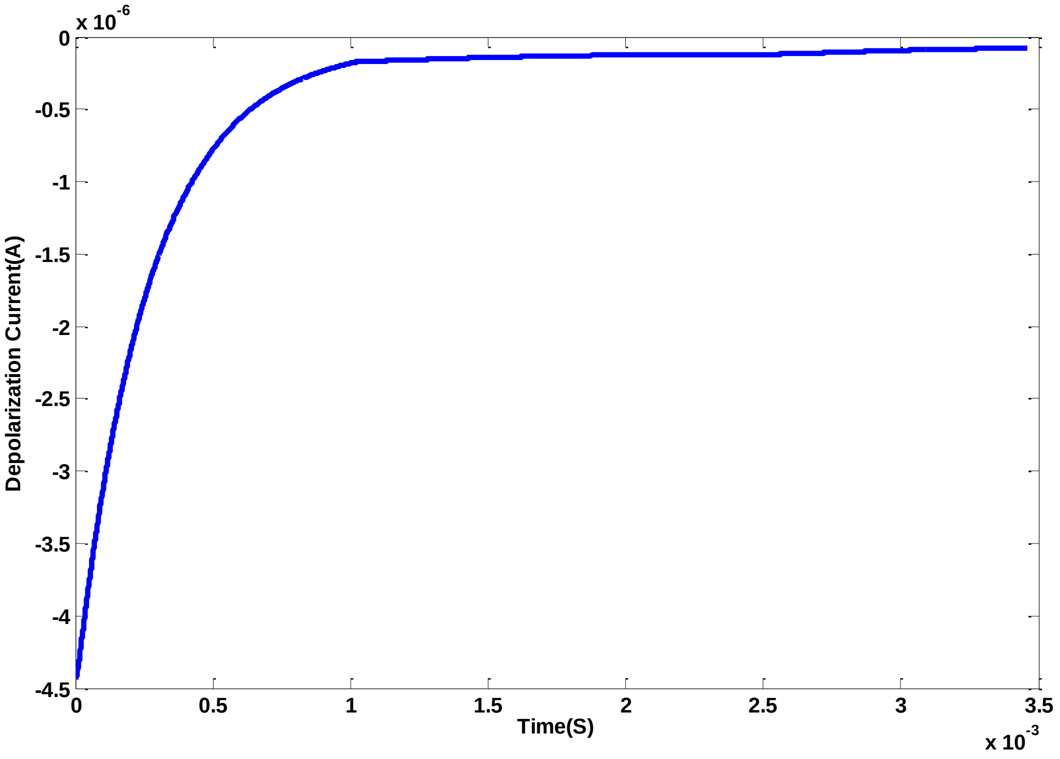


Figure 5.4 Depolarization Current Characteristic of PP insulating material.

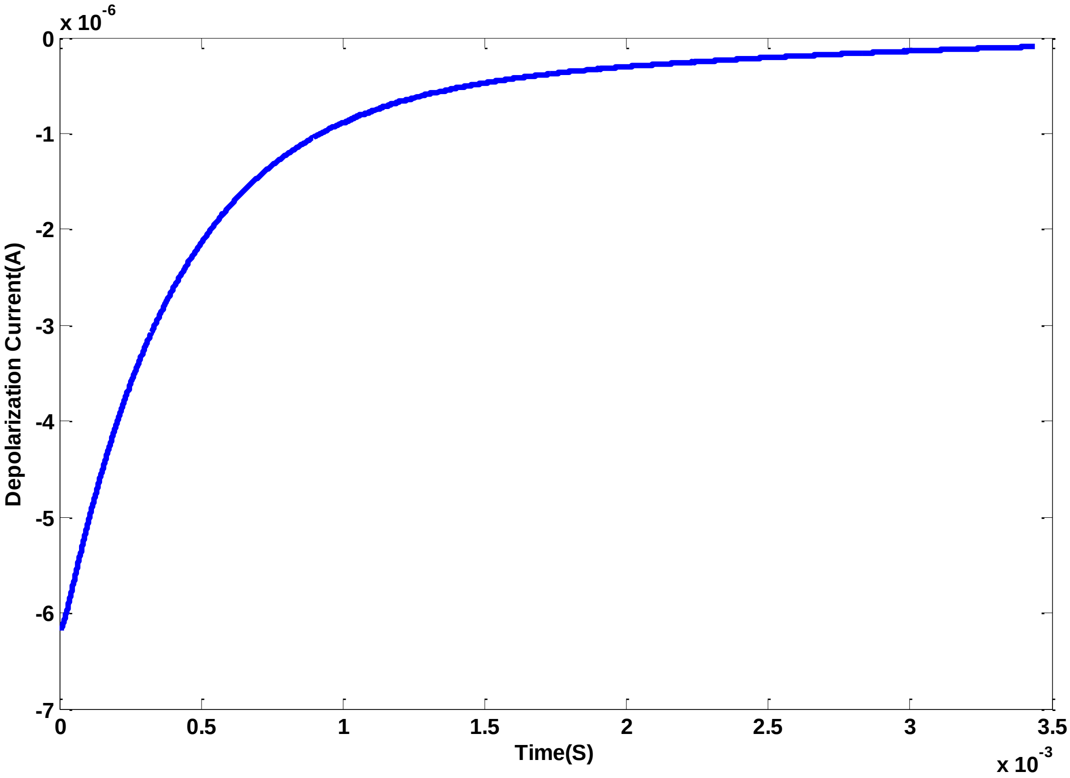


Figure 5.5 Depolarization Current Characteristic of RUBER insulating material.

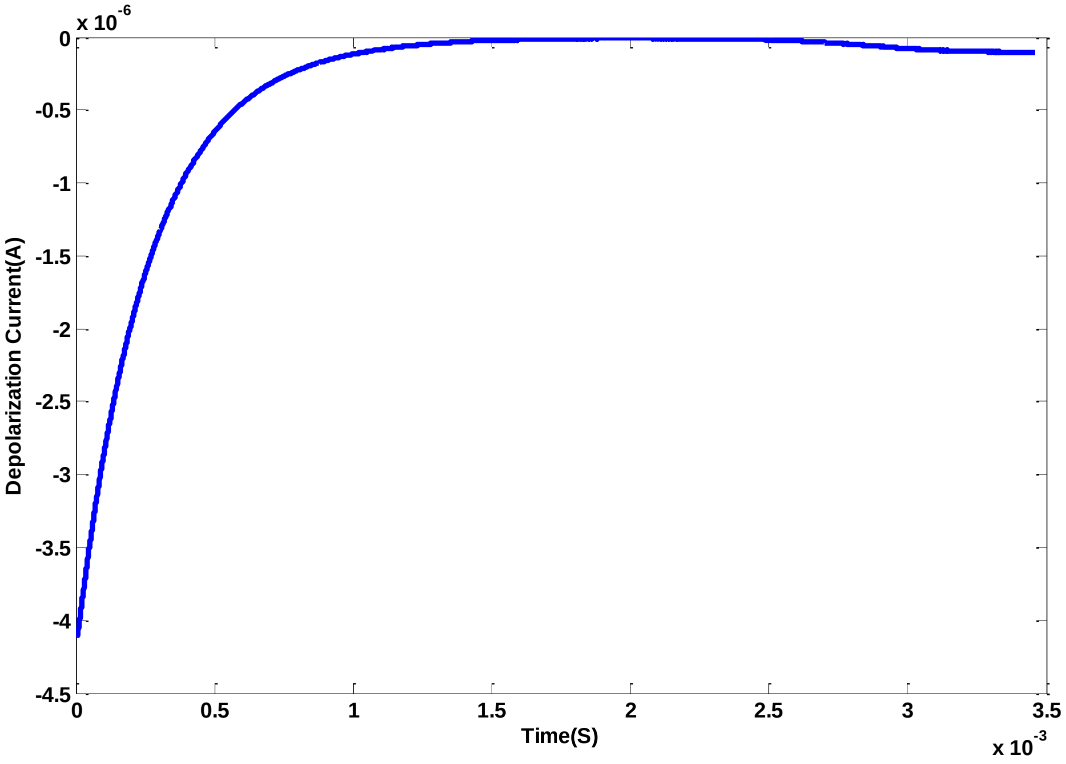


Figure 5.6 Depolarization Current Characteristic of PTFE insulating material.

From Figure 5.1 -5.6 it is clear that the peak current and settling time observed is highly dependent on the chosen material. For HDPE, PP, PMMA and PTFE (Teflon) the peak depolarization current is almost same, around (4.5 µA), but for rubber it is much higher (around 6µA). Lowest peak current was observed in case of LDPE, around 3.5 µA. The settling time also varies for different materials. Therefore, it can be concluded that the depolarization characteristics are unique to material properties.

From depolarization current of each high voltage insulating material, the number of branches, value of branch capacitances, branch resistances, and branch time constants are calculated by using the Debye model which is described in the section 3.3.1 .This section provides the plot of depolarization current due to each branch and the resultant depolarization current. The depolarization current plot of each branch has been shown by the red curve and their resultant depolarization current has been shown by the blue curve in figs 5.7, 5.9, 5.11, 5.13, 5.15, 5.17 respectively. The first section of these figures shows the plot of depolarization current of each branch and resultant curve in logarithm scale and next section shows the same plot in normal scale. In figs 5.8, 5.10, 5.12, 5.14, 5.16, 5.18 the depolarization curves of capacitors are plotted in logarithm scale respectively. Depolarization current.

HDPE insulating materials

Geometric capacitance: 22.80 picofarad

Insulation resistance: $1.50E + 12\ Ohm$

Number of branch: 2

Branch value

Table 5.2: Branch Resistance, Capacitance and Time Constant value HDPE insulating materials

Branch	$\boldsymbol{Ri}$**(Ohm)**	$\boldsymbol{Ci}$**(Farad)**	$\boldsymbol{\tau i}$**(Second)**
Branch 1	2.28E+07	2.18E-11	4.97E-04
Branch 2	8.26E+06	2.36E-11	1.95E-04

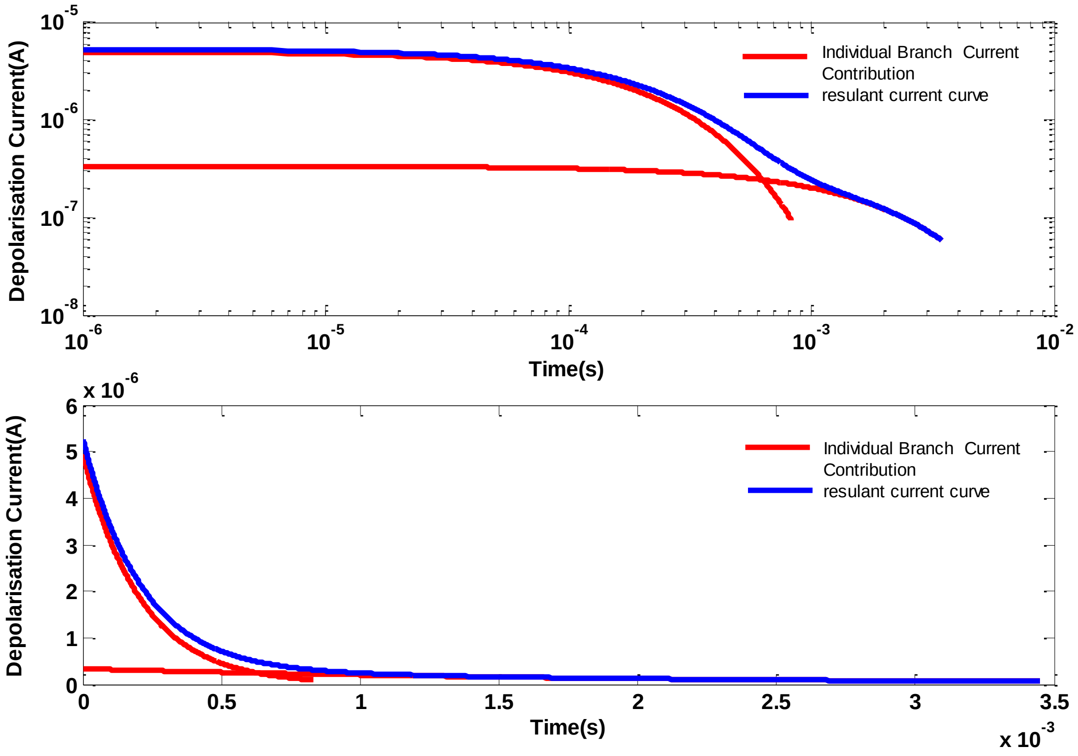


Figure 5.7.: Depolarization current curve of different branch and their resultant in logarithm scale and normal scale of HDPE insulating materials

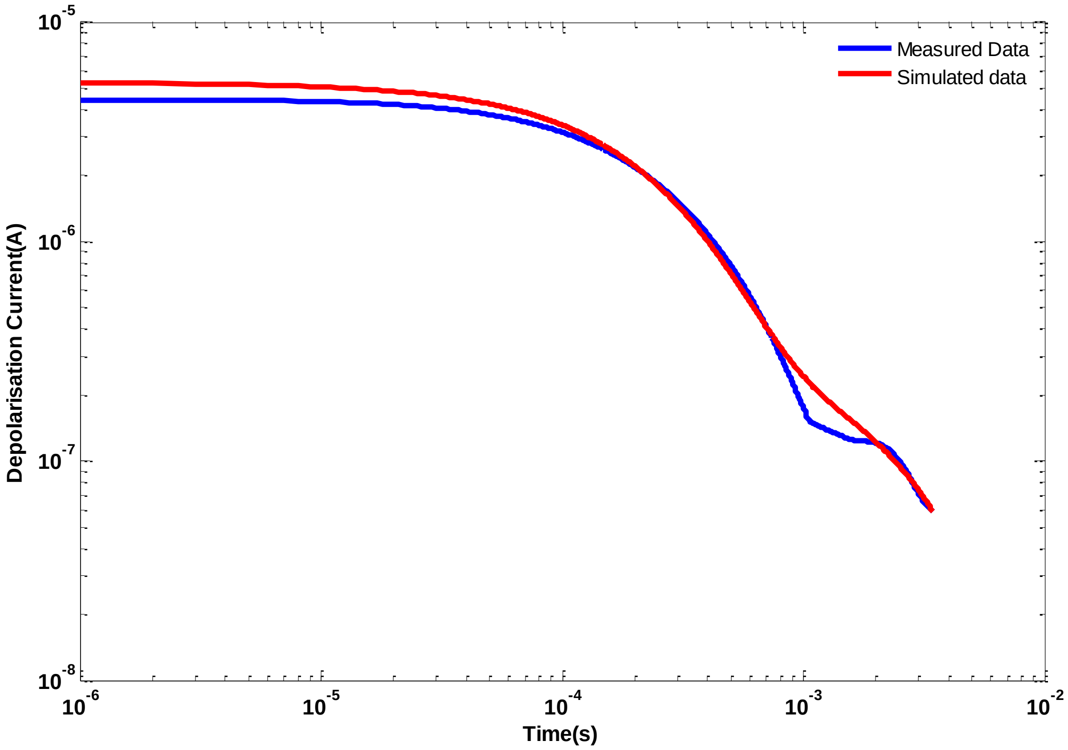


Figure 5.8: Depolarization current curve of HDPE insulating materials

LDPE insulating materials

Geometric capacitance: 15.352 picofarad

Insulation resistance: $1.57E + 12\ Ohm$

Number of branch: 2

Branch value

Table 5.3 Branch Resistance, Capacitance and Time Constant value LDPE insulating materials

Branch	Ri**(Ohm)**	Ci**(Farad)**	τi**(Second)**
Branch 1	2.84E+07	1.69E-11	4.79E-04
Branch 2	1.06E+07	1.77E-11	1.87E-04

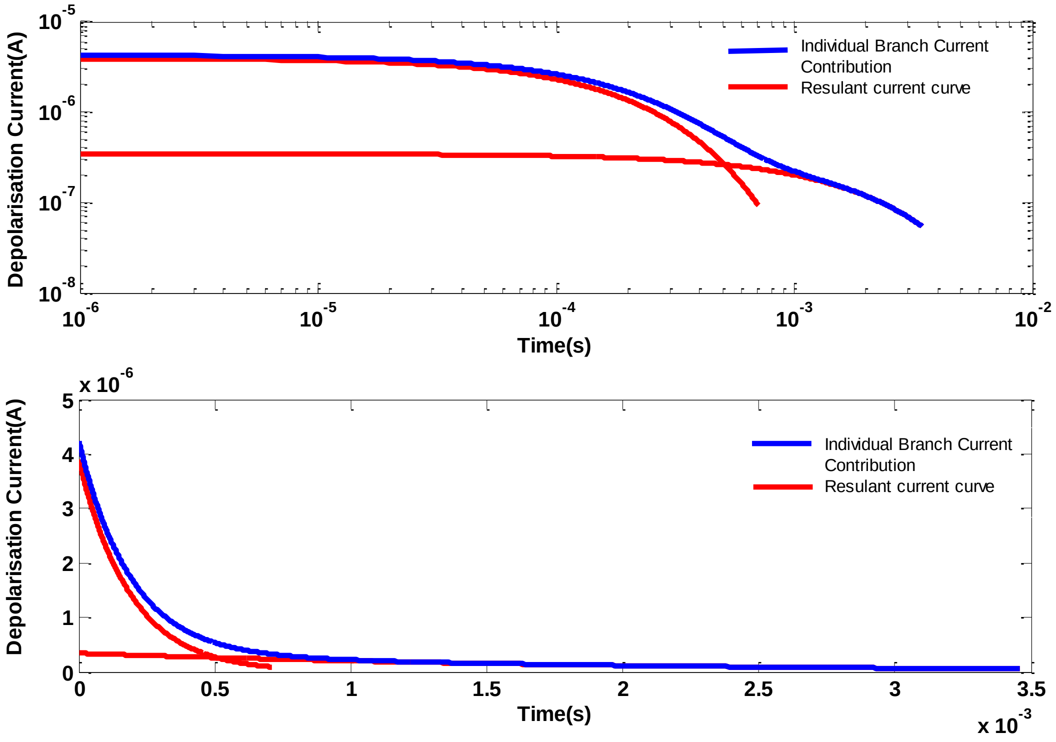


Figure 5.9.: Depolarization current curve of every branch and their resultant in logarithm scale and normal scale of LDPE insulating materials

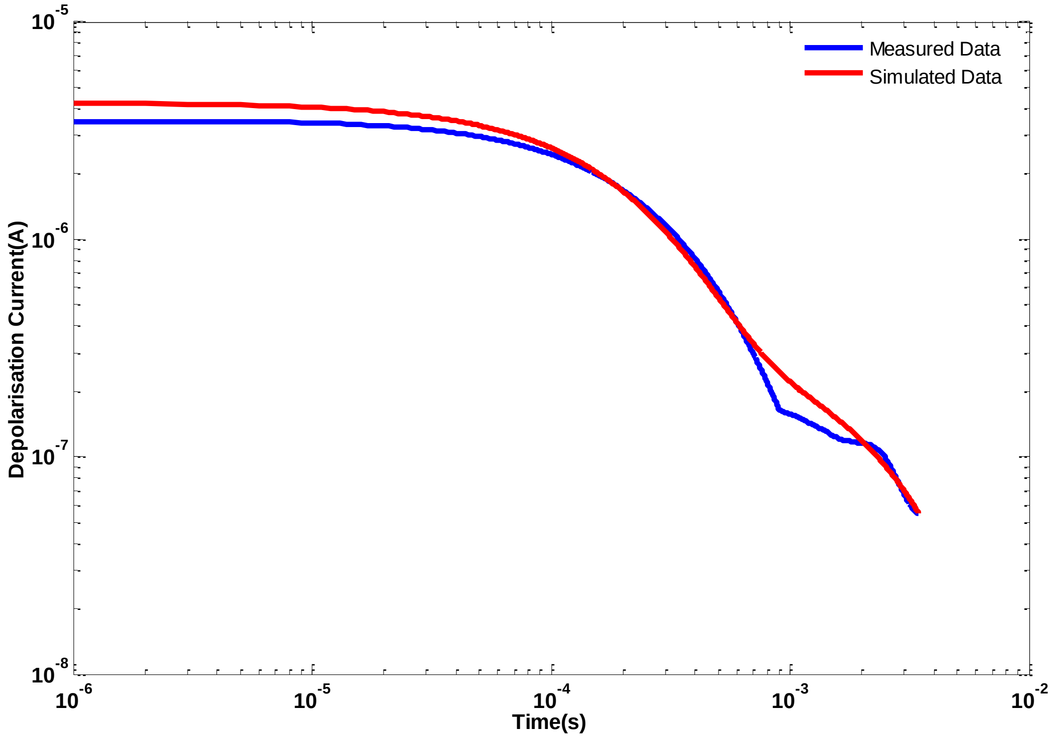


Figure 5.10: Depolarization current curve of LDPE insulating materials

PMMA insulating materials

Geometric capacitance:22.001 picofarad

Insulation resistance: $1.57E + 12\ ohm$

Number of branch: 2

Branch value

Table 5.4 Branch Resistance, Capacitance and Time Constant value PMMA insulating materials

Branch	Ri**(Ohm)**	Ci**(Farad)**	τi**(Second)**
Branch 1	2.23E+07	2.29E-11	5.09E-04
Branch 2	8.45E+06	2.27E-11	1.92E-04

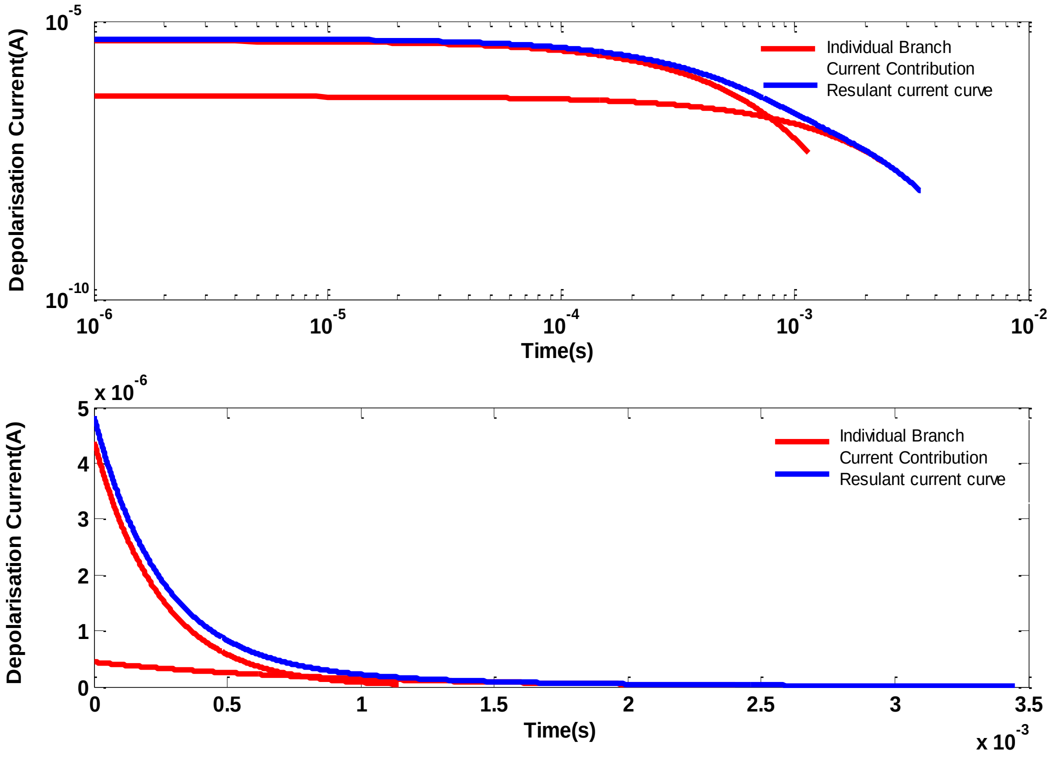


Figure 5.11.: Depolarization current curve of every branch and their resultant in logarithm scale and normal scale of PMMA insulating materials

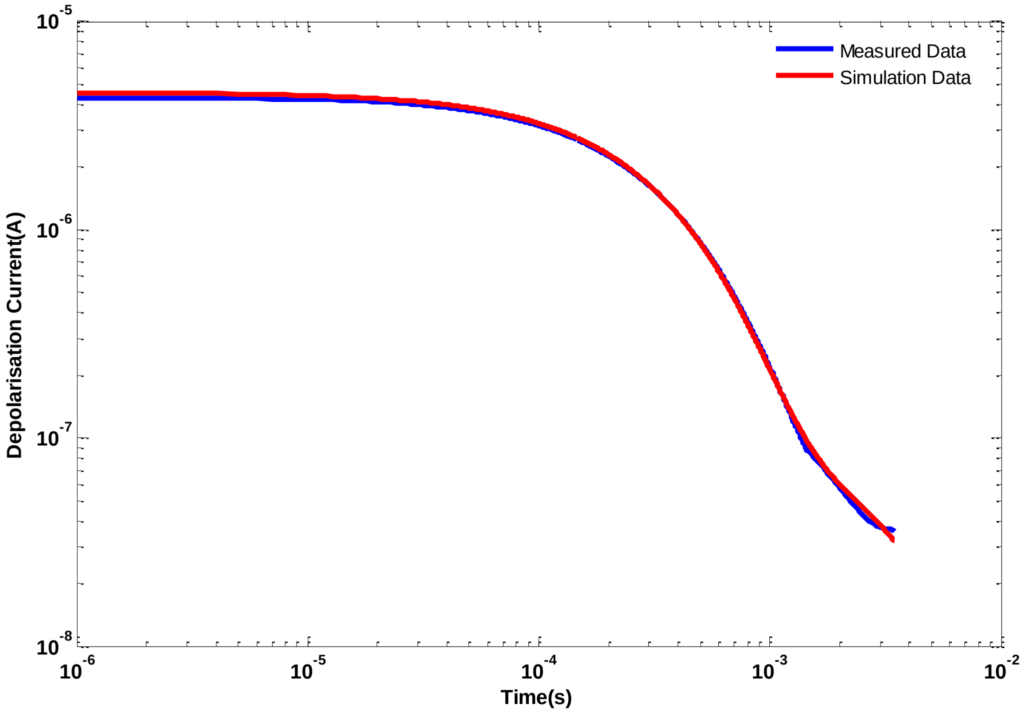


Figure 5.12: Depolarization current curve of PMMA insulating materials

PP insulating materials

Geometric capacitance:21.298 picofarad

Insulation resistance: $1.50E + 12\ Ohm$

Number of branch: 2

Branch value

Table 5.5 Branch Resistance, Capacitance and Time Constant value PP insulating materials

Branch	Ri**(Ohm)**	Ci**(Farad)**	τi**(Second)**
Branch 1	2.23E+07	2.29E-11	5.09E-04
Branch 2	8.45E+06	2.27E-11	1.92E-04

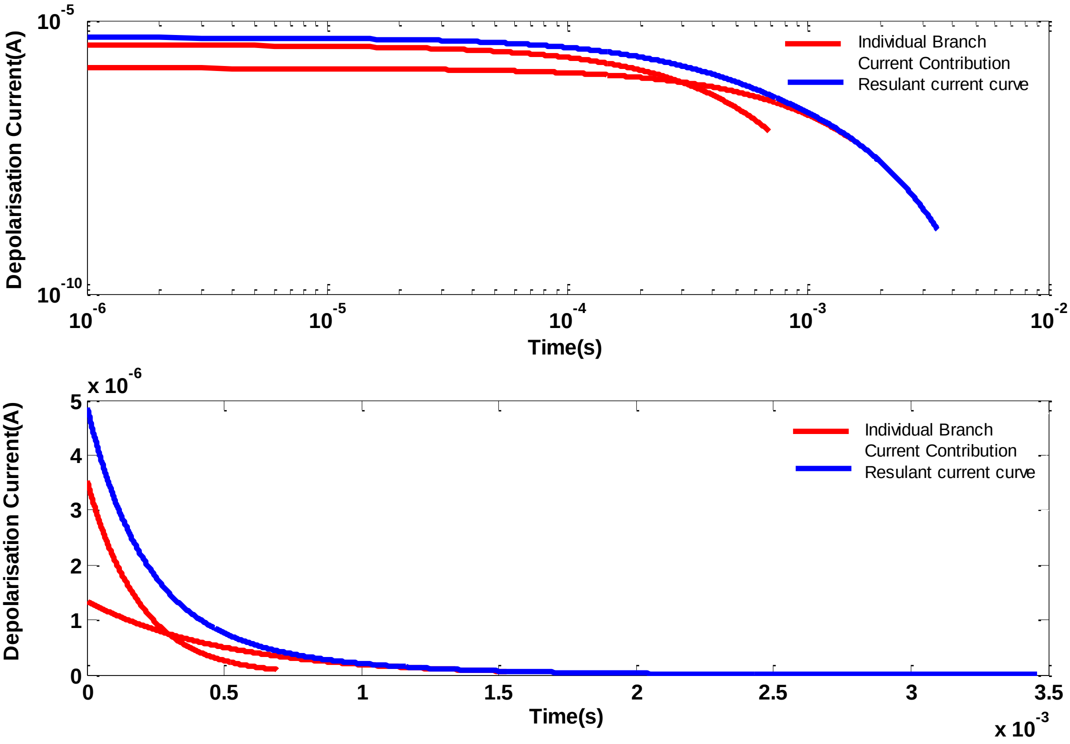


Figure 5.13.: Depolarization current curve of every branch and their resultant in logarithm scale and normal scale of PP insulating materials

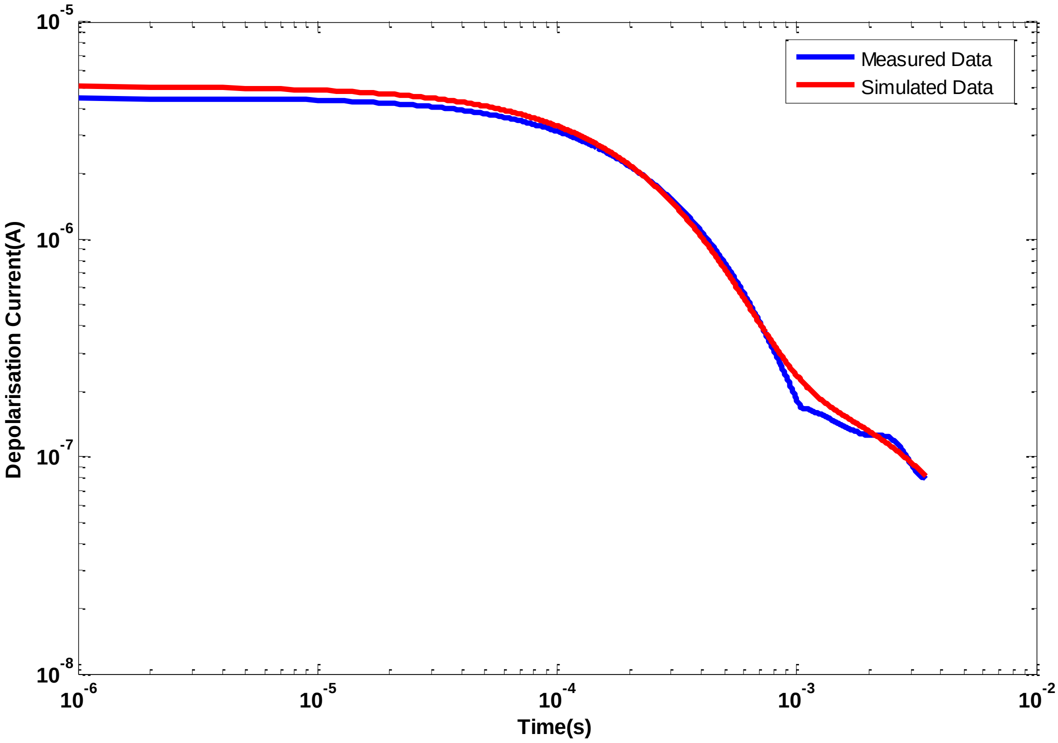


Figure 5.14: Depolarization current curve of PP insulating materials

Rubber insulating materials

Geometric capacitance:30.161 picofarad

Insulation resistance: $1.24E + 11\ ohm$

Number of branch: 2

Branch value

Table 5.6 Branch Resistance, Capacitance and Time Constant value RUBER insulating materials

Branch	**Ri(Ohm)**	**Ci(Farad)**	**τi(Second)**
Branch 1	1.89E+07	6.68E-11	1.26E-03
Branch 2	5.50E+06	5.61E-11	3.09E-04

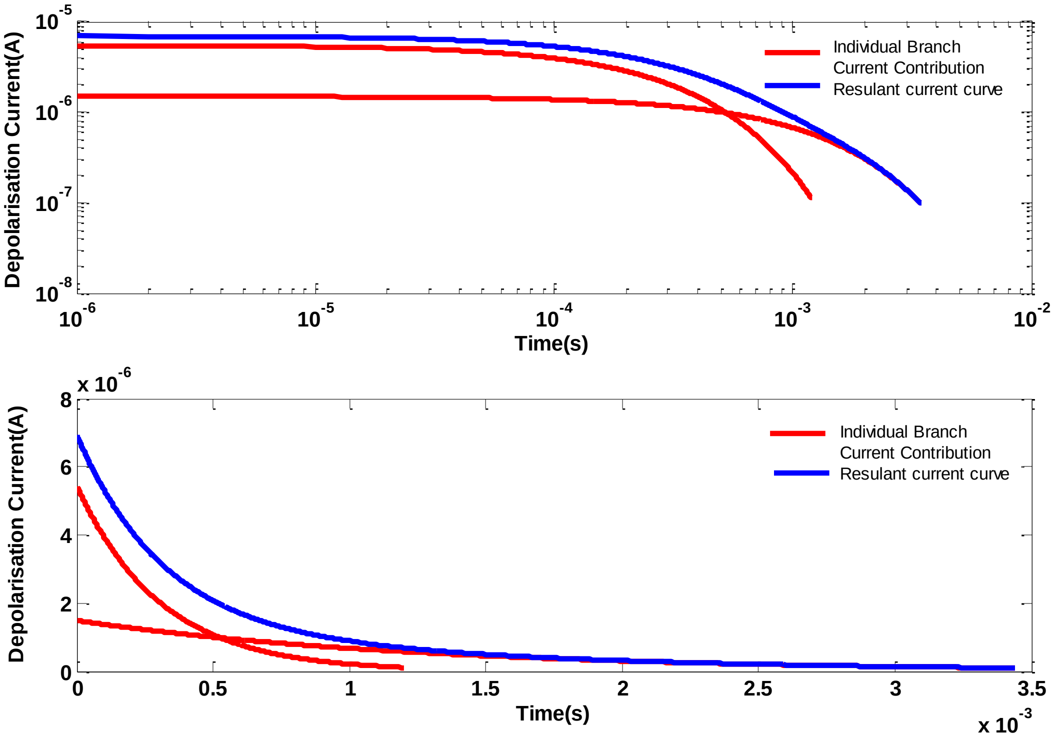


Figure 5.15.: Depolarization current curve of every branch and their resultant in logarithm scale and normal scale of RUBER insulating materials

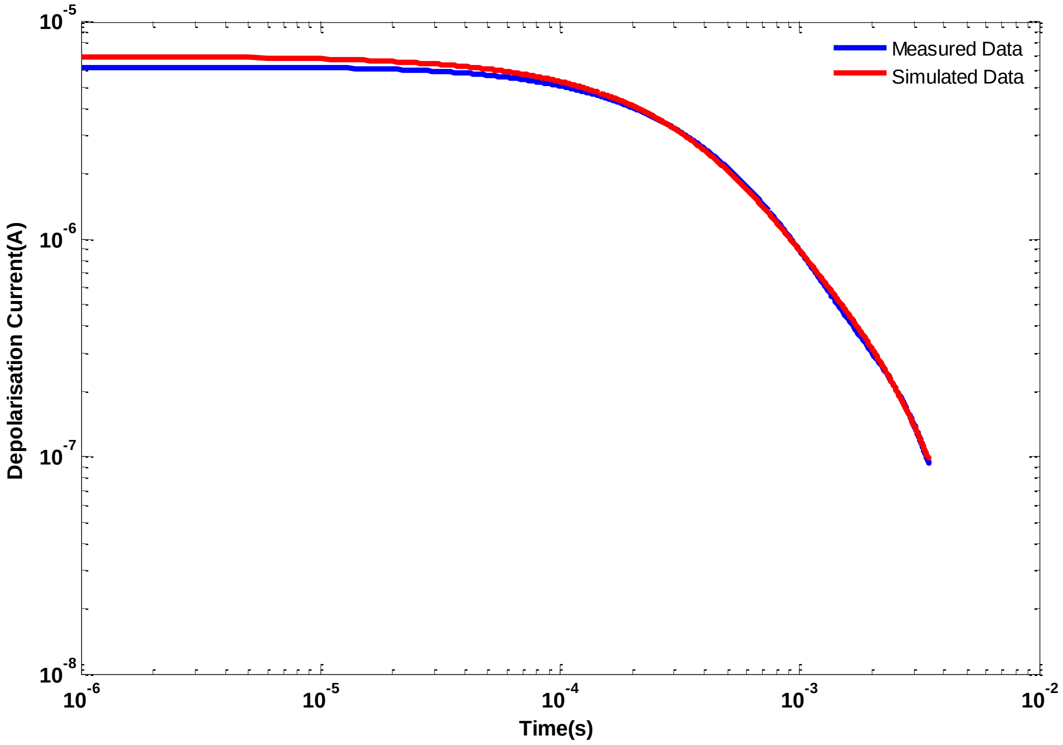


Figure 5.16: Depolarization current curve of rubber insulating materials

PTFE(TEFLON) insulating materials

Geometric capacitance: 20.407picofarad

Insulation resistance:1.14E+12 ohm

Number of branch: 2

Branch value

Table 5.7 Branch Resistance, Capacitance and Time Constant value PTFE (TEFLON) insulating materials

Branch	**Ri(Ohm)**	**Ci(Farad)**	**τi(Second)**
Branch 1	1.35E+07	2.45E-11	3.32E-04
Branch 2	1.33E+07	1.38E-11	1.84E-04

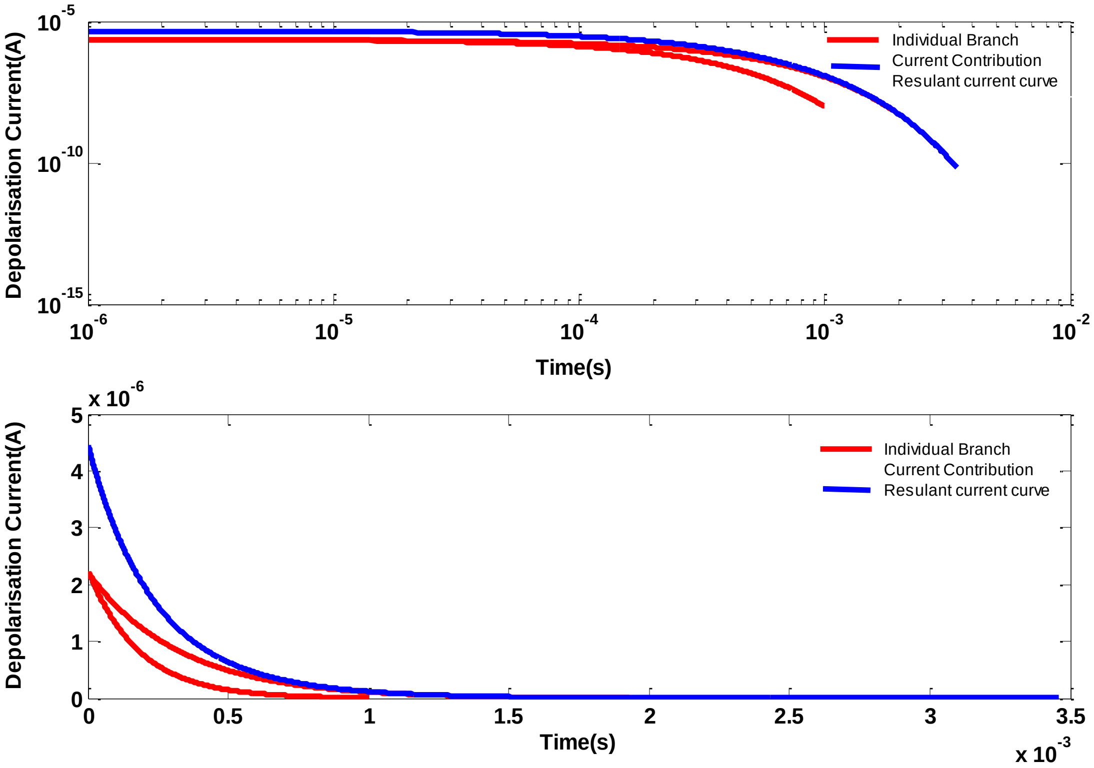


Figure 5.17.: Depolarization current curve of every branch and their resultant in logarithm scale and normal scale of PTFE (TEFLON) insulating materials

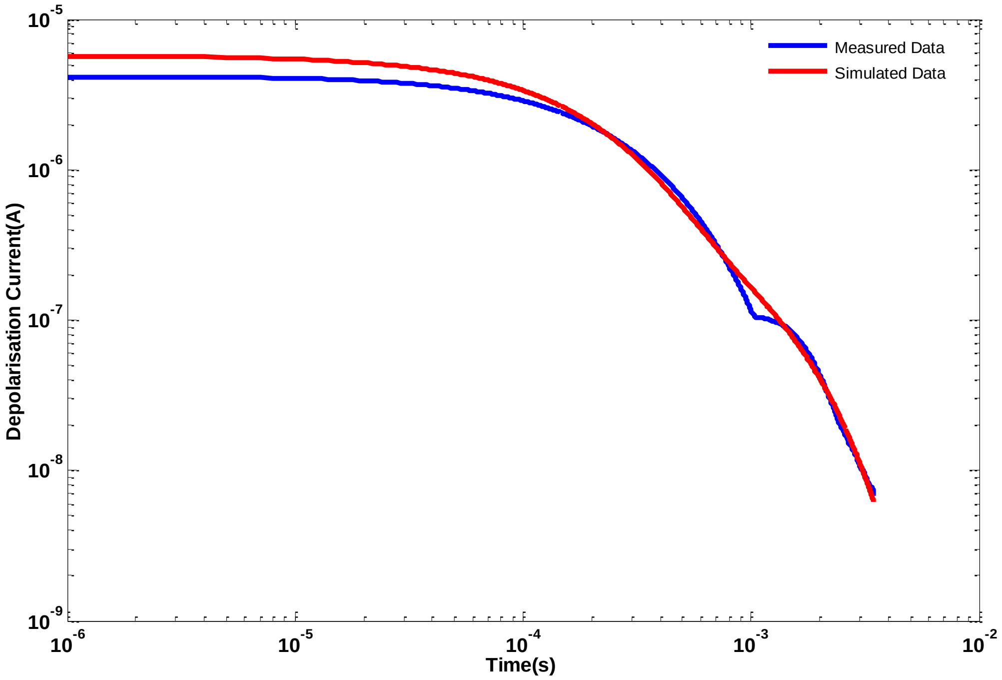


Figure 5.18: Depolarization current curve of PTFE (TEFLON) insulating materials

A comparison of branch resistances and capacitances for different insulating materials is given in Table 5.8

Table 5.8 Comparison table of Branch Resistance and Branch Capacitance of different insulating materials.

Sl.No	Materials	Branch resistance-1 ☐	Branch resistance-II ☐	Branch capacitance-I f	Branch capacitance-II f
1	HDPE	2.28E+07	8.26E+06	2.18E-11	2.36E-11
2	LDPE	2.84E+07	1.06E+07	1.69E-11	1.77E-11
3	PMMA	2.23E+07	8.45E+06	2.29E-11	2.27E-11
4	PP	2.23E+07	8.45E+06	2.29E-11	2.27E-11
5	RUBBER	1.89E+07	5.50E+06	6.68E-11	5.61E-11
6	PTFE	1.35E+07	1.33E+07	2.45E-11	1.38E-11

From Table 5.8 it is observed that LDPE has the highest value of branch resistance, in both branches. HDPE, PP and PMMA have similar values of branch resistances. A comparatively lower value is observed for rubber. Lowest value of branch resistance is observed with PTFE.

Similarly, in case of branch capacitances, highest value of capacitance is observed in Rubber. HDPE, PMMA and PP have almost similar value of branch capacitances. LDPE has comparatively lower value of branch capacitance. As in case with branch resistance, lowest value of branch capacitance was also observed in PTFE.

5.3 POLARIZATION CURRENT CURVE:

Polarization currents of each insulating material are calculated by using the procedure as discussed in section 3.3.1. This section provides the plot of the measured polarization current of different insulating materials has been given hereafter.

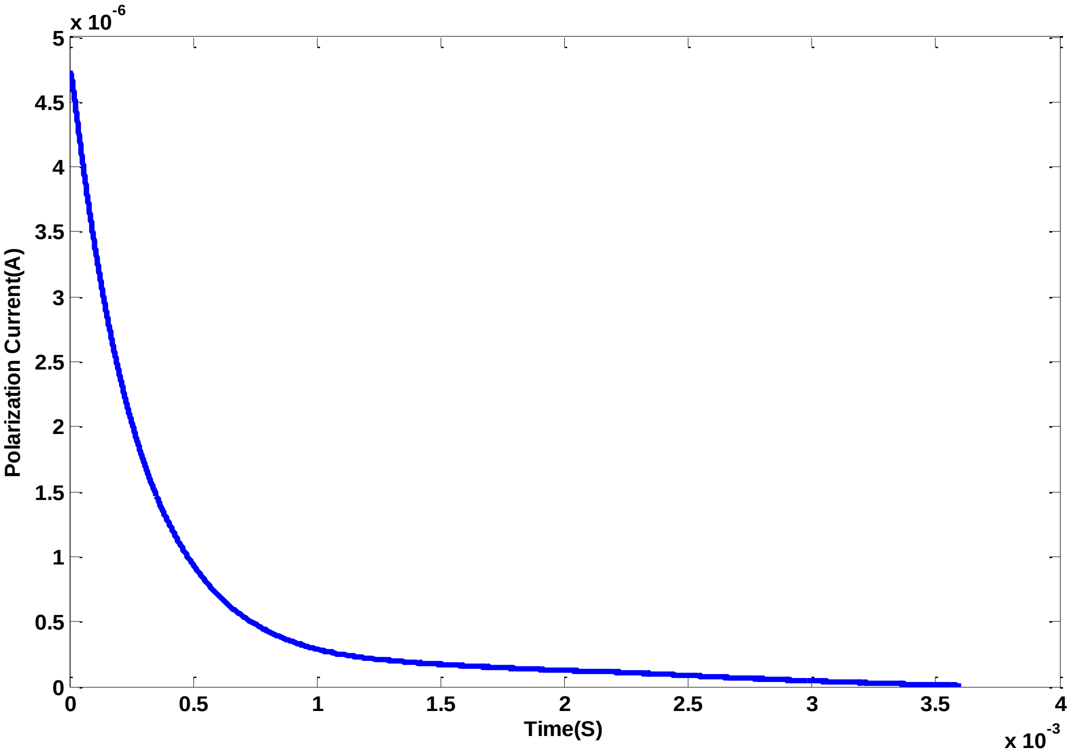


Figure 5.19: Polarization current curve of HDPE insulating materials

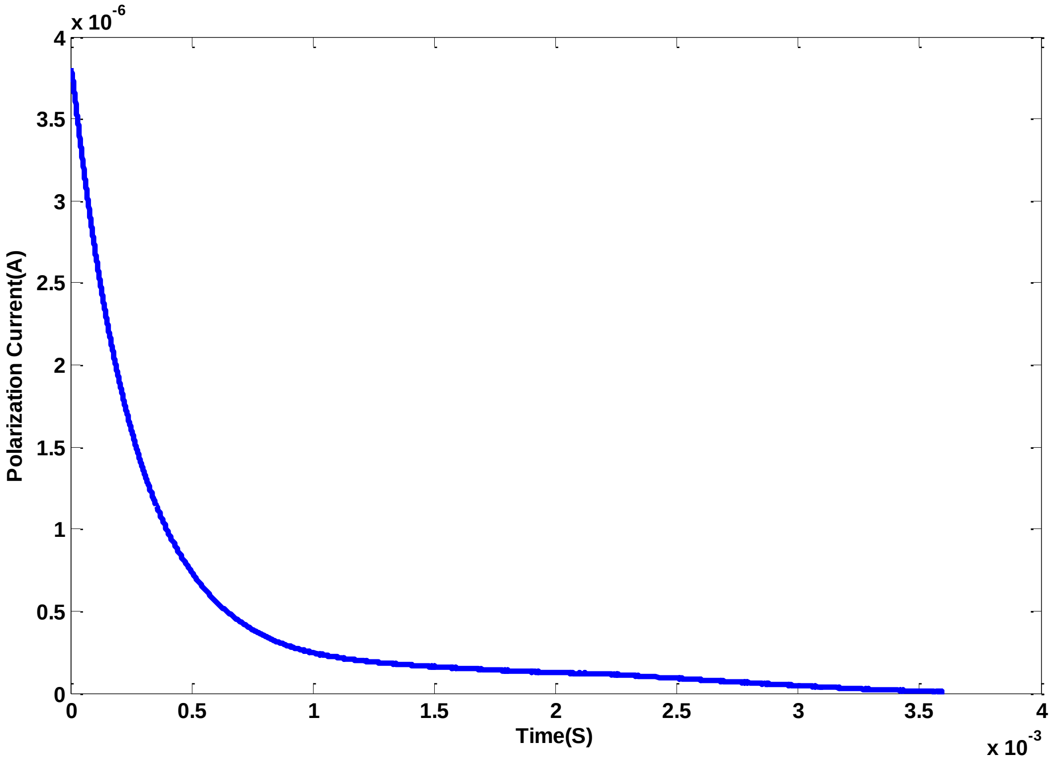


Figure 5.20: Polarization current curve of LDPE insulating materials

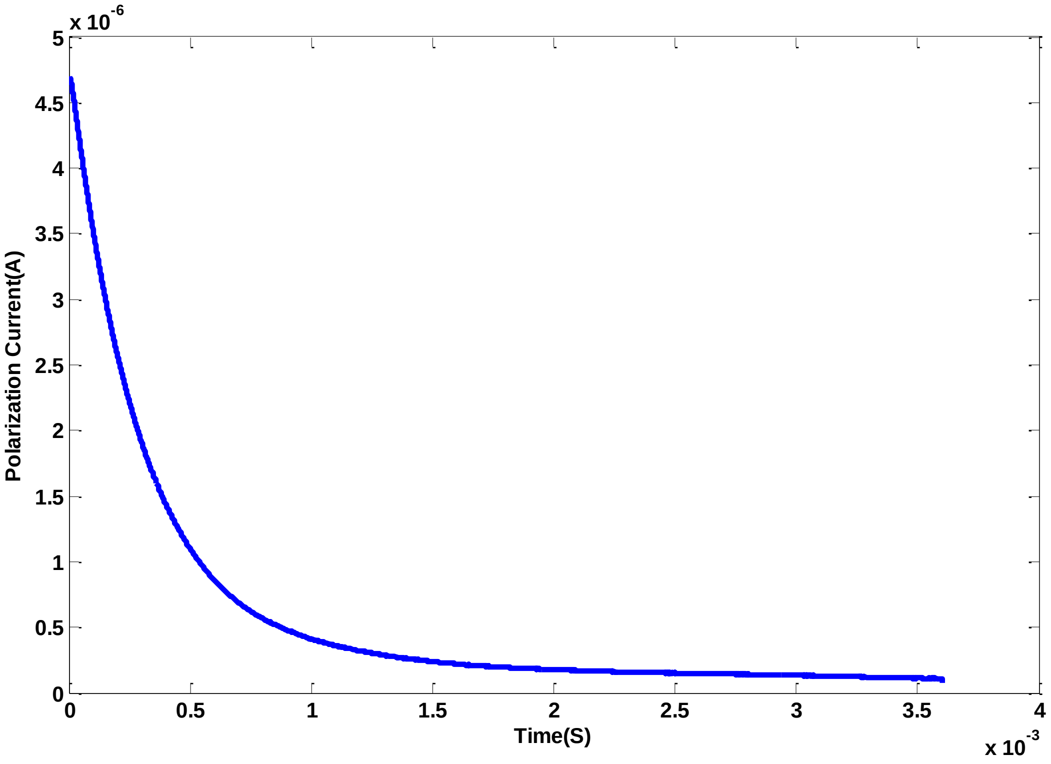


Figure 5.21: Polarization current curve of PMMA insulating materials

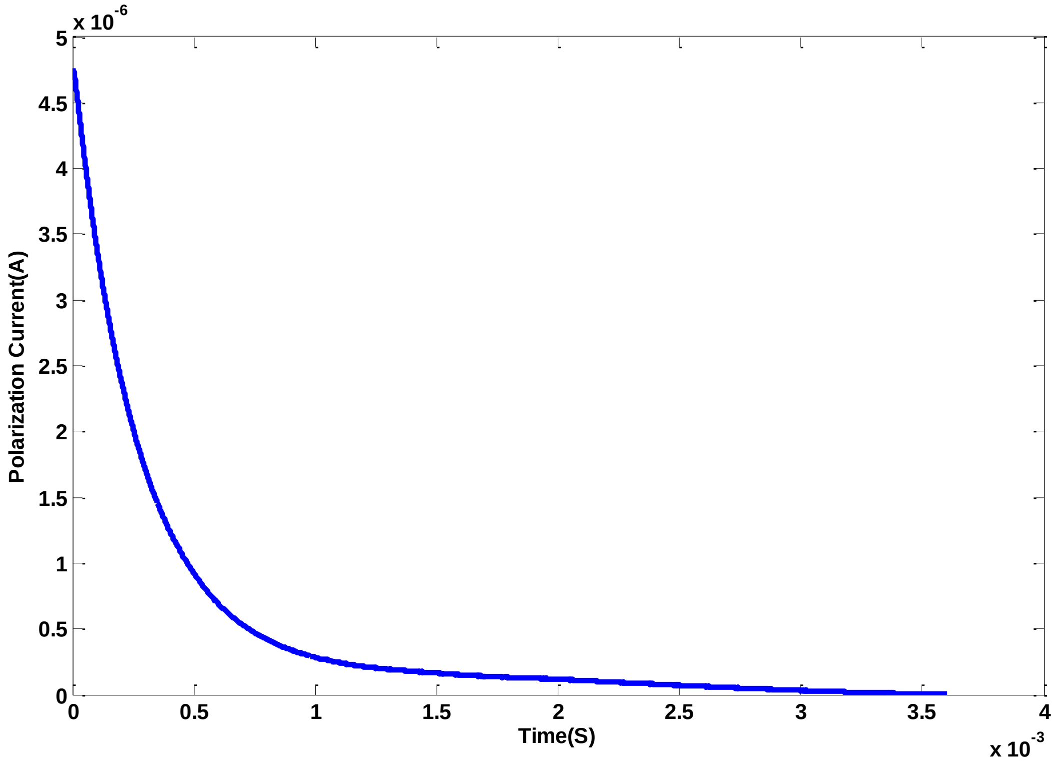


Figure 5.22: Polarization current curve of PP insulating materials

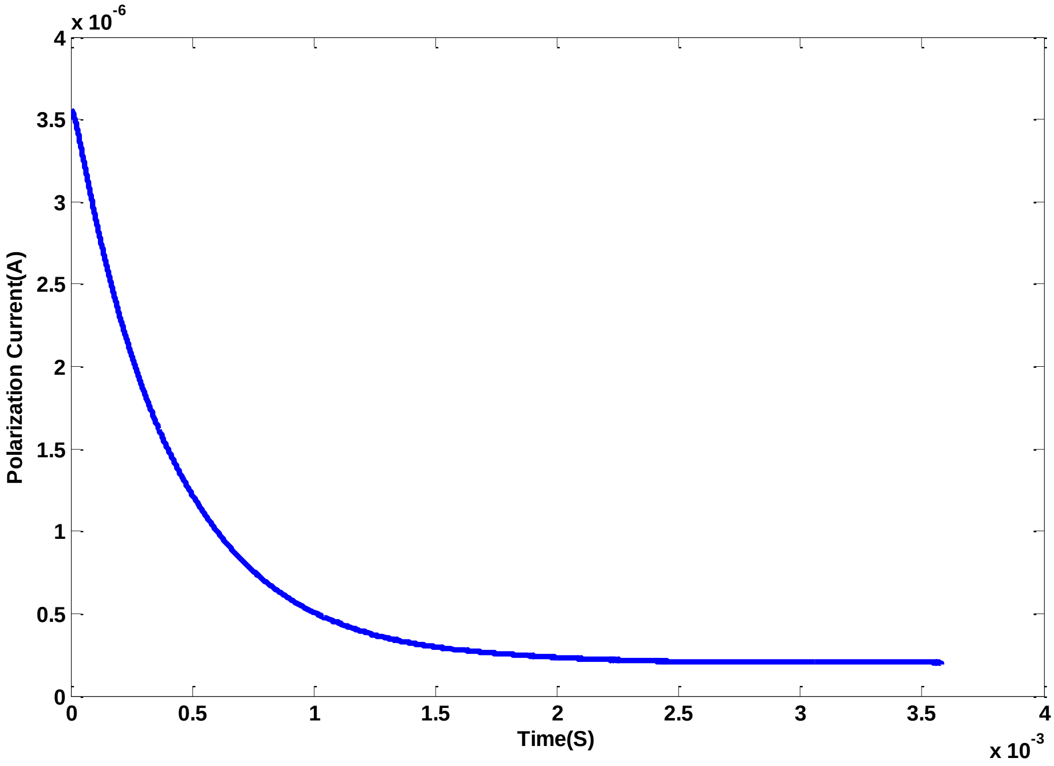


Figure 5.23: Polarization current curve of RUBER insulating materials

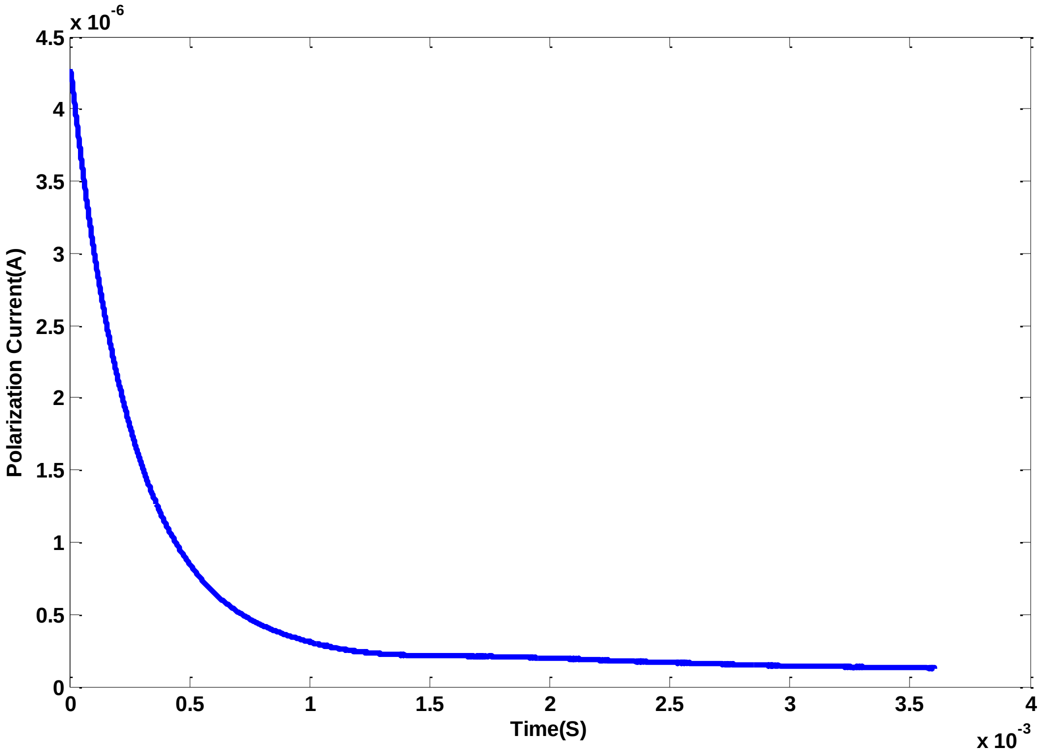


Figure 5.24: Polarization current curve of PTFE (TEFLON) insulating materials

From Figure 5.19 -5.24 it is clear that the peak current and settling time observed is highly dependent on the chosen material. For HDPE, PP, PMMA and PTFE (Teflon) the peak polarization current is almost same, around (4.2-4.7 µA). Lowest peak polarization Current was observed in case of LDPE (around 3.8µA) and Rubber (around 3.5 µA). The settling time also varies for different materials. Therefore, it can be concluded that the polarization characteristics are unique to material properties.

5.4 Effect of temperature on PDC measurement of solid insulating materials:

In order to investigate the effect of temperature on the insulating properties of aforesaid insulating materials, the PDC measurements were carried out on the sample keeping it an environmental chamber present in High Tension Laboratory, Jadavpur University. The environmental chamber used in these studies is procured from Thermotron, and it offers controlled chamber environment from -40°C to 200°C. In addition with temperature, humidity can also be controlled from 10% to 97% inside the chamber. The sample under study is kept in the environment chamber at a certain temperature and humidity and PDC measurements. Before starting the measurement, the sample was kept inside the chamber for one hour so that equilibrium conditions are reached. In this study, the humidity was kept constant at 20% in all measurements and the chamber temperature was varied from 20°C to 90°C.

For simplification of the analysis, the depolarization characteristics obtained were fitted with single exponential decay with the expression of $I_0 exp(-t/T)$, where I_0 is the peak depolarization current, T is the time constant and t is time. The variation in peak depolarization current and time constant with temperature for different materials are plotted below.

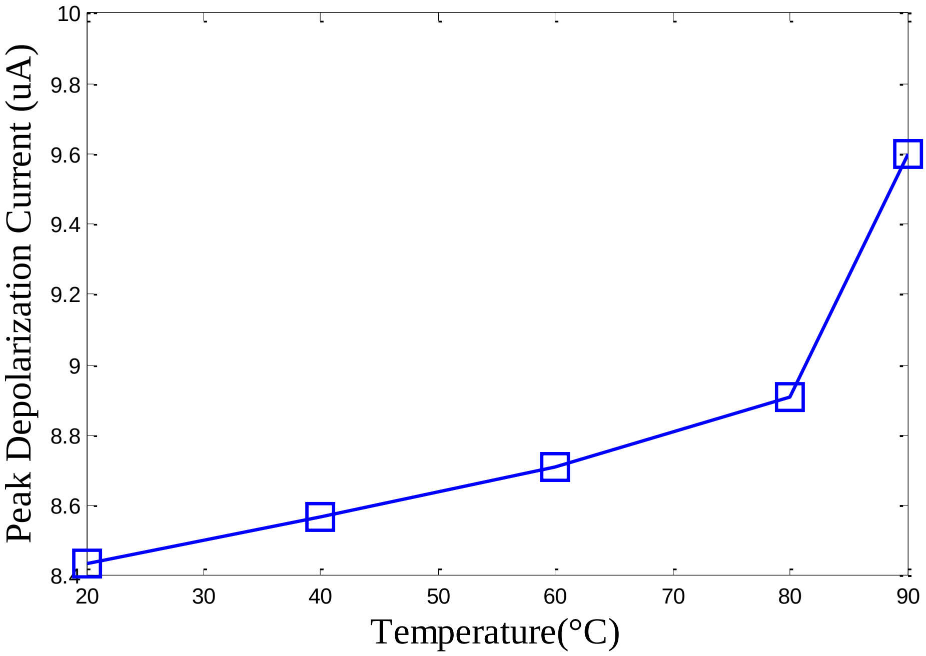


Figure 5.25: Current verses temperature characteristic of PMMA insulating materials

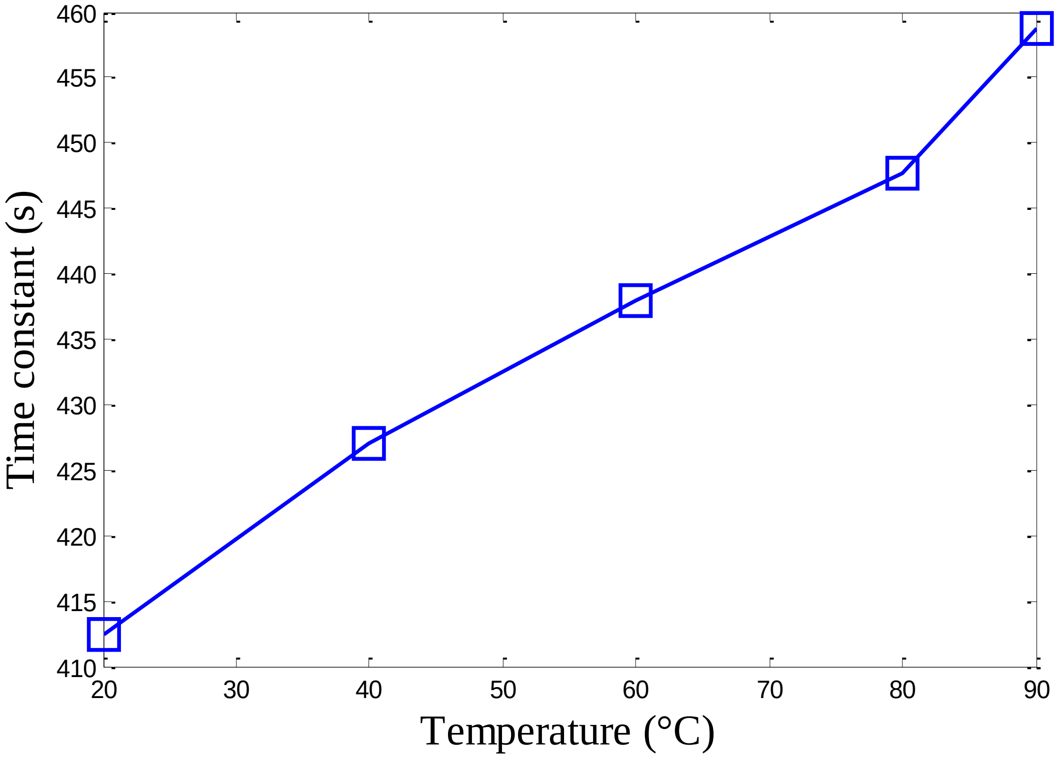


Figure 5.26: Time Constant verses temperature characteristic of PMMA insulating materials

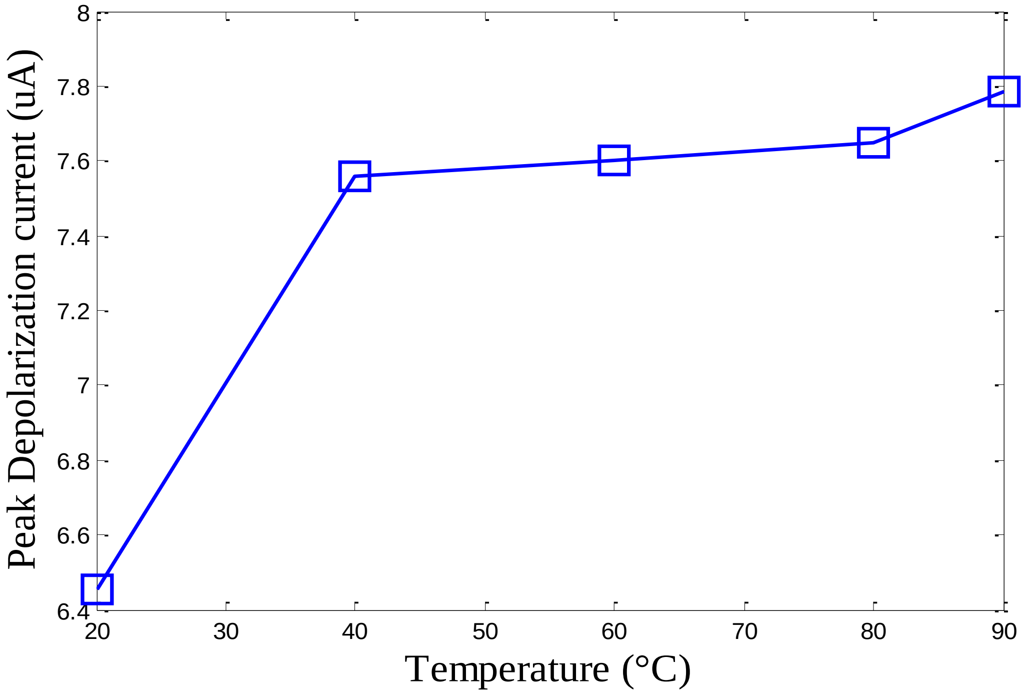


Figure 5.27: Peak depolarization Current verses temperature characteristic of PP insulating materials

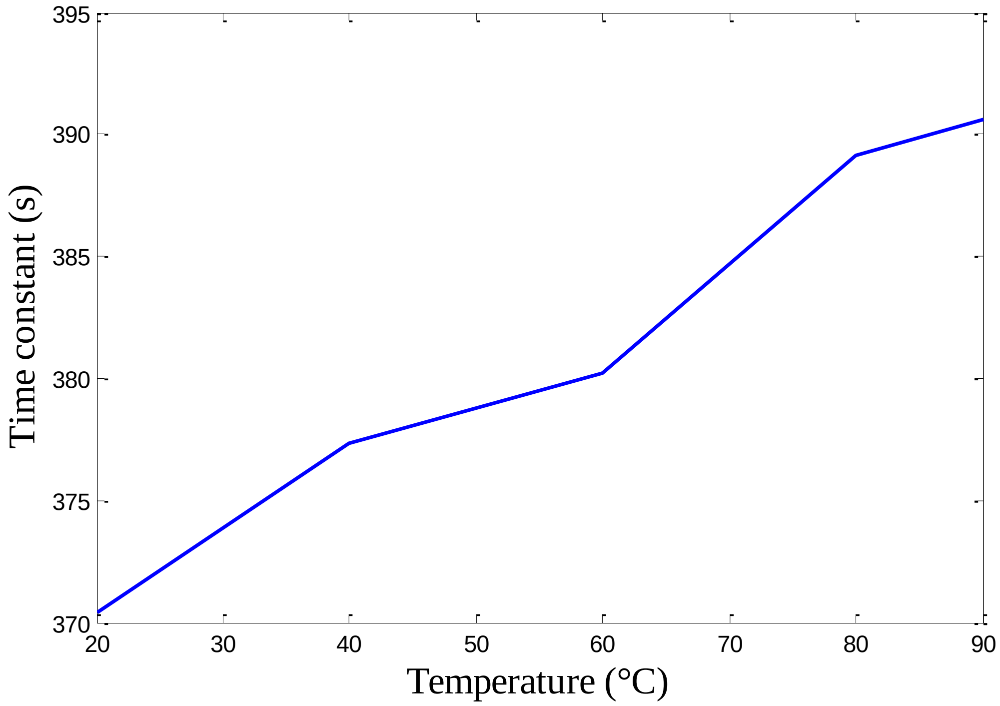


Figure 5.28: Time Constant verses temperature characteristic of PP insulating materials

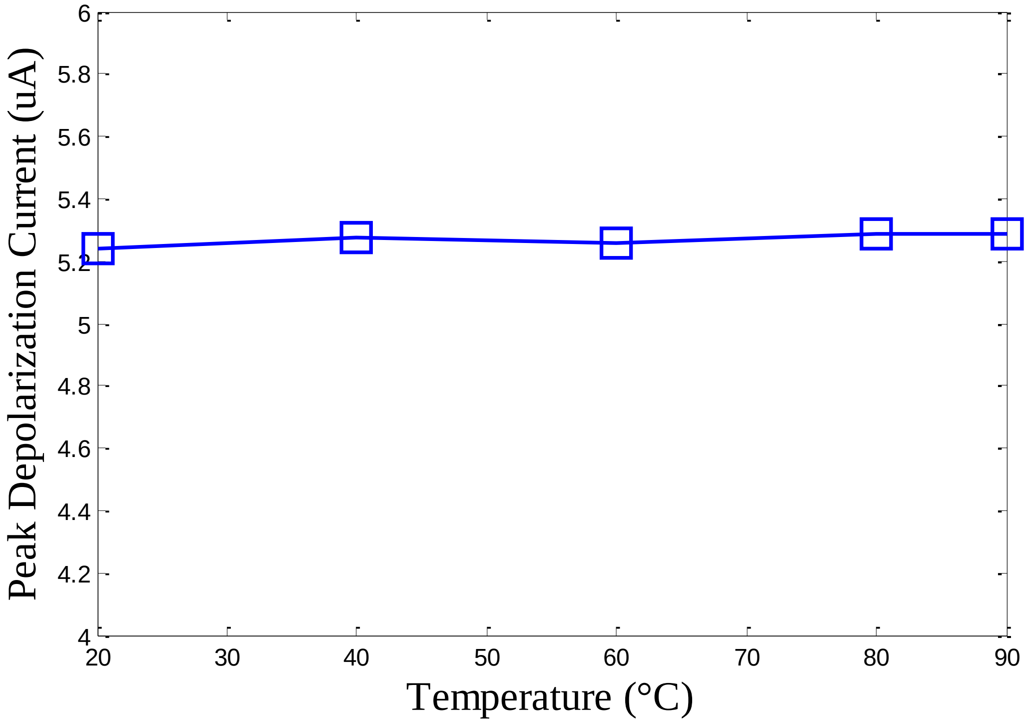


Figure 5.29: peak depolarization Current verses temperature characteristic of PTFE(Teflon) insulating materials

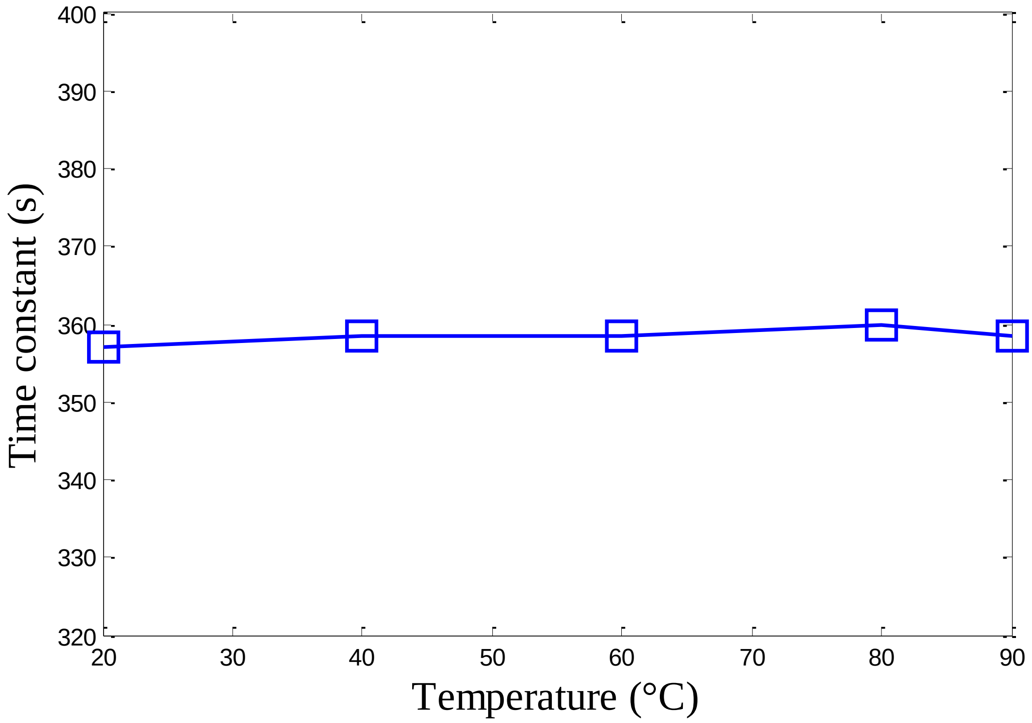


Figure 5.30: Time Constant verses temperature characteristic of PTFE(Teflon) insulating materials

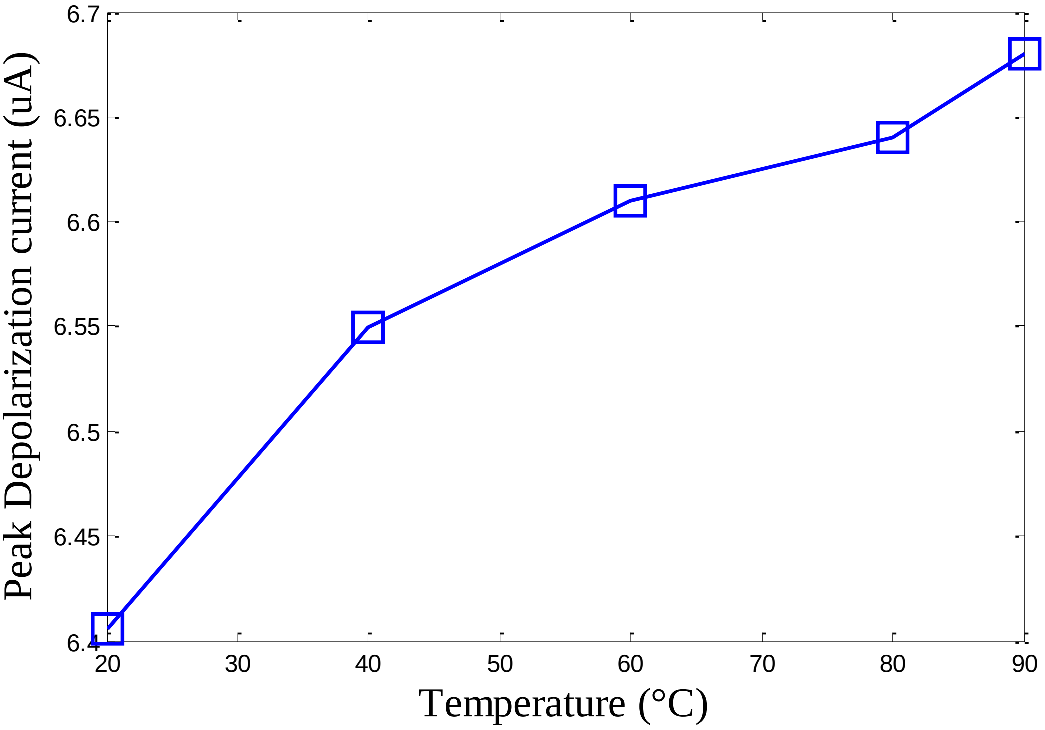


Figure 5.31: peak depolarization Current verses temperature characteristic of HDPE insulating materials

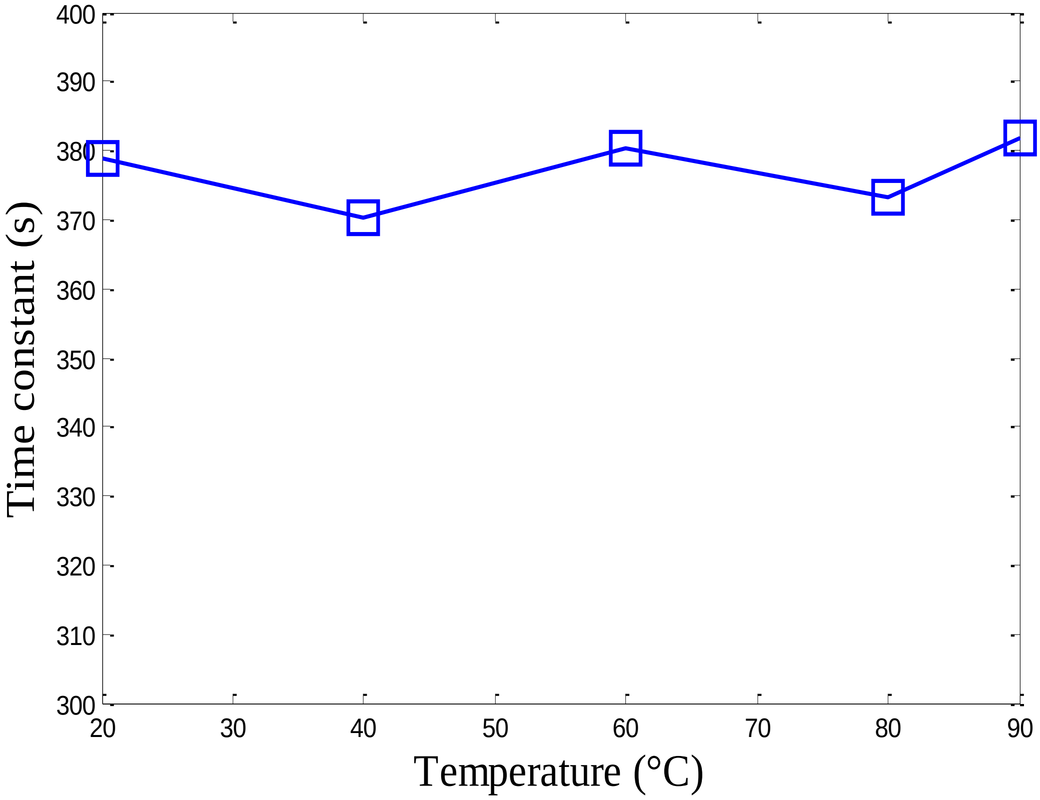


Figure 5.32: Time Constant verses temperature characteristic of HDPE insulating materials

From the figures 5.25- 5.32, it was observed that in case Polypropylene (PP) and PMMA both the values of peak depolarization current and time constant increases with temperature. However in case of Teflon, the response is flat i.e. there is little temperature variation of peak depolarization current and time constant. It is an interesting observation, as these parameters are found specific to material properties.

5.5 Dielectric Dissipation Factor Measurement$(tan\delta)$

This section provides the value of dielectric dissipation factor $(tan\delta)$ of different insulating materials at different frequencies. The measurements were carried out with ISA substation test set, as discussed in chapter 4. Tan delta measurements of different insulating material at different frequencies are plotted hereafter.

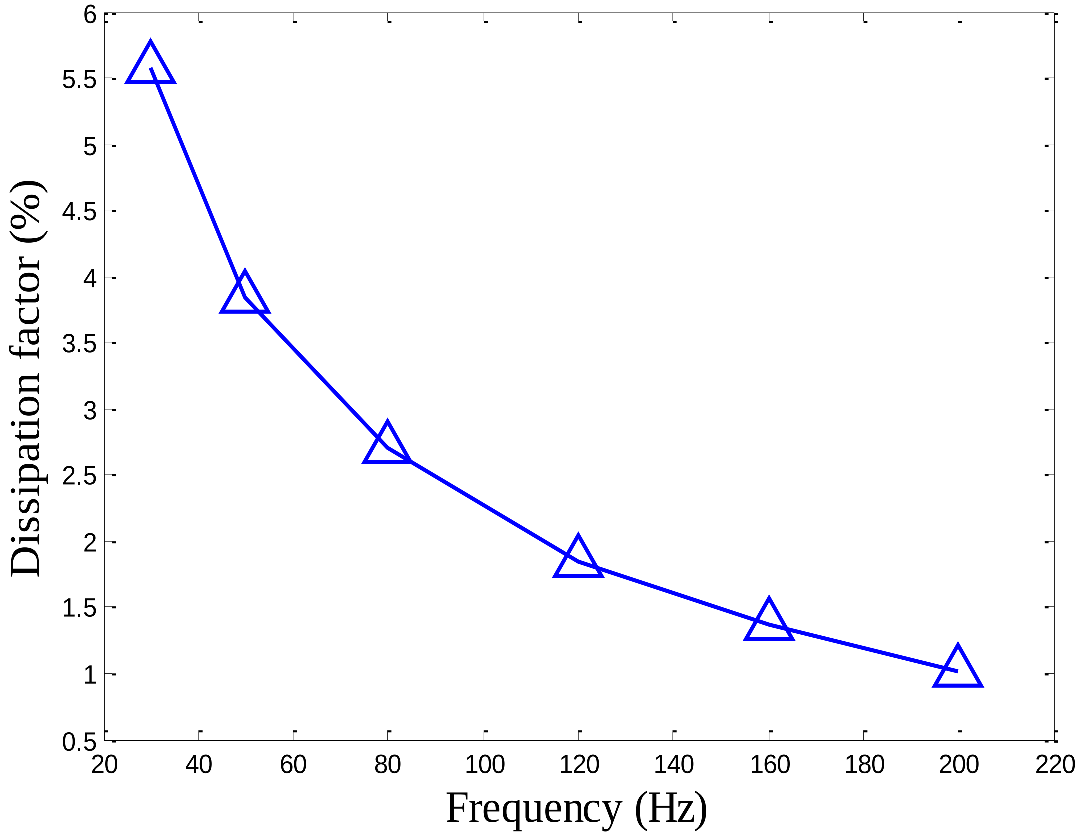


Figure 5.33: The relationship between the Dielectric dissipation factor $(tan\delta)$ and frequency of LDPE insulating materials

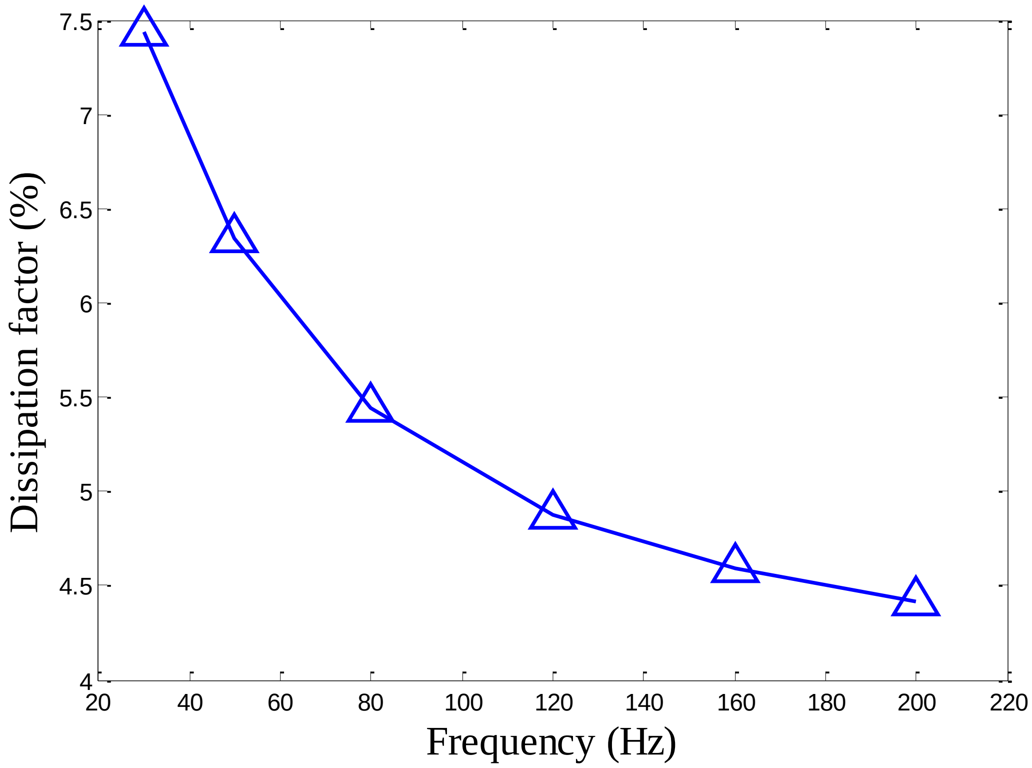


Figure 5.34: The relationship between the Dielectric dissipation factor ($tan\delta$) and frequency of HDPE insulating materials

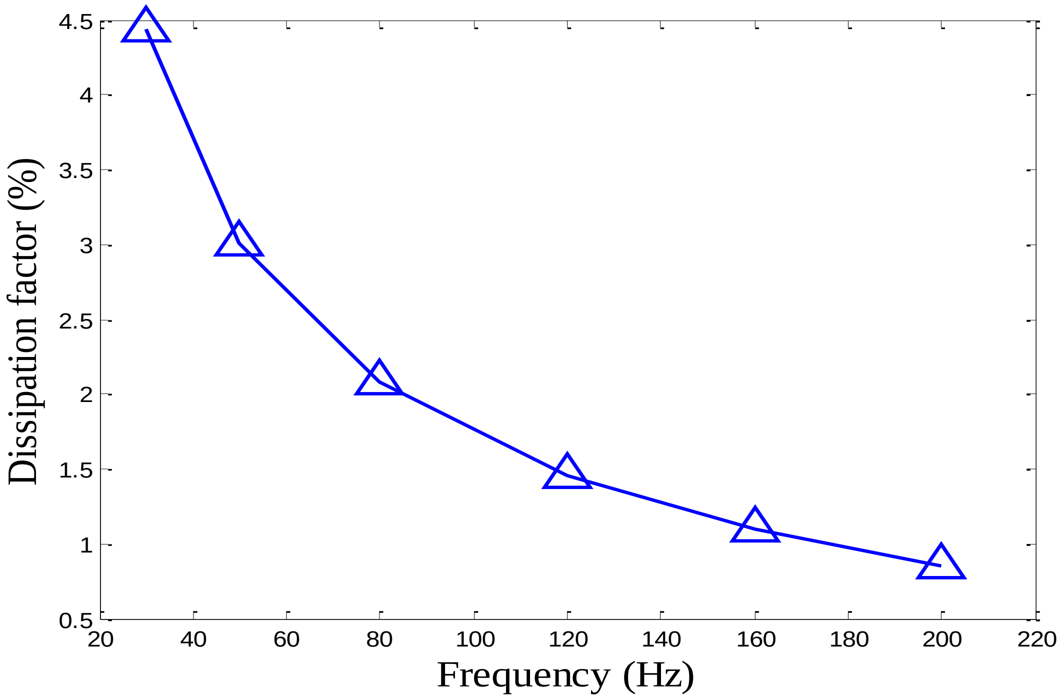


Figure 5.35: The relationship between the Dielectric dissipation factor ($tan\delta$) and frequency of PP insulating materials

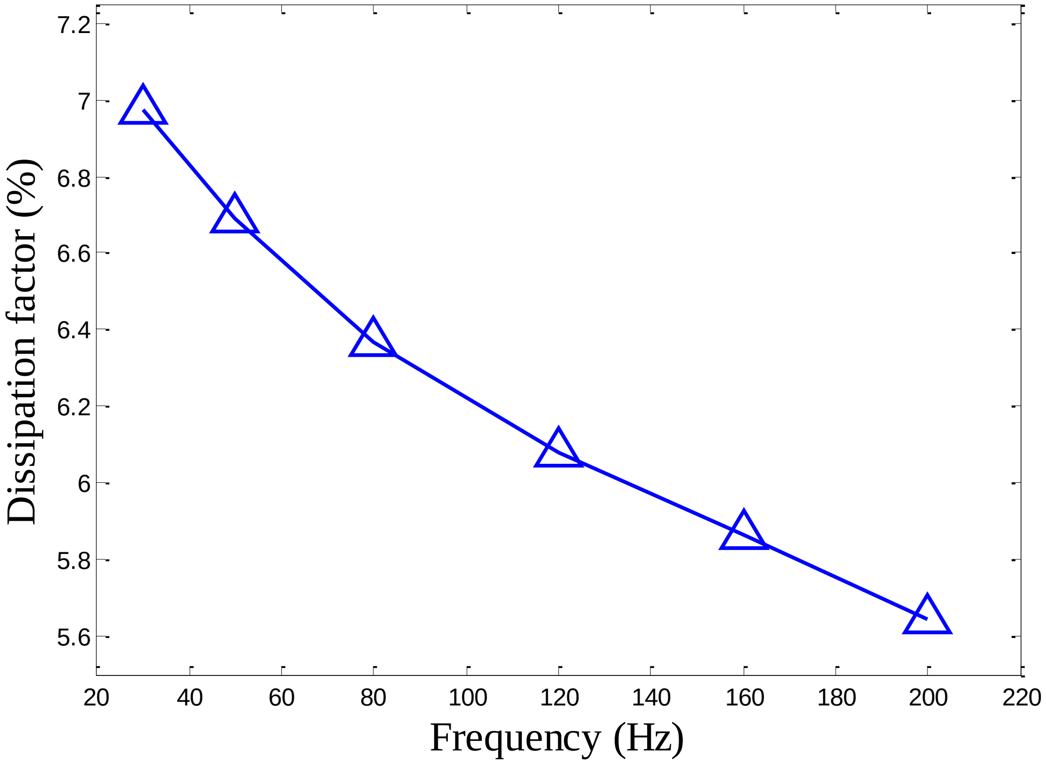


Figure 5.36: The relationship between the Dielectric dissipation factor ($tan\delta$) and frequency of PMMA insulating materials

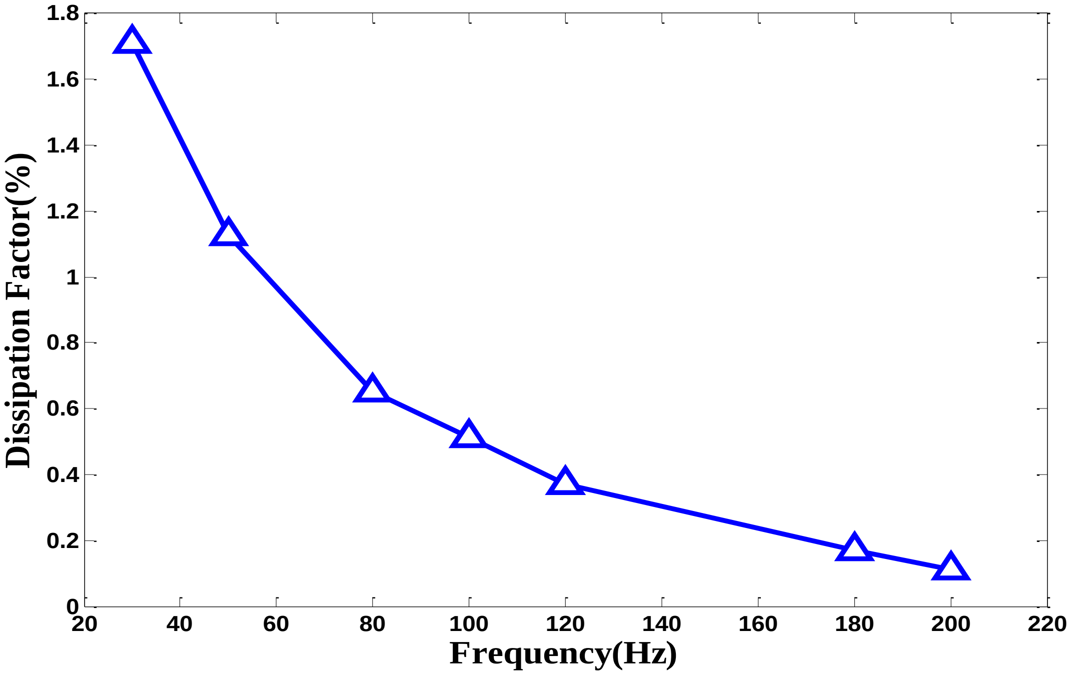


Figure 5.37: The relationship between the Dielectric dissipation factor ($tan\delta$) and frequency of PTFE insulating materials

From Figure 5.33-5.36, it was observed that the frequency dependency of Dielectric Dissipation Factor is different for different material. For all the five materials (LDPE, HDPE,PP, PMMA and PTFE) dissipation factor decreases with increase in frequency. However, in case of LDPE, PP and PTFE this decrease is very sharp. For PTFE the dissipation factor decreases from 1.71% to 0.11% as the frequency increases to 30 Hz to 200 Hz. In LDPE it was observed that dissipation factor decreases from 5.57% to 1.013 % as the frequency is increased from 30 Hz to 200 Hz. Similarly in Polypropylene (PP) dissipation factor decreases from 4.04% to 0.852% as the frequency is varied in the aforesaid range. In HDPE, This dependence is somewhat less, as dissipation factor reduces from 7.494% to 4.417% in the mentioned frequency range. The variation is much less in PMMA, where it varies from 6.973% to 5.644%. Therefore it can be said that the variation of dissipation factor with frequency is specific to material properties.

CHAPTER 6

CONCLUSION

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CONCLUSIONS

6.1 Conclusions

Solid polymeric materials are being increasingly used in various high voltage equipments. Condition monitoring of these equipments is becoming highly important for power utilities as the approach of maintenance is changing from time-based maintenance to condition based maintenance for cost cutting and other economic reasons. In this thesis, studies were conducted on a few polymeric insulating materials to assess the feasibility of dielectric response analysis as a condition monitoring method for solid polymeric insulation used in high voltage systems.

Before experimental work, a brief study was conducted on basic physical and chemical properties of various polymeric insulating materials. Then, a detailed literature review was conducted on the present status of different condition monitoring techniques of solid type insulation. From the critical analysis of different condition monitoring technologies, it was concluded that focus will be given to dielectric response as it offered (i) simplicity in the arrangement of experimental set up and (ii) the analysis method is quite straight forward. Theoretical investigation was done to understand the operating principle dielectric response analysis. An experimental set-up was developed in the high voltage laboratory for carrying out polarization-depolarization current (PDC) specifically for solid insulating materials. Similarly, ISA substation testing set instrument was used to measure dissipation factor of different polymeric insulating materials.

From obtained results, it was evident that both polarization-depolarization current (PDC) measurement and dissipation factor measurements are highly dependent on material properties. With change in material, the peak of polarization and depolarization current as well as the time constant changes considerably. These measurements were analyzed through Debye model. The measured results and calculated results through Debye model were compared. The effect of temperature on PDC measurements was also studied. For Teflon, the effect of temperature was found minimal. Similarly, the effect of frequency on dissipation factor for different materials was also studied. It was observed that with frequency, dissipation factor of LDPE, HDPE and PP changes considerably. However, for PMMA the change is quite less.

6.2 Future work

In this work, insulation diagnostics of solid insulating materials were carried out using PDC and dissipation factor measurements. Condition of solid insulating materials can also be monitored by conducting space charge measurements and conduction current measurements. From conduction current measurements space charge initiation voltage can be evaluated, as this will be the particular voltage above which the conduction current will show strong non-linearity. This initiation voltage will be sensitive to insulation condition, as degraded samples will show lower voltage levels for space charge initiation. Similarly, the conduction current will also be sensitive towards temperature, which also needs to be carried out.

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