TIME DOMAIN RESPONSE ANALYSIS OF SOLID DIELECTRICS IN HIGH VOLTAGE SYSTEM

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CHAPTER-1

INTRODUCTION

Power transformers are a very important part of the power system network. Regular condition monitoring and maintenance will be helpful to provide the trouble free service for power transformer.The solid insulating materials are used as insulation on behalfof liquid insulating medium in the dry-type transformer.The condition of the insulating system is related to the life span of the transformer. The good insulation must have these following dielectric properties, like low dielectric dissipation factor (tan δ), high dielectric breakdown strength and very low conductivity. After a certain operating span (a few years) the insulation system of the transformer is degraded day by day. This degradation occurred due to the temperature, moisture and some chemical particles are presentin the environment. Another factor is the aging of the transformer. Overall degradation of insulation will lead to the failure of the transformers**.**

The solid insulation is costlier than the liquid insulation. Due to the high insulation cost, the cost of the dry-type transformer is higher than oil cooled transformer of the same power rating. The main disadvantage of the dry-transformer is that during the operation time the temperature of the transformer rises when the temperature of the transformer exceeds a certain limit. Hence, a hotspot is created in windings of the transformer. The surface of the insulation degraded and some tiny voids are created into the insulation, due to this hotspot.The main cause of partial discharge that is presence of void, leads to breakdown of the insulation. The insulation system of the transformers are affected by the moisture that is present in the air due to wet weather condition.Due to the presence of moisture content in the atmosphere, the insulation system of the transformer will be degraded, then the monomer link of insulating material will be weaker. This will lead the degree of polymerization. For the cause of the degree of polymerization, the insulation has become fragile. To save a huge amount of economic loss, the equipment of the power system will be *monitoring* and *analyzing* regularly.

There are several methods for the monitoring and diagnosis of the high voltage equipment.By using these methods a transformer will provide maximum service life. Time domain dielectric response measurement and frequency domain response analysis are the two methods of dielectric response analysis employed for condition monitoring of high voltage equipment. Polarization and depolarization current (or PDC) measurement and recovery voltage measurement (RVM) are the parts of time domain dielectric response measurement. By using frequency domain spectroscopy determine the information about power loss coefficient or dielectric dissipation factor.

1.1 Dry-type Transformer

The dry-type transformer is such an electrical device with less maintenance to provide the services for many years. It can use for long duration of time, under normal conditions. For the cooling of the dry-type transformer, we do not need any kind of liquid or mineral oil. The dry-type transformer doesn’t require fireproof vaults. Dry type transformer provides a safe and reliable power source, these are installed too near the load center or the consumer. The Dry-type transformer core is made from CRGO or cast iron as similar to an ordinary transformer. The windings of the dry-type transformer are impregnated by resin or varnish under high vacuum pressure [1-2].

1.1.1 Classification of Dry-type Transformers

Depending on the manufacturing and working environment, the dry-type transformer is four different types- (a) Open Wound, (b) Impregnated Vacuum Pressure, (c) Encapsulated Vacuum Pressure and (d) Cast Coil.

1.1.1.1 Open Wound Dry-type Transformer

Open wound transformers are constructedby *dip-and, baked* method. It is completed by preheating and heating the conductor coils, dip them into the varnish under high temperature. Then the coils are baked into the varnish cure.Open wound transformers are also fire-proof, explosion proof, dustproof, better overload capacity [3]. Open Wound transformers are providing for easy to maintenance compare to other transformers.The winding of the open wound transformer has a high fire resistance and thermal shock and it doesn't release any hazardous gas into the atmosphere below the temperature of 750 ° C.

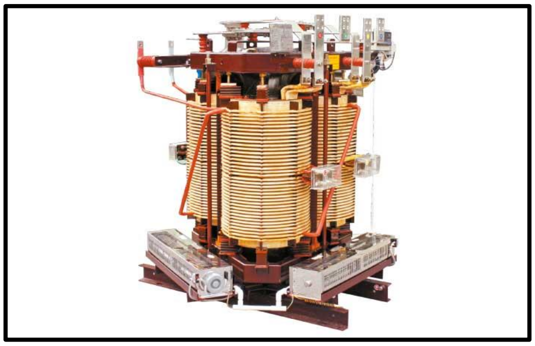


Fig. 1.1. Open wound Dry-type Transformer [3].

Specification of Open wound transformer

- **Capacity:** 50 kVA to 3000 kVA
- **Voltage level:** up to 36 kV
- **Class of insulation:** C
- **Cooling system:** AN
- **Impregnation:** Varnish

1.1.1.2 Vacuum Pressure Impregnated (VPI) Dry-type transformer

Vacuum Pressure Impregnated transformers areimpregnated with a polyester varnish under high-temperature vacuum pressure. The ventilated designed VPI Dry-type transformers are used in most industrial and commercial applications. VPI transformers have excellent mechanical and short-circuit strength. Also, it does not have any fire or explosion hazard as well as there is no leakage liquid.The varnish coating applies this technique in the interchange of pressure and vacuum cycles.The method of vacuum pressure impregnation is better than any standard method for dry-type transformer. This method allows the varnish to be better infiltrated into the coils of transformers. This transformer canresist the corona effect.

Fig. 1.2. Vacuum Pressure Impregnated Transformers [4].

Specification of Vacuum Pressure Impregnated transformer

- **Capacity:** 5 kVA to 500 kVA
- **Voltage level:** Up to 11 kV
- **Classes of insulation:** H/C
- **Cooling System:** AN / FA
- **Impregnation:** Polyester Varnish

1.1.1.3 Vacuum Pressure Encapsulated (VPE) Dry-type transformer

The *vacuum pressure encapsulated* transformer coils have always been encapsulated at high-temperature vacuum pressure in Silicone varnish to achieve ultimate moisture safety. These transformers are made by applying several dip processes in an oven. For the construction of VPE transformers, the coating layer of resin is four times greater than the layer of polyester coating in VPI transformers [5].

The transformer's coils obtain at least four cycles of silicone varnish and a corrosion-resistant sealant that prevents moisture and industrial pollutants. Silicone varnish offers excellent dielectric strength, which even after thermal aging remains flexible. The normal withstand temperature of silicone varnish insulation of VPE transformers is in the range of 220 °C to 250 °C.

Fig. 1.3. Vacuum Pressure Encapsulated Transformer [5].

Specification of Vacuum Pressure Encapsulated transformer

- **Capacity:** 5 kVA to 30000 kVA
- **Voltage level:** 1.1 kV to 36 kV
- **Classes of insulation**: F and H
- **Cooling System:** AN / FA
- **Impregnation:** Silicone Varnish

1.1.1.4 Cast Coil Dry-type transformer

This transformer's coils are made of solid cast resin under a high vacuum.This epoxy resin has offer the high dielectric barrier and superior safety under the rough working environment. The cast material is a durable compound of fiberglass that offers extraordinary mechanical strength and stress of the short-circuit resistivity. Also, the cast coil dry-type transformers provide low noise and less loss. The maximum working temperature for a cast coil dry-type transformer is about 220° C.

Fig. 1.4. Cast Coil Transformer [6].

Specification of Cast Coil Transformer

- **Capacity:** 10 kVA to 20000 kVA
- **Voltage level:** 6 kV to 35 kV
- **Classes of insulation:** F and H
- **Cooling System:** AN / FA
- **Impregnation:** Cast Resin Varnish

1.1.2 Advantages and Disadvantages of Dry-type Transformer

Advantages of Dry-type Transformer [7]

- Safe operating condition for people and property.
- Easy installation.
- Excellent capacity to support overloads.
- No fire hazard.
- Excellent resistance at short circuit currents.
- Long lasting due to thermal and dielectric heating.
- Suitable for wet, contaminated and mining areas.

Disadvantages of Dry-type Transformer [7]

- In the case of oil transformer when small fault occurs then these parts will be changed but for the Dry-type transformer whole system will be changed. So the operation of Dry-type transformer is more cost effective.
- For same power and voltage rating, dry type transformer is costlier than oil cooled transformer.

1.1.3 Application of Dry-type Transformer

- Chemical, oil and gas industry.
- Environmentally sensitive areas.
- Fire-risk areas.
- Inner-city substations.
- Indoor and underground substation.
- Renewable power generation.
- High residential areas.

1.2 Scope of the Thesis

In this thesis the dielectric response of solid insulation of the dry-type transformer has been analyzed. This analysis has been done in the time domain by varying the temperate of the sample.

A dielectric response analyzer (or electrometer) is used to measure the polarization and depolarization current from the samples under different temperature.The aim of the thesis is to analyze the polarization and depolarization current data to investigate the condition of the samples under different circumstances.

1.3 Contribution of the Thesis

- Dielectric Response Analyzer is used to study the insulation condition of different solid insulation like Nomex Film, Epoxy, and LDPE etc. by using polarization and depolarization current measurement technique.

- The value of the branch parameter of various samples can be determined from the data depolarization current by using the Debye model [8].
- The value of dielectric dissipation factor (tan δ) is determined by using ISA STS 3000 & TD5000. The value of Activation Energy is determined from Arrhenius Equation from the branch parameter data. [9].

1.4 Thesis Outline

- **Chapter 1** describes about the scope and contribution of the thesis, also provides the information about dry-type transformer.
- **Chapter 2** provides the information about the insulating samples.
- **Chapter 3** describes about the different techniques of condition monitoring of Dry-type transformers.
- **Chapter 4** explains about the aspects of dielectric response of the dielectric material and also explain the RC modelling of PDC analysis and the useful parameters which are derived for the indicators of insulation condition.
- **Chapter 5** describes about the experimental details.
- **Chapter 5** describes about the results of the experiment and estimation of activation energy of dielectric from the recorded PDC data.
- **Chapter 7** describes about the conclusions and future work scope**.**

CHAPTER-2

BACKGROUND OF VARIOUS INSULATING SAMPLES

Insulation degradation is the major drawback for an operating transformer. The insulation of a transformer is degraded due to temperature, moisture, and aging. A transformer is failed from operation due to the degradation of the insulation system. To protect a transformer from the failure condition monitoring is done regularly. The condition monitoring can save a huge amount of economic loss and increases the stability of electrical supply system.

The non-invasive methods are more popular than other methods of Condition Monitoring of transformer. The uses of this non-invasive methods are increases day by day. The main advantage is that non-invasive method need not shut down the whole system for a long time. The measurement of Polarization and Depolarization Current is such as a non-invasive method for the condition monitoring of high voltage transformer.

This chapter contains the electrical and chemical properties of insulation samples, and also gives the explanation about the experimental setup for the PDC measurement.

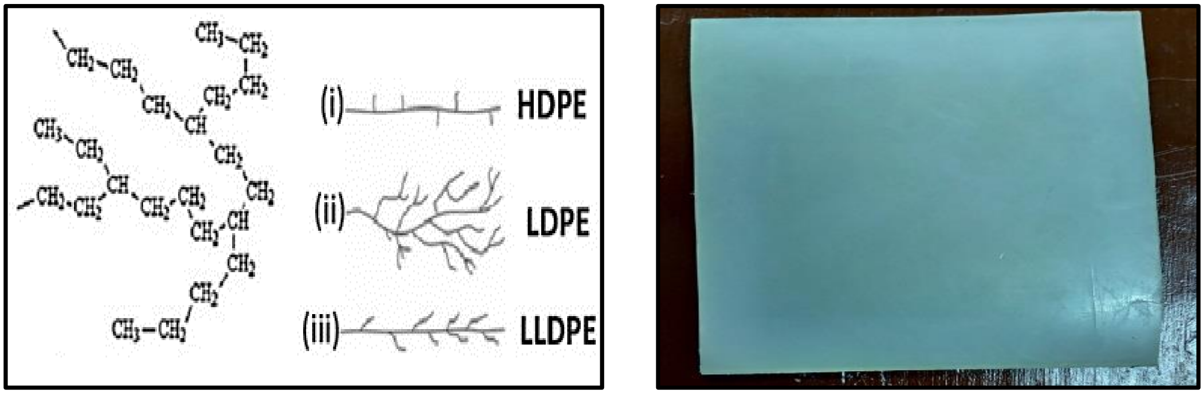
2.1 Various Insulating Samples used in the Experiment

For this thesis, solid insulations is used for condition monitoring of dry-type transformer. In dry-type transformer carbon polymeric based insulation is used as an insulating system. Such kinds of insulation are LDPE (Low-Density Polyethylene), NOMEX, Epoxy Resin, Cellophane tape.

2.1.1 Low-Density Polyethylene (LDPE)

Low-density polyethylene (LDPE) is a product of the monomer ethylene. LDPE is the first polyethylene that produced in 1933 by Imperial Chemical Industries by using a high-pressure process via free radical polymerization [10].

LDPE sample is active at room temperature. But under solar radiation the LDPE sample is produced two greenhouse gases, Methane (CH_4) andEthylene (C_2H_4). The density of LDPE sample is in the range of 0.917-0.930 g/cm^3. Due to lower density the surface of LDPE is easily breakdown.It is can be withstand temperature of 80 °C for continuous time of operation and 90 °C for a short duration of operating time. The LDPE cannot be any effected by aldehydes, ketones and vegetable oils. The tensile strength of LDPE is about 0.20-0.40 N/mm^2.



(a) (b) (c)

Fig. 2.1. (a) Chemical structure of LDPE, (b) Monomer Link and (c) LDPE sample.

The typical dielectric strength of LDPE sample is in the range 20 kV/cm to 160 kV/cm. The melting temperature of LDPE is about 110℃.

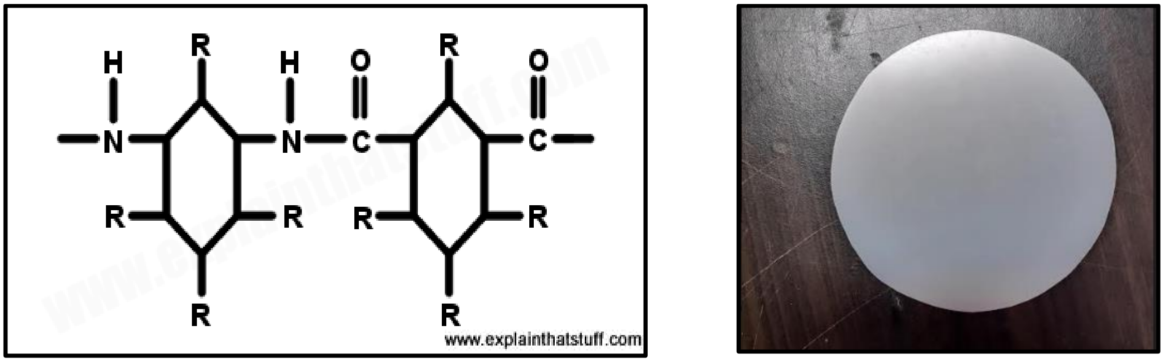
Application of LDPE

- General purpose containers.
- Very soft and pliable parts such as Snap-On lids.
- In the manufacture of flexible water pipes as well as in cable jacketing.
- For manufacturing bowls and buckets.
- Juice, milk or liquid packaging containers.
- Use in computer hardware, hard disk drives, screen cards and optical disc drives.

2.1.2 NOMEX

Nomex is the product of DuPont chemical company. It is firstly produced by Du Point in 1961. It is a heat and flame resistant textiles. Nomex is a family of aromatic polyamide fiber [11]. These polyamide fibers are the best class of heat-resistant and synthetic fibers. This type of fibers are made from two forms of aramid polymer. Nomex is meta-aramid fibers are made by polymerization of m-Phenylenediamine and dichloride of m-isophthalic chloride. Nomex is an insulating material that provides high dielectric strength, mechanical toughness, flexibility, and resilience. Because of its high mechanical strength and good electrical properties, Nomex is widely used as electrical insulation.

The density of NOMEX is 1.38 g/cm^3. The operating temperature of NOMEX is 220°C. But over 220°C temperature, the electrical and chemical properties is changed. Nomex is does not melt but decomposes at 400°C. Nomex has excellent resistance to sunlight, mildew, and aging.



(a) (b)

Fig. 2.2. (a) Chemical Structure of NOMEX and (b) LDPE sample.

The dielectric strength of NOMEX is 18 kV/mm. to 34 kV/mm. The dielectric constant of the Nomex sample is about 1.6 to 4.1.

Application of NOMEX

- Nomex is used as insulation for manufacturing of the windings of transformer and generator.
- Nomex is used for manufacturing the hybrid electric vehicles (HEV).
- Nomex paper is used in mobile phones, computers, LCD, Televisions, and Microwave, etc.
- Nomex is used as a filter in the exhaust filtration system for asphalt plants, cement plants, other industries.
- Nomex is used in Aerospace application.
- Nomex paper is used in electrical lamination of circuit board and transformer core.
- Nomex is used in the purpose of the production of racing and firefighting equipment.

2.1.3 Epoxy Resin

Epoxy resins are the product of epoxide functional group. Epoxy resins are the pre-polymers with low molecular weight or polymers with higher molecular weight. Epoxy resin is contains two groups of the epoxide.They are known as poly-epoxides, are a class of pre-polymers. Epoxy resins can be reacted with themselves by catalytic homo-polymerization. They are reacted with a wide range of co-reactants along with polyfunctional amines, acids (and acid anhydrides), phenols, alcohols, and thiols [12]. Epoxy resins are polymeric or semi-polymeric components.

(a) (b) (c)

Fig. 3.3. (a) Chemical structure of Epoxy Resin, (b) Pure Epoxy Resin and (c) Epoxy Resin with carbon dust impurities.

Applications of epoxy resin

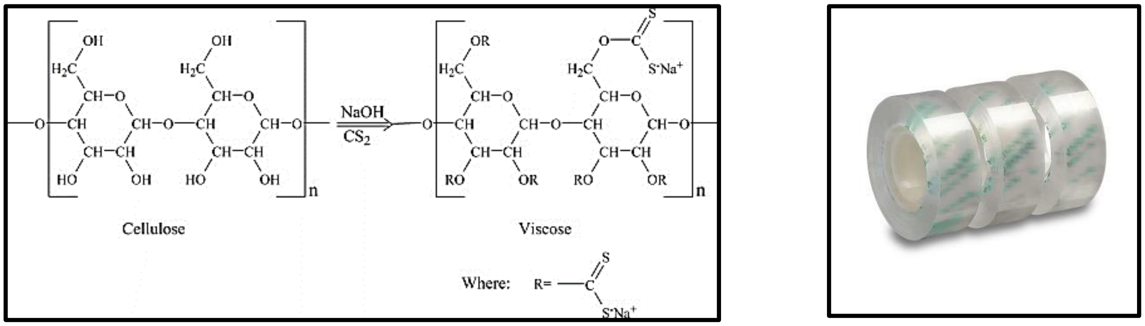
- Epoxy resins are used for paints and coatings purpose.
- Epoxy resins are used as adhesives for the construction of aircraft, automobiles, bicycles, boats, golf clubs, skis, snowboards, and other applications.
- In industrial purpose to improve efficiency and reduction of production cost, epoxy resin is used as the replacement of metal, wood and other traditional materials.
- Epoxy resins are used in construction of aircraft, automobiles, bicycles, boats, golf clubs, and other applications.
- Epoxy resin used in aerospace industry.
- For manufacturing of dry-type transformer epoxy resins used.
- Epoxy resin used in motors, generators, switchgear, bushing and insulators.

2.1.4 Cellophane Tape

Cellophane is a thin, transparent cellulose sheet.In the past, the tapes are manufactured from natural rubber. At present, most of the tapes are produced from synthetic materials.The backing for cellophane tape usually consists of cellulose acetate and a cellulose synthetic, that are coming from wood pulp or cotton seeds [13].

Cellophane tape is a high grade insulator. It is used in a wide variation of temperature range. The temperature range for the application of Cellophane tape is about-75° to +260°C. The density of

Cellophane tape is about 1.42 g/cm^3. The value of dielectric constant of cellophane tape is about 3.2 to 6.4.



(a) (b)

Fig. 2.4. (a) Chemical Structure of Cellophane and (b) Cellophane Tape.

Application of Cellophane Tape

- Cellophane tape is used for the food packaging industry.
- Cellophane tape is used in the joining place of two wire.
- Cellophane tape is used for an adhesive purpose.
- Cellophane tape is used as an insulation medium in the construction of a transformer.

CHAPTER-3

CONDITION MONITORING TECHNIQUES FOR TRANSFORMER INSULATION

Transformers has been a part of the electrical industry since the nineteenth century. The transformer is playing a major role for Generation, Transmission, and Distribution of Electrical Power. The power rating of the transformer is a few kVA to several of MVA. The replacing of the transformer is a cost-effective function. The cost transformer is sometimes goes up to several million dollars, it is depending upon the rating of the transformer. So the failure of the transformer causes of a huge amount of economic loss. A sudden failure in a running transformer may lead to a huge amount of economic loss but this failure also may be causes of the environmental damage, explosion, and sometimes it is dangerous for human life. The failure of the transformers are classified as an external and internal failure. The external failure is occurred due to causes of lightning strikes, switching over-voltages, system faults, system overload etc. The internal failure is occurred due to the causes of insulation degradation, PD, increased moisture content, overheating, and winding resonance etc.

3.1 Classification of Fault in Transformer which are Visually Detected

The visually detectable faults of a power transformer are classified into five different types according to IEC 60599 [14]. These faults are- (a) PDs which creates tiny carbonized punctures in the paper insulation, (b) low energy discharge that because of larger punctures in the paper insulation, (c) high energy discharges with power follow through this may occur by extensive carbonization, metal fusion, and possible tripping of a transformer, (d) for the thermal fault, the temperature below 300℃ the paper turn into brownish and higher than 300℃ evidenced by paper carbonization and (e) The thermal fault over 700℃ is indicated by oil carbonization, metal coloration or fusion.

3.2 Conventional Diagnostic Techniques

The *condition monitoring* is an important task for *maintenance* and *diagnosis* of power transformer. Sometimes the failure of a transformer is the cause of the interruption of the power supply, and also leads to a huge amount of replacement cost of equipment. So condition monitoring is very important for power transformer.

The oxygen and moisture in the operating environment along with thermal stress are the strong contributors for aging of insulation system of a transformer. During the aging period, the insulation of the transformer is degraded slowly. So, the electrical and chemical properties of the insulation are changes due to aging. Different methods are used for condition monitoring of the transformer to analyze the dielectric properties of the insulation system of a dry-type transformer [15].

In the case of a dry-type transformer, for detection of the overheating parts of a transformer or detection hotspot in transformer winding Overheating Monitoring System is used [19].

3.2.1 Electrical Diagnostic Technique

When a transformer is operating under high mechanical, electrical and thermal stress, then the degradation rate of insulation is increasing with transformer aging. Due to this degradation, the surface of the insulation is becomes breakable.These mechanical stress is occurred due to- (a) short-circuit currents, (b) thermal expansion and contraction, and (c) vibration of a transformer. The most common conventional electrical diagnostic techniques are- (1) *Insulation Resistance (IR) measurement and Polarization Index (PI) Test* (2) *dielectric dissipation factor (or tan δ) measurement* (3) *Breakdown Strength & Tensile Strength Measurement* and (4) *Measurement of Partial Discharge (PD).*

3.2.1.1 Insulation Resistance (IR) and Polarization Index (PI) Test

Insulation Resistance (IR) measurement is used to know about the condition of the insulation of motors, generators, transformers, and switchgear [15]. The measurement of IR must be made periodically from the new and good condition of the insulation, and always compare between the new values of IR with the previous value of IR. This comparison is gives information about the insulation, like- voltage withstands capability, and also the breakdown voltage of insulation. Insulation resistance testing is commonly measured directly in me ohms or can be calculated from applied voltage and leakage current measurements.

The main methods is used today for measuring insulation resistance are- (a) Spot reading test, (b) Time versus Resistance test, and (c) Stepped Voltage test.

The typical measurement of IR is taken over an interval of time (i.e. 1-minute intervals over 10 minutes) to generate a curve, this is called a Dielectric Absorption Curve [16]. The Polarization Index is the steepness of the curve at a given temperature, and it is defined according to the following equation,

$$\mathrm{PI} = \frac{\mathrm{R_{10}}}{\mathrm{R_1}} \tag{3.1}$$

Where, $\mathrm{R_{10}}$= Insulation resistance at 10 minutes

$\mathrm{R_1}$ = Insulation resistance at 1 minute

3.2.1.2 Breakdown Strength and Tensile Strength Measurement

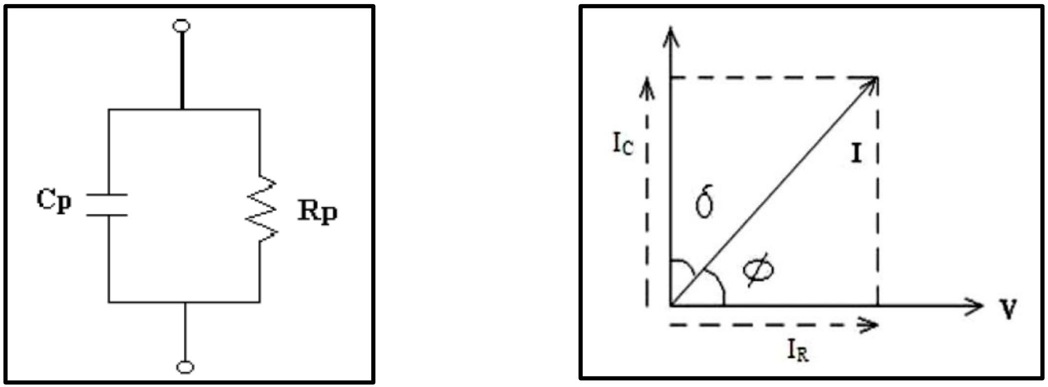
Breakdown tests are carried out to verify the voltage withstand capacity of the insulation system of an electrical machine by applying over rated voltage. The main objective of the breakdown test is used to check the reliability of the insulation. The mechanical strength of the insulation is determined by its tensile strength. The insulating material (Nomex film, LDPE, Epoxy Resin, and Cellophane Tape) is provides the electrical and mechanical strength. The tensile strength is define as the breaking strength per unit cross sectional area of the insulating material. The strength of the paper can be determined and the suitable of the insulation used can be predicted for suitable voltage level [17]. After the breakdown test the insulating properties of material are destroyed completely or the material cannot be used again.

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

The measurement of *Dielectric Dissipation Factor* ($tan\delta$) is one the most important diagnostic technique to check the condition of the insulation in a transformer [15]. *Dielectric Dissipation Factor* is provides information about aging of insulation. *Dielectric Dissipation Factor* is increase with aging of the insulation. Dielectric Dissipation Factor is an imaginary part in power system, it is resents the loss coefficient in high voltage equipment. *Dielectric Dissipation Factor* is the tangent angle between the capacitive current and total current.

Basically, all insulation is in capacitive in nature. But due to impurities (moisture, dust particle, etc.), the insulation is modeled by a series combination of resistance (R_p) and capacitor (C_p) or by a parallel combination of a resistor and a capacitor. For the analysis of insulation, it considers the parallel combination of the resistance (R_p) and capacitor (C_p). When the insulation is charge or a voltage is applied across the insulation, then a current will flow through it. This current is divided into two component (i) Resistive Current (I_R=V/R) and (ii) Capacitor Current (I_c=VωC).

Dielectric Dissipation Factor (tanδ) is defined as the ratio of the Resistive Current (I_R) and the capacitive current (I_c). The *Dielectric Dissipation Factor (tanδ)* is increases with the increment of the resistive component of leakage current. This increment of resistive current is due to the transformer insulation aging in hygroscopic atmospheric condition or pollutant atmosphere.



(a) (b)

Fig. 3.1. (a) Insulator model and (b) Phasor Diagram [15].

The expression of Dielectric dissipation factor ($tan\delta$) is given by

$$tan\delta = I_R/I_c = 1/\omega CR \qquad 3.2$$

Where ω is the frequency in rad/sec, C is the capacitance of the insulation in farad and R is resistance in ohms. High value of $tan\delta$ indicate the high amount of energy loss so for a good insulation material should be low value of $tan\delta$.

3.2.1.4 Measurement of Partial Discharge (PD)

The Partial Discharge (DP) is one type of electrical discharge, which isoccurred in the insulation between the conductors, as per IEC 60270:2000 [18]. Partial discharges generally is occurred, when the intensity of the electrical field at a certain location in the insulation exceeds the dielectric strength of the insulation.

Diagnosing health of insulation is very important to increase the reliability of high voltage equipment. For any insulation of the high voltage equipment. Partial Discharge (DP) is the sign of dielectric defects and also degradation of the insulationsystem of an electrical machine. The Partial Discharge (DP) has been lead the failure of thehigh voltage equipment. The earlier detection of DP sources of any high voltage transformer can prevent the failure of an electrical machine. The insulation of adry-type transformer is attacked by PD due to voids in insulation voids in insulation, delamination at insulation interfaces, cracking in insulation, metallic protrusions and maybe also manufacturing errors, incorrect design, etc. Another main reason is behind the appearing of PD in insulation is aging. This aging may be occurred due to the electrical, thermal, and mechanical stresses in operation.

Fig. 3.2. Partial Discharge on Dry-type Transformer.

3.2.2 Overheating Monitoring System

The low voltage terminal of a dry-type transformer is integrated with a temperature fuse, PTC (Positive Temperature Coefficient). The PTC is created a signal due temperature expansion of high operating current. This internal short circuit is occurred due to because of partial discharge of solid aged insulation. For this short circuit local hotspot is created in to the high voltage coils of a transformer [31]. Sometimes this local hotspots are cannot be detected by the PTC then this reason leading the first stage of breakdown the insulation of the transformer [19,32-33]. It is a very important factor of a transformer, isalways monitoring the temperature distribution in high voltage windings and also disconnect the transformer form the supply system to avoid a massive accident. This new technology, overheating monitoring system is protect the windings and the core of a dry-type transformer form the local overheating. The overheating monitoring system consists of a fiber optic sensor and a control unit. Under the abnormal condition, this system is signalizes an alarm.

CHAPTER-4

BASIC THEORY ON DIELECTRIC SPECTROSCOPY

The increased demand for transformers in utilities around the world has resulted in the growing interest in transformer insulation condition assessment and monitoring in recent years. The interest of condition assessment and monitoring transformer insulation because of, the transformer is the nucleus of electrical transmission and distribution system and it plays a vital role for reliable and trouble-free electrical power supply. During the operating period of a transformer, the insulation of a dry-type transformer deteriorates under a combination of thermal, electrical, mechanical, chemical and environmental stresses.

Nowadays for condition monitoring of a transformer condition-based maintenance (CBM) used in place of time-based maintenance (TBM) due to less operating cost [15]. The fundamental benefits of such techniques are that they are non-invasive or non-destructive, as well as terminal measurements.Dielectric response measurement is divided into two different way. One part of the Dielectric response measurement is Time Domain Spectroscopy (TDS) and another is Frequency Domain Spectroscopy (FDS). Polarization and Depolarization Current (PDC) and Recovery Voltage (RV) measurements are the two main techniques in Time Domain Dielectric Response analysis [30].

When a dielectric media is under on d.c. field then a current flows through on it. This current of two parts, one is the conduction current and another polarization current.

4.1 Dielectric Time Domain Spectroscopy

The dielectric is considered to be homogenous and isotropic. When an electric field is applied to the dielectric externally, then the process of polarization starts [20-21]. In a vacuum insulated electrode arrangement the flux density D is proportional to electric field vector E,

$$D = \varepsilon_0 E \tag{4.1}$$

If the vacuum medium is exchanged by a homogeneous isotropic medium the polarization, P should consider in the above relation,

$$D = \varepsilon_0 E + P \tag{4.2}$$

Where,

$$P = \chi \varepsilon_0 E \tag{4.3}$$

Here χ is the electric susceptibility of the material.

If a time-varying voltage generates the electrical field, then equation 4.3 can be written as,

$$P(t) = \chi(t)\varepsilon\ E(t) \qquad 4.4$$

Similarly the electric flux density D(t) can be expressed as,

$$D(t) = \varepsilon_0 E(t) + P(t) = \varepsilon_0 (1 + \chi(t))E(t) \qquad 4.5$$

The polarization process, P(t), within the dielectric medium is the combined effect of all the polarization mechanisms. The electronic and ionic polarization are very fast among all the polarization mechanism. These two are active in high frequency range $(10^8\ Hz\ to\ 10^{18}\ Hz)$.As all the polarization processes are finite in magnitude, they will settle at long times and finally becomes static i.e. P(t→∞)=P_S. When a step voltage Vd.c. is applied to charge free dielectric medium the polarization vector P(t) maintains as monotonically increasing profile.

This polarization vector P(t) can be expressed as by the following equation,

$$P(t) = (P_S - P_\infty)g(t - t_0) + P_\infty \delta(t - t_0) \qquad 4.6$$

Where $\delta(t-t_0)$ is dirac delta function which is considered for the fast polarization processes and $g(t-t_0)$ is monotonically increasing function with time, is considered for the interfacial polarization process.

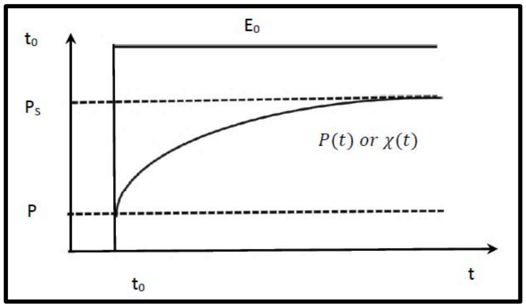


Fig. 4.1. Variation of Polarization with voltage and time.

Where,

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

$$g(t - t_0) = 0\ for\ all\ t \leq t_0$$

$$g(t - t_0) = 1\ when\ t \to \infty \qquad 4.7$$

$$P(t) = \varepsilon_0 [\chi_\infty + (\chi_S - \chi_\infty)g(t - t_0)]E(t) \qquad 4.8$$

Since susceptibility is related to the permittivity of the dielectric medium so the equation (8) can be expressed as,

$$P(t) = \varepsilon_0[(\varepsilon_\infty - 1) + (\varepsilon_S - \varepsilon_\infty)g(t - t_0)]E(t) \qquad 4.9$$

In general, a material cannot polarize instantaneously in response to an applied field. The polarization is a convolution of the electric field at previous times with time dependent susceptibility. So this P(t) can be expressed by,

$$P(t) = \varepsilon_0(\varepsilon_\infty - 1)E(t) + \varepsilon_0 \int_{-\infty}^{t} f(t - \tau)E(\tau)d\tau \qquad 4.10$$

Where f(t) is dielectric response function [22-23]. It is monotonically decrease function. It is expressed by,

$$f(t - \tau) = (\varepsilon_0 - \varepsilon_\infty)\frac{dg(t-\tau)}{dt} \qquad 4.11$$

Therefore under an electric field E(t) total current density J(t) in the dielectric medium can be represented by,

$$J(t) = \sigma_0 E(t) + \varepsilon_0\varepsilon_\infty \frac{\partial E(t)}{\partial t} + \frac{\partial P(t)}{\partial t} \qquad 4.12$$

where, σ_0 is d.c. conductivity of the dielectric medium and ε_0 is the permittivity in free space. For a homogenous and isotropic dielectric medium, the total current through the dielectric medium can be written as,

$$i(t) = C_0[\frac{\sigma}{\varepsilon_0}U(t) + \varepsilon_r \frac{dU(t)}{dt} + \varepsilon_0 \frac{d}{dt}\int_0^t f(t - \tau)U(\tau)d\tau \qquad 4.13$$

Where,

C_0 is geometric capacitance of that insulating material.

The first term of equation 4.13 is represents the d.c. conductivity of the sample and other parts represents the different polarization process occurring in the sample. Equation 4.13 is valid for both single and multiple dielectric materials in series or in parallel.

4.2 Polarization and Depolarization Current (PDC) Measurement

For the measurement of PDC, a d.c. voltage is applied to the dielectric medium. Due to this applied voltage or field, the dipoles of the dielectric medium are trying to align in the direction of the applied voltage or field then the process of polarization initiate. At the time of polarization, a current flows through the dielectric medium is known as 'Polarization Current'. The nature of this current is continuously decreasing. The process of polarization stops when all the dipoles of the insulation are oriented to the applied field. When the process is stopped, only the conduction current flows through the surface of the insulation and polarization current reaches zero. The value of conduction current depends upon the d.c. resistance of the insulating materials. For measurement of depolarization current at these time the terminal of the insulation medium is under short-circuited and the voltage source is removed. At this time the stored energy (or charge) during polarization of the insulating medium starts releasing and the dipoles of the insulation trying to move their original position. The nature of depolarization current is reversed form the polarization current also continuously decreasing and finally, it goes to zero after a long time. This is phenomena for depolarization current [20].

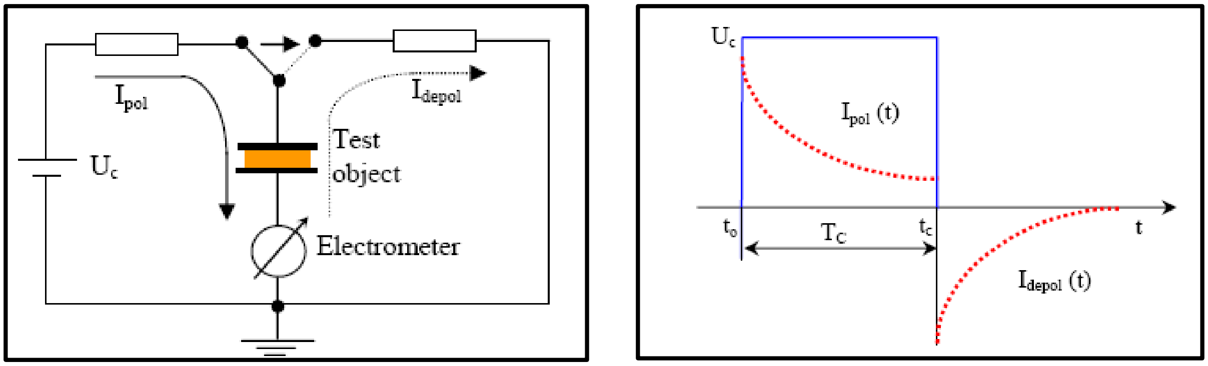


Fig. 4.2. (a) PDC measuring circuit and (b) Nature of PDC currents [20].

Fig. 4.2 (a) shows that the experimental circuit for PDC measurement. If a ripple and noise free d.c. voltage V_{dc} is applied to the insulation materials then polarization current is flowing through the body of the materials, it can be expressed by,

For $0 < t < t_c$

$$i_{pol}(t) = C_0 V_{dc}[\frac{\sigma_0}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t)] \quad 4.14$$

During the time period t_c in the equation 4.14 the insulating material is under a field and the material gets charged, this period of time is represented charging time. The first part of the equation is conduction current. The part f(t) is the dielectric response function.

After the time period t_c the terminal of the insulating material is under short circuited and the voltage source is removed. Therefore, after the time t_c the insulation material begins to release the stored energy then the dipoles of the material try to move their original position. The dipoles are reoriented when the depolarization current is flowing through the body the insulating material. The depolarization current express by,

$$i_{depol}(t) = -C_0 V_{dc}[f(t) - f(t + t_c)] \quad 4.15$$

For $0 < t < \infty$

Therefore the value of f(t+t_c) is less compare to f(t) for a long charging time t_c and can be neglected. As a result the equation for depolarization current is rewritten as,

$$i_{depol}(t) = -C_0 V_{dc} f(t) \quad 4.16$$

For $0 < t < \infty$

The dielectric response function can be obtained from equation 4.16 once it is measured.

4.2.1 Flowchart for PDC Measurement [15]

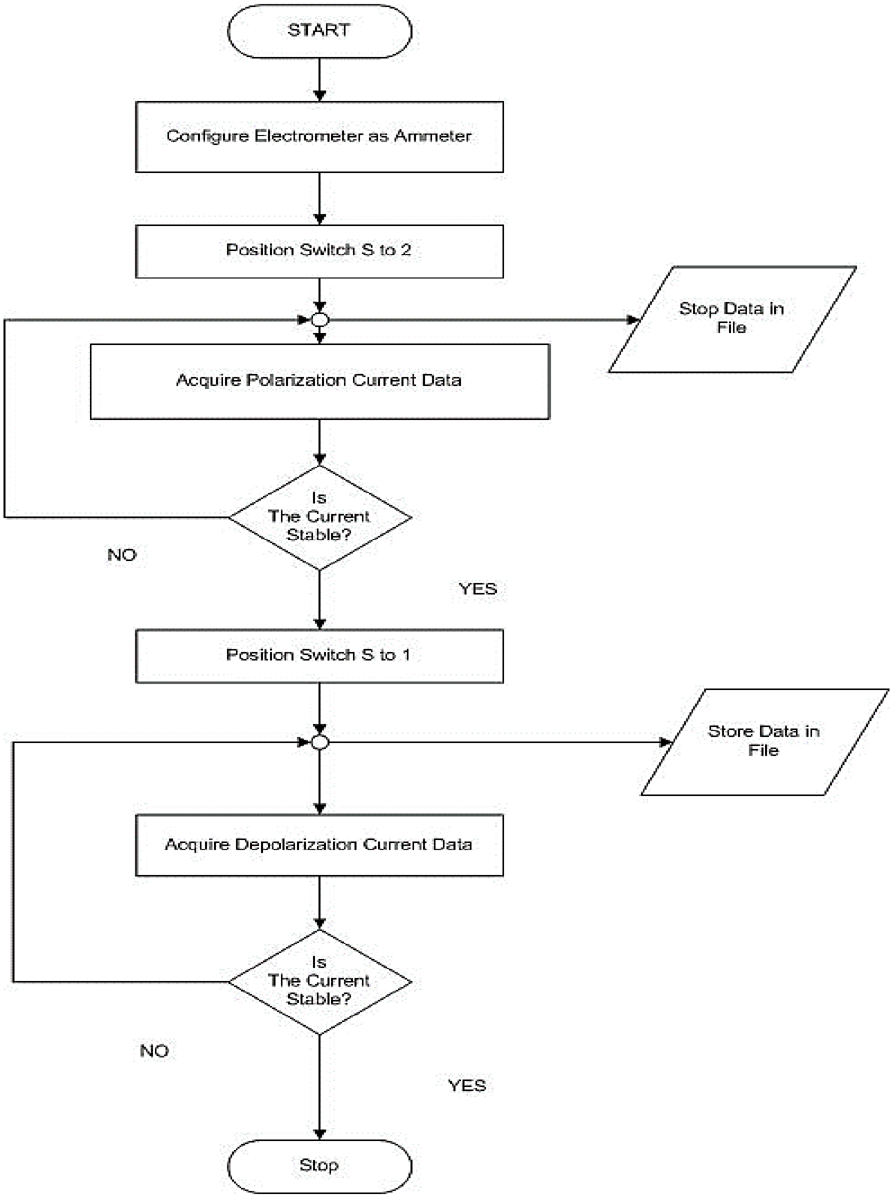


Fig. 4.3. Flowchart for PDC measurement.

4.2.2 Advantages of PDC Measurement

- Other diagnostic quantities like activation energy and polarization spectra can be calculated from PDC measurements directly.
- It provides very fast response at low frequencies with good accuracy.

4.3 Dielectric Frequency Domain Spectroscopy

Although time domain spectroscopy (TDS) is widely used for the condition monitoring of insulation of the transformer, some limitation in using TDS. The main limitation of TDS are, (i) a high value of voltage source is required and (ii) for the high value of voltage source having some noise. To avoid these difficulties now a day dielectric response in frequency domain is used for condition monitoring for the insulation of transformer. In this test AC voltage is applied for determination of tan delta or dissipation factor. The insulation is energized under the application of pure sinusoidal excitation voltage, polarization process starts and a current flows through the insulating medium. The test (FDS) is done with a variable load frequency (VFL) in a range between 0.1 MHz to 10 kHz. The test basically relates to impedance measurement at the variable frequency and sometimes variable voltage. This measured impedance is helped for the estimation of power factor, capacitance, dissipation factor, permittivity, etc.

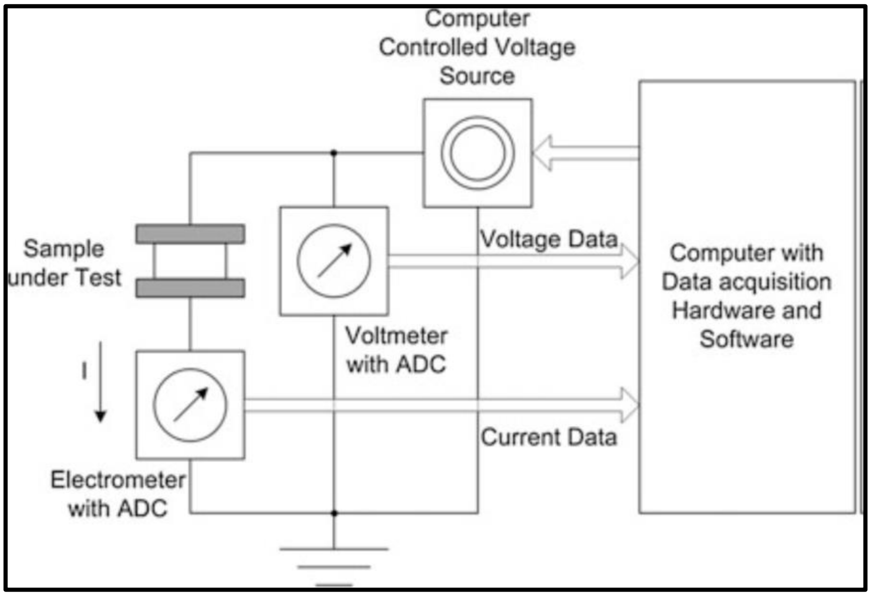


Fig. 4.4. FDS Measurement Circuit [15].

An analytic approach to convert time domain to frequency domain is Laplace transformation technique. Using Laplace to Fourier transform we can rewrite the equation 4.14,

$$I(s) = C_0[\frac{\sigma_0}{\varepsilon_0}V(s) + \varepsilon_\infty sV(s) + sF(s)V(s)] \quad 4.17$$

Put $s = j\omega$ in the equation 4.17,

$$I(\omega) = C_0[\frac{\sigma_0}{\varepsilon_0}V(\omega) + j\omega\varepsilon_\infty V(\omega) + j\omega F(\omega)V(\omega)] \qquad 4.18$$

Here, F(ω) is the Fourier transform of the dielectric response function f(t). F(ω) is actually related to the susceptibility of the dielectric media as represented in equation 4.19,

$$F(\omega) = \chi(\omega) = \chi'(\omega) - \mathrm{j}\chi''(\omega) \qquad 4.19$$

$$= \int_0^\infty f(t)\exp(-j\omega t)dt$$

Here $\chi(\omega)$represents the complex susceptibility of the dielectric sample. $\chi'(\omega)$ is the real and $\chi''(\omega)$is the imaginary part of the $\chi(\omega)$. Therefore the resultant dielectric response current, I(ω) can be written as,

$$I(\omega) = j\omega[C'(\omega) - C''(\omega)]V(\omega) \qquad 4.20$$

From equation 4.20, C(ω) is the frequency dependent complex capacitance of insulating medium. The frictional loss due to interactions among the dipoles under sinusoidal excitation, is represented by the imaginary part $C''(\omega)$. The energy storage in the dielectric medium during polarization is represented by the real part $C'(\omega)$.

The dielectric dissipation factor is defined as the ratio of energy loss to the energy storage in dielectric media, can be represented as,

$$tan\delta(\omega) = \frac{\frac{\sigma_0}{\omega\epsilon_0}+\chi''(\omega)}{\epsilon_\infty+\chi''(\omega)} = \frac{C''(\omega)}{C'(\omega)} \qquad 4.21$$

So dielectric loss factor ($tan\delta$) of the dielectric is an angular frequency depended function of applied voltage.In FDS test pure sinusoidal voltage with a wide range of frequency (0.1 MHz – 10 kHz) is applied to the dielectric material to determine the dielectric characteristics of the material over the entire frequency range so it is possible to estimate relationships between different dipolar groups [24-25].

4.3.1 Advantages of FDS Method

- Dielectric frequency domain spectroscopy (FDS) enables measurements of the composite insulation capacitance, permittivity, conductivity (and resistivity) and loss factor in dependence of frequency.

- The real and imaginary part of the complex capacitance and permittivity can be separated
- This nondestructive technique also provides the moisture content in the solid insulation material and C-ratio diagnostic quantity.
- FDS has better noise performance and separates the behavior of polarizability (χ') and losses (χ'') of a dielectric medium.

4.4 Debye Model of Linear Dielectric

Due to electrical, thermal and environmental stresses, the condition of the insulation system a transformer deteriorated day by day. The electrical and chemical properties of insulation changes due to the effect of moisture and aging of insulation [35]. These factors are the main reason behind the insulation failure of any high voltage equipment. To get the relationship between measured dielectric parameters and the fundamental polarization processes we can simulate the dielectric processes in the form of some circuit. During polarization and depolarization process different relaxation mechanisms appear in various part of the insulation system.

The polarization process can be described as a process of energy storage in the form of various time constants. So we can say that polarization and depolarization current curves are the summations of different exponential curves of different time constant and magnitude. Therefore the insulation system of power transformer consists of the various number of series R-C branches in parallel. This insulation system can be modeled by the Debye model [26-27] as shown in the figure.

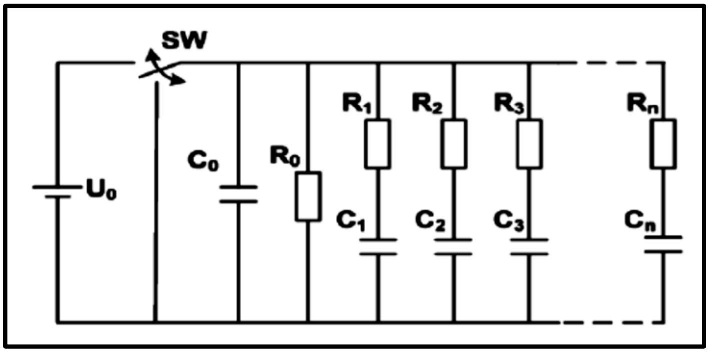


Fig. 4.5. Equivalent circuit model considering a linear dielectric.

Here C_0 is the geometric capacitance, R_0 is the insulation resistance. Parallel R-C branches represents the different dielectric relaxation processes.

4.4.1 Calculation of Branch Parameters of Debye Model from Depolarization Current

A model for insulation analysis can be established from the measured PDC current. The model recommends a circuit equivalent to the time domain response measured. The measured current consists of three parts that can be considered as equivalent parameters of the circuit. The first part of the measured current represents d.c. conductivity of the dielectric, is modeled as a resistance in parallel to the applied step voltage. The second part of the polarization current is an impulse function represents the fast polarization process, is constructed as a capacitor in parallel to the applied voltage. The last part is considered as a reflection of the mechanism of interfacial polarization normally measured in the power frequency range as a parallel combination of series R-C branches with the applied d.c. voltage [26]. Therefore the depolarization current curve is the summation of different exponential curves with various magnitude and time constants. By fitting the depolarization current curve with the following equation, the individual branch parameters ($R_i - C_i$) with the corresponding time constant $\tau_i = R_i * C_i$can be estimated,

$$i_{depol}(t) = \sum_{i=1}^{n} A_i \,.\, e^{(-t/\tau_i)} \qquad 4.22$$

$$A_i = V_{dc}.\left(\frac{1-e^{-t/\tau_i}}{R_i}\right) \qquad 4.22$$

Thus the branch parameters of the one with the largest time constant can be calculated by the exponential curve fitting method from the final part of the depolarization current. Once the exponential component is found due to the largest time constant branch, the response to all other branches with significantly smaller time constants is subtracted from the original depolarization current. The same process is continued to get the branch parameters of the other branches having shorter time constants in the descending order.Once the values of A_i and τ_i of different branches are obtained, the values of R_i and C_i can be found out easily and the equivalent Debye model can be constructed.

CHAPTER-5

EXPERIMENTAL SETUP

This chapter describes about the experimental setup.

5.1 Equipment Used in the Thesis

Several number of equipment were employed for this experiment. The High Tension Laboratory of Jadavpur University hosts all the equipment and instruments for this experiment. The major types of equipment that are used for this experiment elaborated as follows.

5.1.1 Setup used for Measurement of Dielectric Dissipation Factor

STS 3000 & TD 5000 is used to perform *Dielectric Dissipation Factor (or tan δ)* and *Capacitance* measurement for Power Transformer and CB, etc. shown in below Fig. 5.1(a) and Fig. 5.1(b).This is a fully automaticinstrument.This instrument is performs a wide frequency range 15Hz to 500Hz. The output voltage level of this instrument is up to 12kV.

(a) (b)

Fig. 5.1 (a) ISA STS 3000 and (b) TD5000.

5.1.2 MEGGER

Megger MIT520 is used to measure of Insulation Resistance (IR) of dielectric materials, shown in Fig. 5.2(b). It can be measure the Insulation Resistance up to 10 TΩ. It is also used for Polarization Index (PI), Dielectric Absorption Ratio (DAR), Dielectric Discharge (DD), Step Voltage (SV) and Ramp test of insulation. Megger MIT520 is provides 5kV d.c. voltage supply.

(a) (b)

Fig. 5.2. (a) Setup to Insulation Resistance Test and (b) MEGGER MIT520.

5.1.3 Digital Oscilloscope

RIGOL DS1102E digital oscilloscope is used for acquisition and store all polarization and depolarization current data shown in Fig. 5.3. The bandwidth of this digital oscilloscope is 100 MHz.The maximum real-time sample rate of this digital oscilloscope is about 1 GSa/s. The memory depth of RIGOL DS1102E is 1Mpts. This digital oscilloscope fitted with a5.6” TFT QVGA (320X240) with 64K color LCD backlit display.

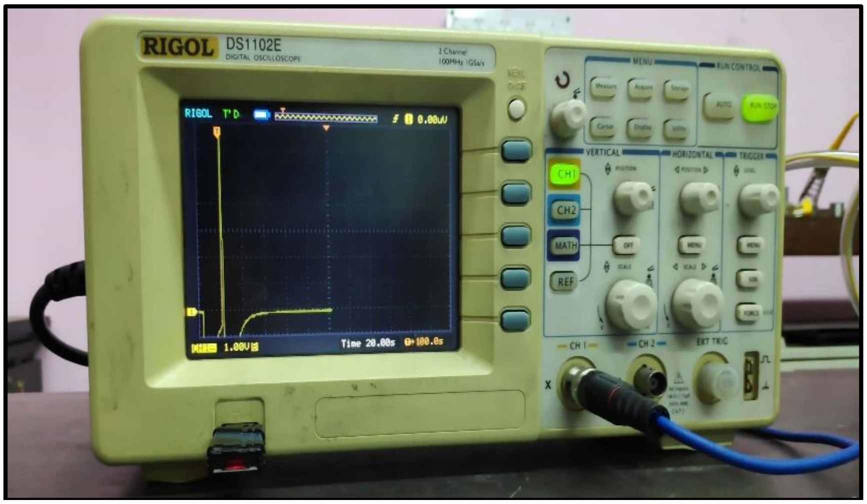


Fig. 5.3. RIGOL DS1102E Digital Oscilloscope.

5.1.4 Dielectric Response Analyzer

Dielectric Response Analyzer (or an amplifier) is used to determine the condition of high voltage insulation systems like in power transformers, cables, bushings, and generators, shown in Fig. 5.4. For dielectric response analysis of any solid insulation, it works effectively.In this present work, it was used for Polarization Depolarization Current (PDC) measurement. It is attached with a resistance box. It can successfully measure a Nano ampere range of current.

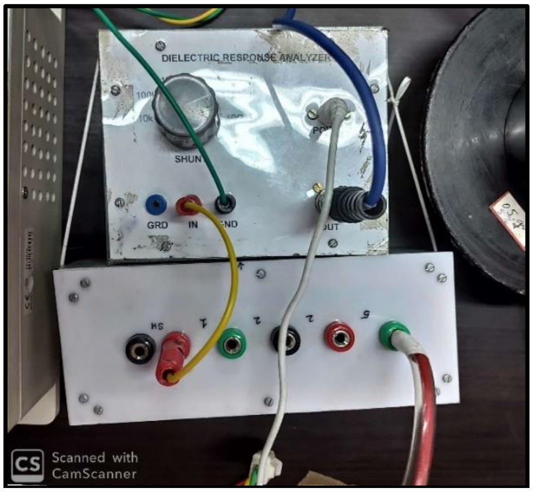


Fig. 5.4. Dielectric Response Analyzer**.**

5.1.5 Heating Oven

The heating oven is used for maintains a controlled temperature in an isolated chamber, shown in Fig. 5.5. The heating oven is also used for shielding purpose of the sample. The heating oven is used as removal of the presence of moisture in the insulation. It is used for the thermal aging purpose of insulation. By using the heating oven experiments was again done at different temperature. In this case, the heating oven has controlled the temperature of the chamber.

Fig. 5.5. Heating Oven.

5.2 Experimental Setup

After the collection of all the sample, PDC data was carried out with the help of manually controlled measuring device named as Dielectric Response Analyzer. All PDC experiment has been done into a heating oven with different temperature. In Fig. 5.6 it is seen the experimental setup for PDC measurement.

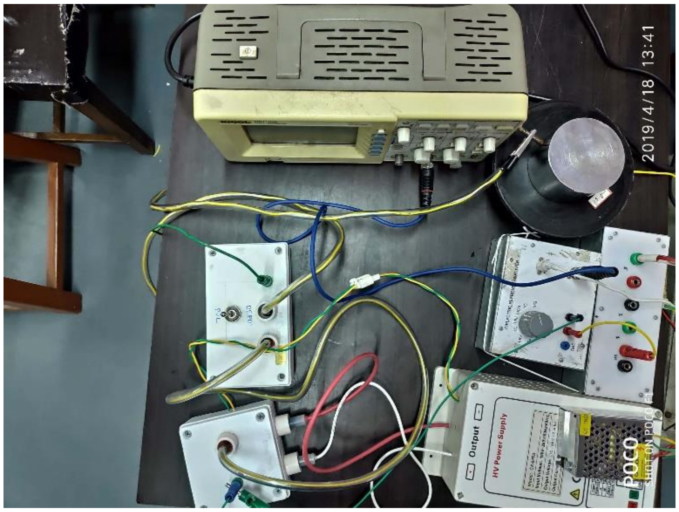


Fig. 5.6. Experimental Setup for PDC measurement.

The different insulating sample cutouts and are placed between two clean copper electrodes. Thereafter the whole setup was placed inside the heating oven. The heating oven is used to de-moisturize the samples as well as to have variation of temperature. Then a d.c. voltage is applied to the sample and get the information about the polarization current. After that when the d.c. source is disconnect from the sample then the sample goes to short circuit and provides the information about depolarization current data.

CHAPTER-6

RESULTS AND DISCUSSIONS

In this chapter, discussions about measuring PDC data and consequent analysis of the obtained data for investigation of the condition of different insulation samples under temperature variation is done.The Dielectric Dissipation Factor is also determined with the help of ISA 3000. The activation energy of the insulation and the branch parameter of the Debye model were determined from the PDC recorded data.

6.1 Experimental parameters of Polarization and Depolarization Current of LDPE Insulation

This section discusses about the various parameters of Polarization and Depolarization current of LDPE insulation.

The charging time (t_c) is kept at 55s throughout the experiment. The Input d.c. voltage (V_s) is set at 1800V.

6.1.1 Sample Description

This section explains the dimension and electrical properties of the sample.

a) Dimension: In this experiment 5cm*5cm square size sample is used for PDC measurement. The typical thickness of the sample is about 5mm.
b) Dielectric Strength: The dielectric strength of LDPE insulation in the range 20 kV/cm to 160 kV/cm.
c) Value of Insulation resistance (R_0)**:** 2.04 GΩ**.**
d) Value of Geometric Capacitance (C_0)**:** 33.6 pF.

6.1.2 Nature of Polarization and Depolarization Current

This section discusses about the nature of recorded PDC data. Fig. 6.1 shows the variation of the polarization current in LDPE insulation with different temperature.

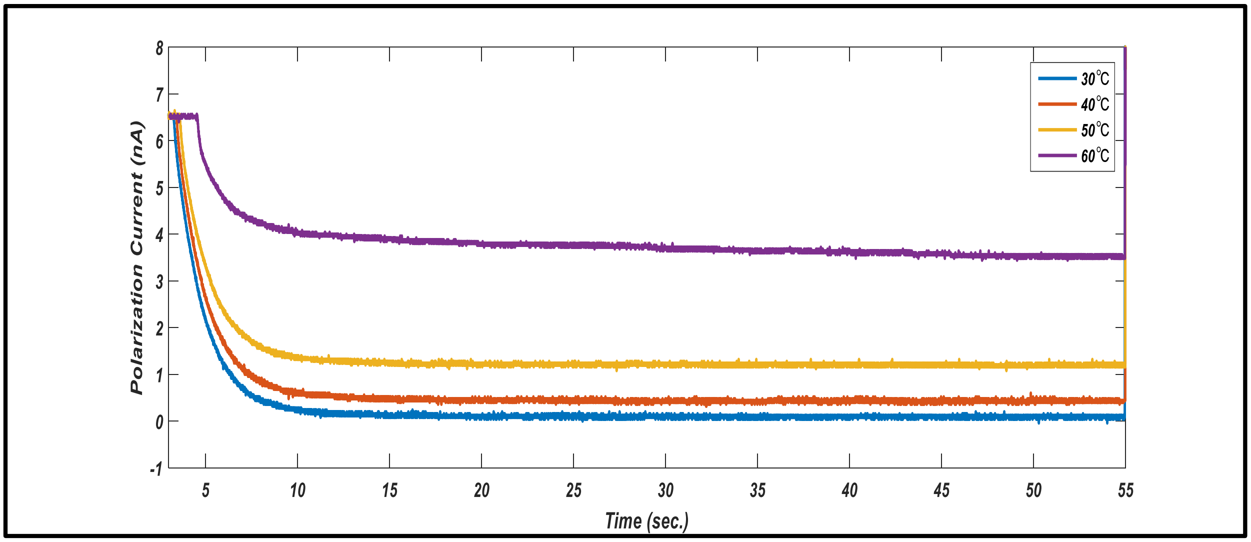


Fig. 6.1. Variation of Polarization current in LDPE insulation with temperature.

In Fig. 6.2 it is seen the variation of depolarization current in LDPE insulation with different temperature.

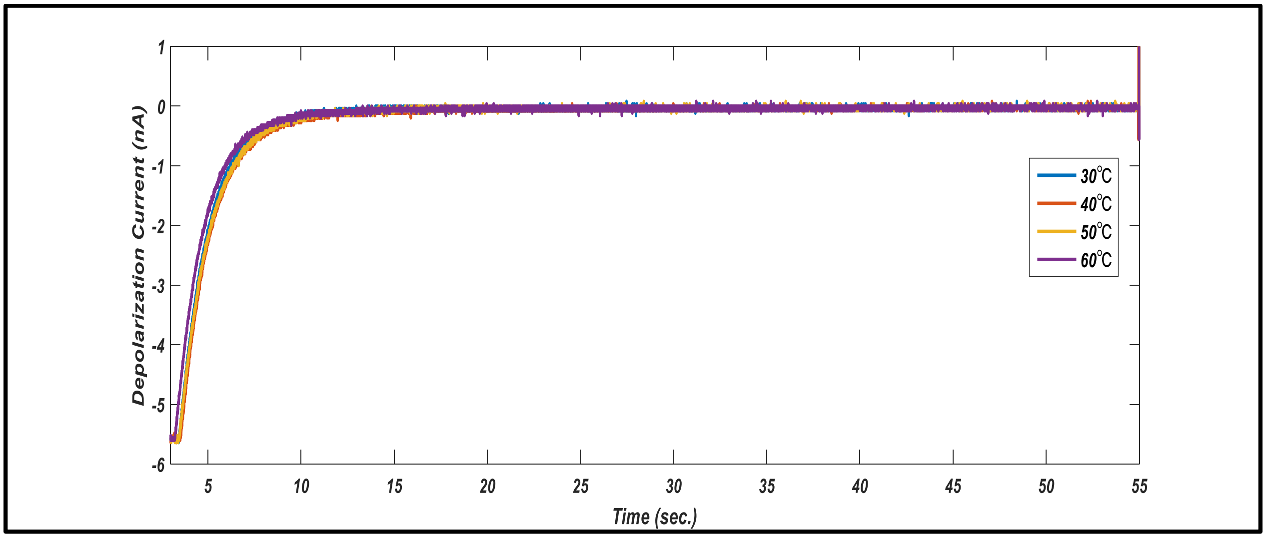


Fig. 6.2. Variation of Depolarization current in LDPE insulation with temperature.

The polarization current is recorded in the temperature range of 30°C to 60°C, shown in the Fig. 6.1. It is observed that the value of the polarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature. Due to increase in temperature, it can be observed from Fig. 6.2 that the conduction current also increases.

In Fig. 6.2 it is seen the nature of the depolarization current curve in LDPE sample with temperature variation. The characteristics of depolarization current curve are almost same as explained in Fig 6.1.

6.1.3 Estimation of Branch Parameters from DEBYE model

From the depolarization current curve of each sample, the branch parameters like resistance, capacitance and time constant of each branchare determined by using the procedure that was discussed in section 4.4.

Table 6.1 Derived Parameters of DEBYE model for LDPE insulation

SL No	***Tempe rature*** (°C)	***Branch resistance***		***Branch capacitance***		***Time constant***	
		R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	τ_1 (s)	τ_2 (s)
1	30°C	3.44E+10	3.19E+12	4.45E-11	2.19E-12	1.530	6.986
2	40°C	3.37E+10	3.43E+12	4.55E-11	6.71E-12	1.533	23.015
3	50°C	2.74E+10	4.58E+12	6.23E-11	1.14E-11	1.707	52.212
4	60°C	4.90E+10	2.12E+12	3.88E-11	3.65E-11	1.901	77.380

6.1.4 Variation of Time Constant with Temperature

The insulation system of a power transformer is consists of the various numbers of series R-C branches in parallel. This series R-C branch is represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant τ_i=R_i*C_i can be estimated. For solid insulating material, the dielectric relaxation time is smaller than oil or oil-paper insulation. The number of the branch parameter is lesser for solid insulating materials. Fig. 6.3(a) shows that Variation of Time Constant of Branch-I with temperature of LDPE insulation using MATLAB curve fitting tool. The curve fitting function is:

Linear model Poly3:

*f(x) = p1*x^3 + p2*x^2 + p3*x + p4*

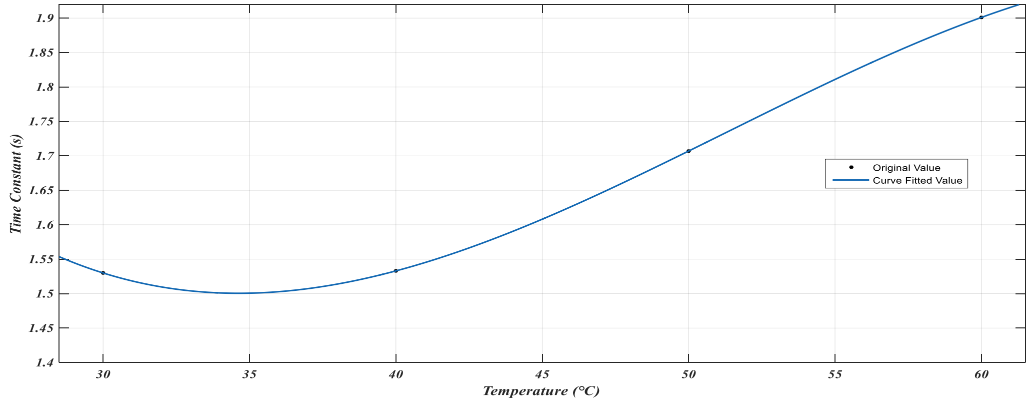
Coefficients:

p1 = -2.517e-05

p2 = 0.003875

p3 = -0.1778

p4 = 4.057



(a)

Fig. 6.3 (b) shows that variation of time constant of branch-II with a temperature of LDPE insulation using MATLAB curve fitting tool. The curve fitting function is:

Linear model Poly3:

*f(x) = p1*x^3 + p2*x^2 + p3*x + p4*

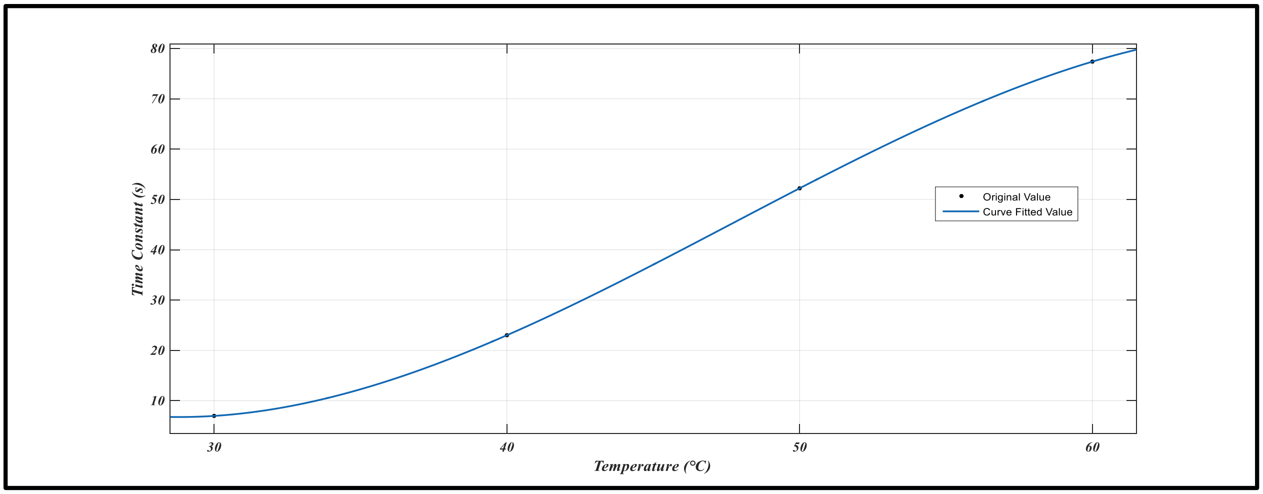
Coefficients:

p1 = -0.002866

p2 = 0.4098

p3 = -16.48

p4 = 209.9



(b)

Fig. 6.3. (a) shows the Variation of Time Constant of Branch-I and (b) shows the Variation of Time Constant of Branch-II

The variation of time constant for branch-i and the variation of time constant for branch-II are shown in the fig. 6.3(a) and fig. 6.3(b) respectively.

The Fig. 6.3(a) shows that the variation of the time constant for branch-I. It can be informed from the curve, the time constant of the LDPE sample increase with the increase in temperature.

The Fig. 6.3(b) shows that the variation of the time constant with temperature for branch-II.

6.1.5 Variation of Dielectric Dissipation Factor with Applied Voltage

The experiment, determination of dielectric dissipation factors can be performed at room temperature with the help of ISA STS 300 LIGHT & TD5000. Fig. 6.4 shows that the variety of Dielectric Dissipation Factor with Applied Voltage in LDPE insulation. In 6.4 it is seen the dielectric dissipation factor plotted with respect to applied voltage using MATLAB curve fitting tool. The smoothing spline tool is used.

$f(x)$ = piecewise polynomial computed from p

Smoothing parameter:

p = 1.5657279e-06

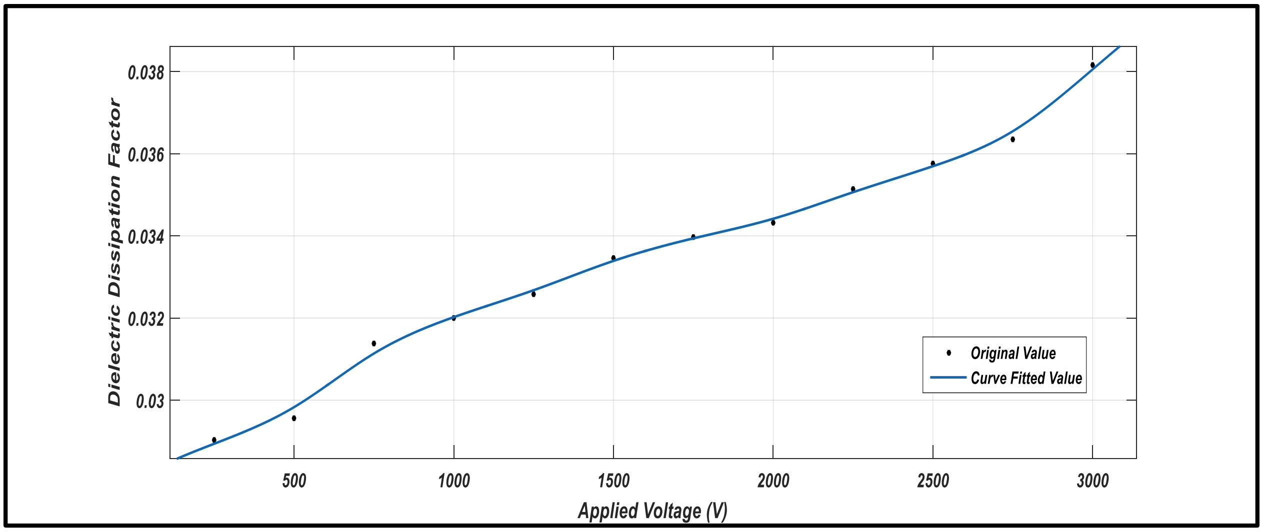


Fig. 6.4 Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of LDPE insulation increases with the increase in applied voltage.

6.2 Experimental parameters of Polarization and Depolarization Current of Thick NOMEX Insulation

This section discusses about the various parameters of Polarization and Depolarization current of thick NOMEX insulation.

The charging time (t_c) is kept at 220s throughout the experiment. The Input d.c. voltage (V_s) is set at 3000V.

6.2.1 Sample Description

This section explains the dimension and electrical properties of the sample.

a) Dimension: In this experiment circle shaped sample with 12cm diameter is used for PDC measurement. Also, the thickness of the sample is about 0.2mm.

b) Dielectric Strength: The typical dielectric strength of NOMEX insulation in the range 18 kV/mm to 34 kV/mm

c) Value of Insulation resistance (R_0)**:** 237 GΩ

d) Value of Geometric Capacitance (C_0)**:** .541 Pf

6.2.2 Nature of Polarization and Depolarization Current

This section explains the nature of PDC curve. Fig. 6.5 shows that the variation of the polarization current in NOMEX insulation with different temperature.

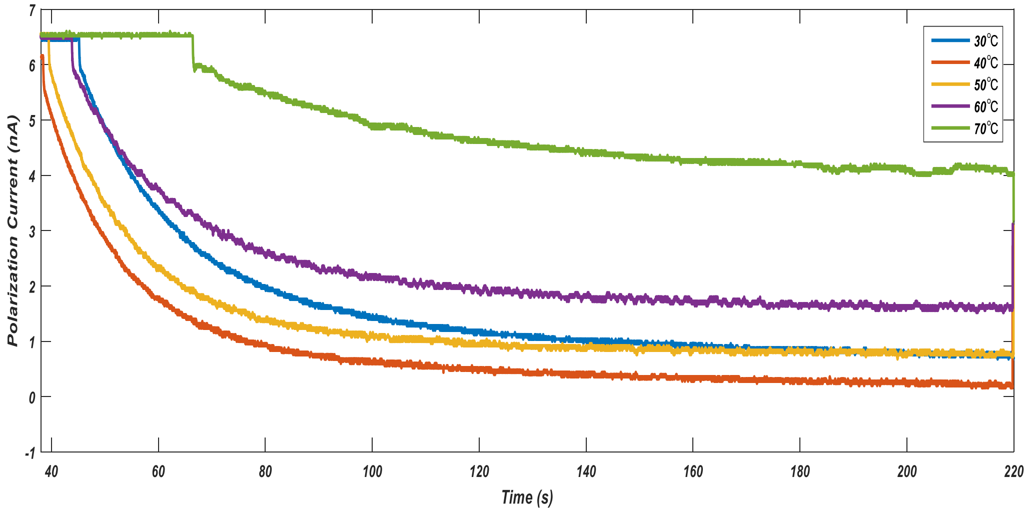


Fig. 6.5. Variation of Polarization current in NOMEX insulation with temperature.

Fig. 6.6 shows that the variation of depolarization current in NOMEX insulation with different temperature.

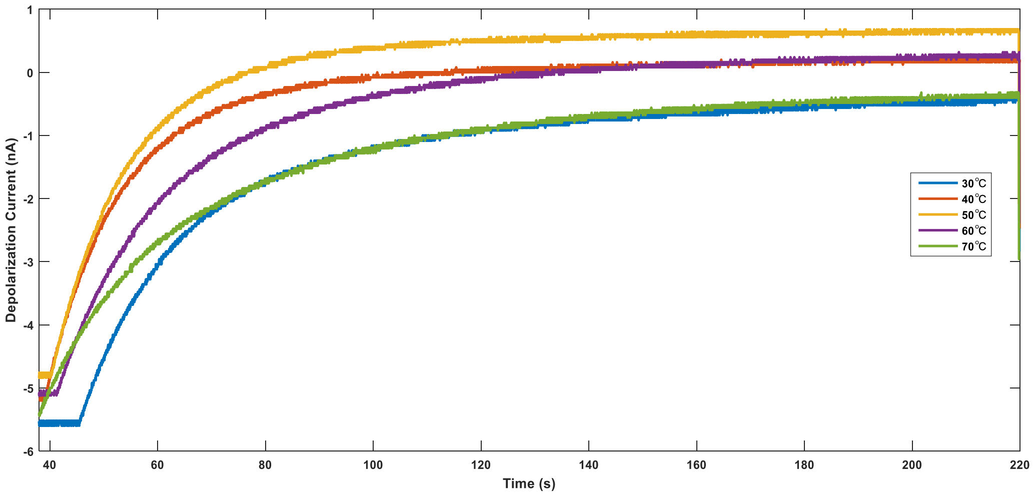


Fig. 6.6. Variation of depolarization current in NOMEX insulation with temperature.

In Fig. 6.5 it is seen the polarization current is recorded in the temperature range of 30℃ to 70℃. It is observed that the value of the polarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature. Due to increase in temperature, it can be observed from Fig. 6.5 that the conduction current also increases.

Fig. 6.5 shows that some spikes are there in the polarization curve of higher temperature. This due to the effect of temperature and as well as from the heating oven that affects the measuring system.

Fig. 6.6 shows that the nature of the depolarization current curve in Thick NOMEX sample with temperature variation. The characteristics of the depolarization current curve are almost same as explained in Fig. 6.5.

6.2.3 Estimation of Branch Parameters from Debye model

From the depolarization current curve of each sample, the branch parameters like resistance, capacitance and time constant of each branch are determined by using the procedure as discussed in the previous section

4.4. Table 6.2 Derived Parameters of DEBYE model for Thick NOMEX insulation

SL No	***Temperature (℃)***	***Branch resistance***		***Branch capacitance***		***Time constant***	
		R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	τ_1 (s)	τ_2 (s)
1	30℃	5.28E+10	3.47E+10	1.91E-10	4.40E-10	10.084	15.268
2	40℃	3.41E+10	9.68E+10	4.30E-10	2.60E-10	14.663	25.168
3	50℃	1.45E+10	8.54E+10	7.54E-10	1.28E-10	10.802	10.932
4	60℃	1.40E+11	5.70E+10	1.87E-10	8.13E-10	26.18	46.341
5	70℃	8.53E+10	3.75E+11	1.81E-10	1.79E-10	15.439	67.125

6.2.4 Variation of Time Constant with Temperature

This section explains the time constant variation of thick NOMEX sample. The insulation system of a power transformer is consists of the various numbers of series R-C branches in parallel. This series R-C branches are represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant $\tau_i=R_i*C_i$ can be estimated. For solid insulating material, the dielectric relaxation time is smaller than oil or oil-paper insulation. So, the number of the branch parameter is lesser for solid insulating materials.

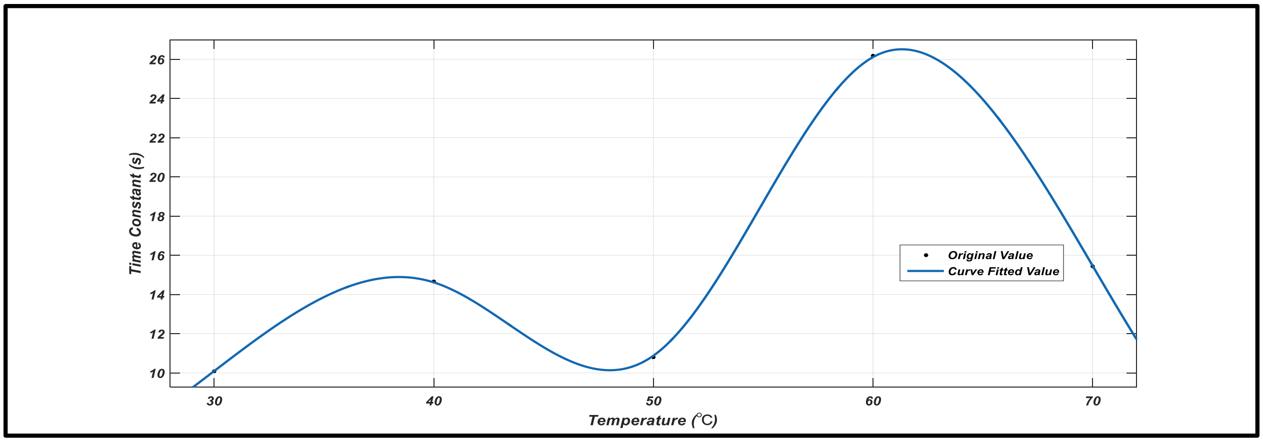
The Fig. 6.7 (a) shows that Variation of Time Constant of Branch-I with temperature of NOMEX insulation using MATLAB curve fitting tool. The curve fitting function is:

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 0.68771737



(a)

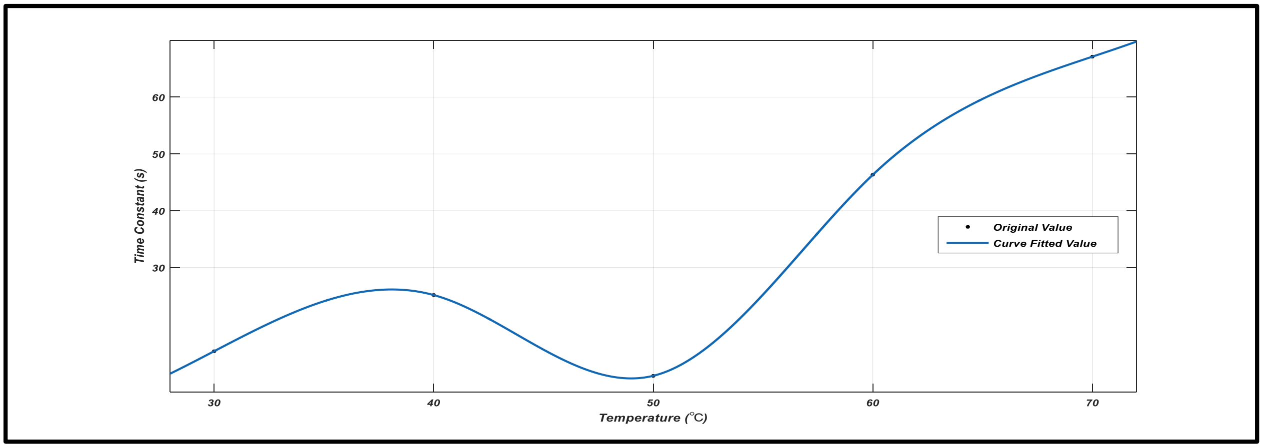
Fig. 6.7 (b) shows that Variation of Time Constant of Branch-II with a temperature of NOMEX insulation using MATLAB curve fitting tool. The curve fitting function is,

Smoothing spline:

f(x) = piecewise polynomial computed from p where x is normalized by mean 50 and std 15.81

Smoothing parameter:

p = 0.99999242



(b)

Fig. 6.7. (a) Variation of Time Constant of Branch-I and (b) Variation of Time Constant of Branch-II with a temperature of NOMEX insulation.

The variation of Time Constant for Branch-I and the variation of Time Constant for Branch-II are shown inFig. 6.7(a) & Fig. 6.7(b) respectively.

6.2.5 Variation of Dielectric Dissipation Factor with Applied Voltage

This section explains the dielectric dissipation factor with an applied voltage of NOMEX insulation. The experiment, determination of dielectric dissipation factors can be performed at room temperature with the help of ISA STS 300 LIGHT & TD5000. Fig. 6.7 shows that the variation of Dielectric Dissipation Factor with Applied Voltage in NOMEX insulation using the MATLAB curve fitting tool. The curve fitting function is shown below,

Smoothing spline:

$f(x)$ = piecewise polynomial computed from p

Smoothing parameter:

p = 1.9074136e-05

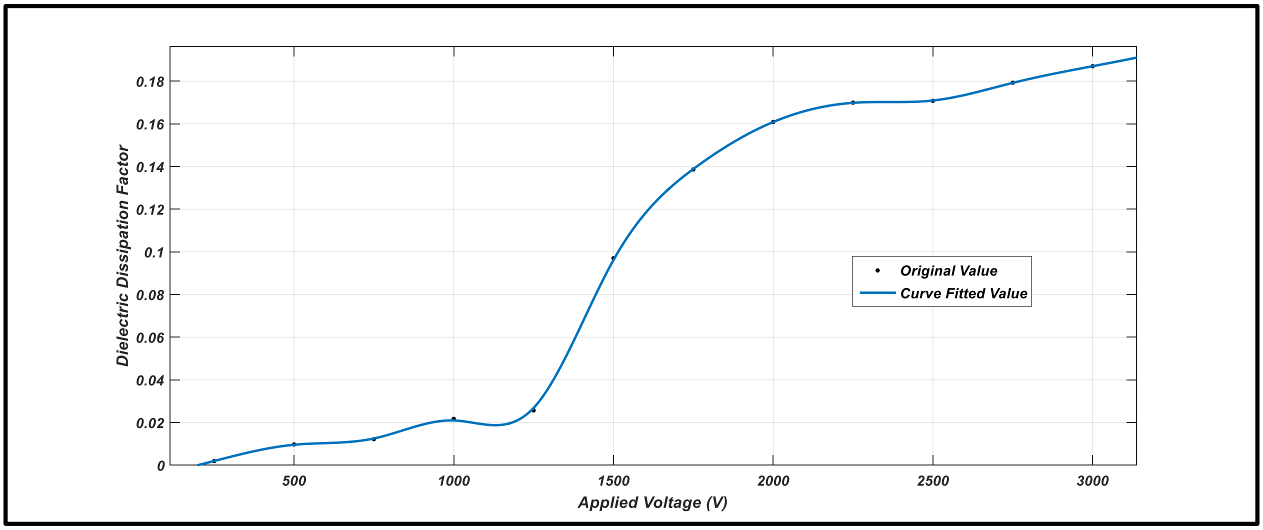


Fig. 6.8. Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of NOMEX insulation increases with the increase in applied voltage.

6.3 Experimental parameters of Polarization and Depolarization Current of Thin NOMEX Insulation

This section discusses about the various parameters of Polarization and Depolarization current of thin NOMEX insulation.

The charging time (t_c) is kept at 220s throughout the experiment. The Input d.c. voltage (V_s) is set at 2000V.

6.3.1 Sample Description

This section explains the dimension and electrical properties of the sample.

a) Dimension: In this experiment circle shaped sample with 12cm diameter is used for PDC measurement. Also, the thickness of the sample is about 0.13mm.

b) Dielectric Strength: The typical dielectric strength of NOMEX insulation in the range 18 kV/mm to 34 kV/mm

c) Value of Insulation resistance (R_0)**:** 191 GΩ

d) Value of Geometric Capacitance (C_0)**:** .558 pF.

6.3.2 Nature of Polarization and Depolarization Current

This section explains the nature of PDC curve. Fig. 6.9 shows that the variation of the polarization current in thin NOMEX insulation with different temperature.

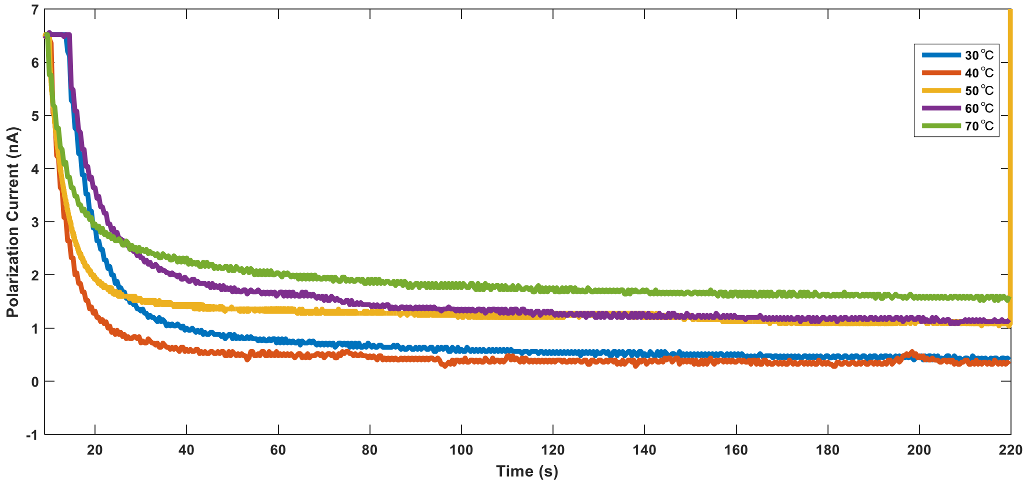


Fig. 6.9. Variation of Polarization current in Thin NOMEX insulation with temperature.

In Fig. 6.10 it is seen the variation of depolarization current in thin NOMEX insulation with different temperature.

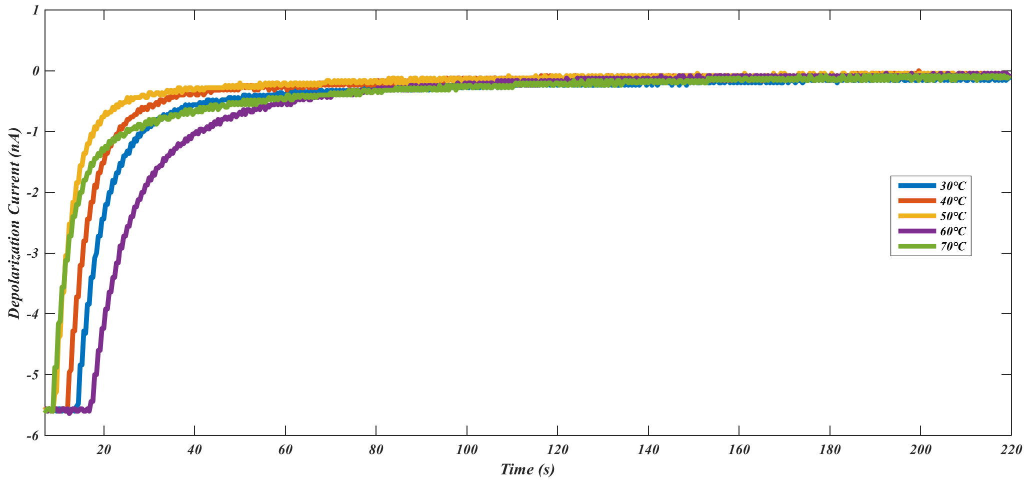


Fig. 6.10. Variation of depolarization current in thin NOMEX insulation with temperature.

In Fig. 6.9 it is seen the polarization current is recorded in the temperature range of 30°C to 70°C. It is observed that the value of the polarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature. Due to increase in temperature, it can be observed from Fig. 6.5 shows that the conduction current also increases.

In Fig. 6.10 it is seen the nature of the depolarization current curve in Thin NOMEX sample with temperature variation. The characteristics of the depolarization current curve are almost same as explained in Fig. 6.9.

6.3.3 Estimation of Branch Parameters from Debye model

From the depolarization current curve of each sample, the branch parameters like resistance, capacitance and time constant of each branch are determined by using the procedure as discussed in the previous section 4.4.

Table 6.3 Derived Parameters of DEBYE model for Thin NOMEX insulation

SL No	***Temperature* (°C)**	***Branch resistance***		***Branch capacitance***		***Time constant***	
		R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	τ_1 (s)	τ_2 (s)
1	30°C	3.96E+10	1.38E+12	1.70E-10	4.17E-11	6.732	57.546
2	40°C	3.10E+10	1.54E+12	1.70E-10	3.43E-11	5.270	52.822
3	50°C	2.89E+10	1.05E+12	1.13E-10	3.21E-11	3.265	33.712
4	60°C	2.69E+10	1.10E+12	1.11E-10	2.90E-11	2.986	31.912
5	70°C	1.74E+10	9.21E+11	2.33E-10	5.80E-11	4.054	53.418

6.3.4 Variation of Time Constant with Temperature

This section explains the time constant variation of the thin NOMEX sample.The insulation system of a power transformer consists of the various numbers of series R-C branches in parallel. This series R-C branch represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant τ_i=R_i*C_i can be estimated. For solid insulating material, the dielectric relaxation time is smaller than oil or oil-paper insulation. Hence, the number of the branch parameter is lesser for a solid insulating materials.

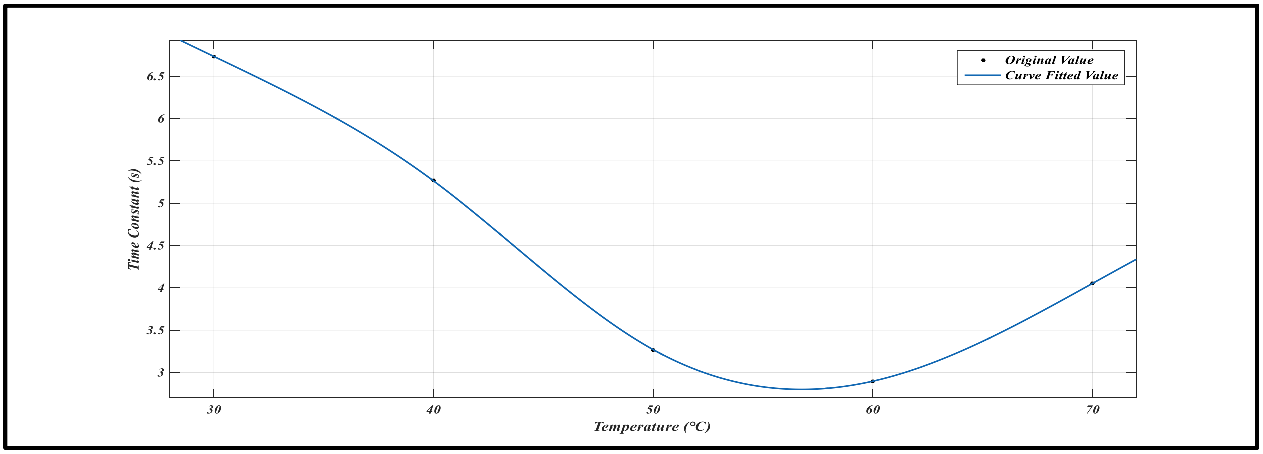
The Fig. 6.11 (a) shows that Variation of Time Constant of Branch-I with temperature of thin Nomex insulation using MATLAB curve fitting tool. The curve fitting function is,

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 0.44756087



(a)

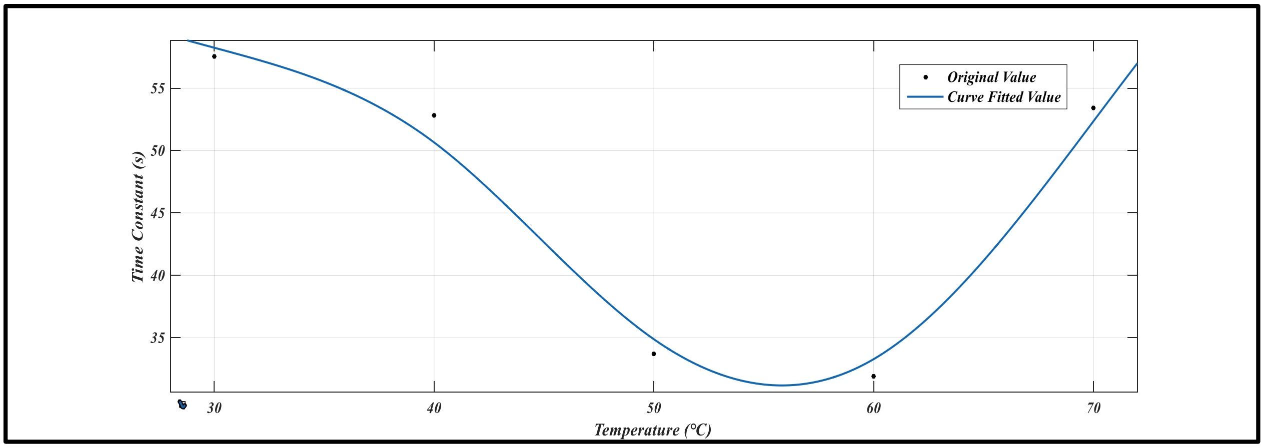
Fig. 6.11 (b) shows that Variation of Time Constant of Branch-II with a temperature of Thin NOMEX insulation using MATLAB curve fitting tool. The curve fitting function is,

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 0.023880316



(b)

Fig. 6.11. (a) Variation of Time Constant for Branch-I and (b) Variation of Time Constant for Branch-II.

6.2.5 Variation of Dielectric Dissipation Factor with Applied Voltage

This section explains the dielectric dissipation factor with an applied voltage of thin NOMEX insulation. The experiment, determination of dielectric dissipation factors can be performed at room temperature with the help of ISA STS 300 LIGHT & TD5000. In Fig. 6.12 it is seen the variation of Dielectric Dissipation Factor with Applied Voltage in Thin NOMEX insulation using the MATLAB curve fitting tool. The curve fitting function is shown below,

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 4.2560782e-06

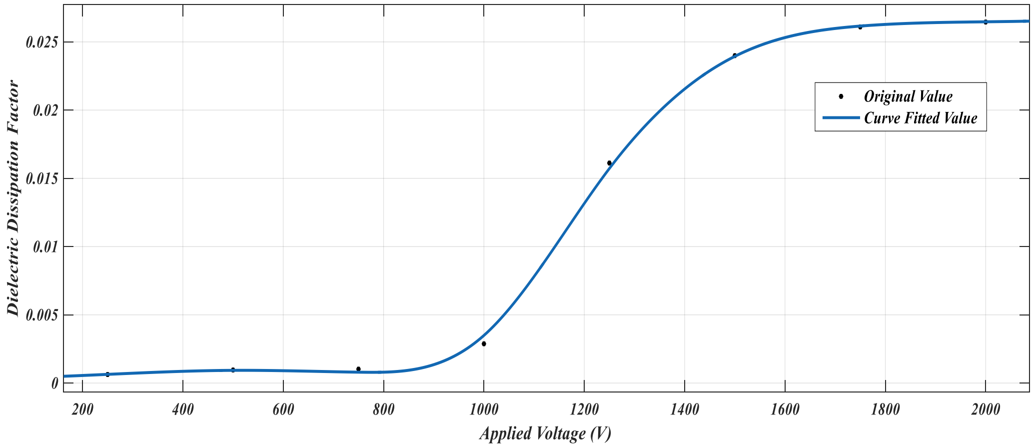


Fig. 6.12. Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of Thin NOMEX insulation increases with the increase in applied voltage.

6.4 Experimental Parameters of Polarization and Depolarization Current of Black Cellophane Tape

This section discusses about the various parameters of Polarization and Depolarization current of Black cellophane tape.

The charging time (t_c) is kept at 220s throughout the experiment. The Input d.c. voltage (V_s) is set at 200V.

6.4.1 Sample Description

This section explains the dimension and electrical properties of the sample.

a) Dimension: The typical thickness of the sample is about 0.03mm.
b) Dielectric Strength: The dielectric strength of black cellophane tape in the range 118 kV/mm to 236 kV/mm
c) Value of Insulation resistance (R_0)**:** 386 MΩ.
d) Value of Geometric Capacitance (C_0)**:** .457 pF.

6.4.2 Nature of Polarization and Depolarization Current

This section discusses about the nature of recorded PDC data. In Fig. 6.13 it is seen the variation of the polarization current in black cellophane tape insulation with different temperature.

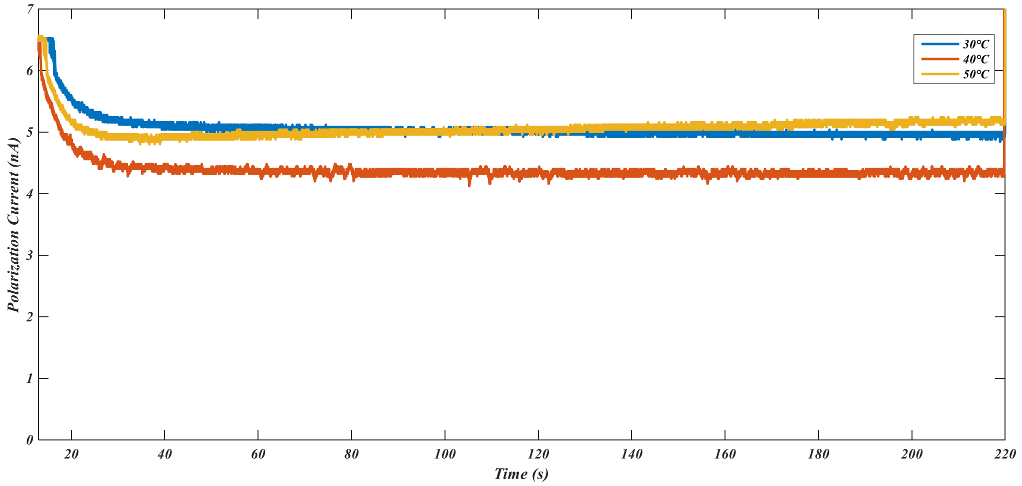


Fig. 6.13. Variation of Polarization current in Black Cellophane Tape with temperature.

In Fig. 6.14 it is seen the variation of depolarization current in black cellophane tape insulation with different temperature.

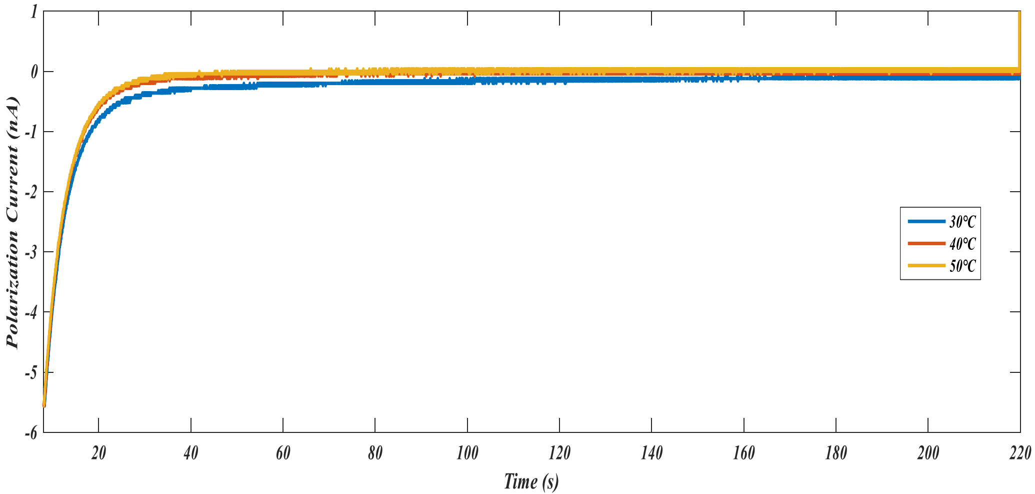


Fig. 6.14. Variation of Depolarization current in Black Cellophane Tape with temperature.

In Fig. 6.13 it is seen the polarization current is recorded in the temperature range of 30°C to 60°C. It is observed that the value of the polarization current decreases with the increase of temperature, it's happening due to the nonlinearity nature of insulation.

In Fig. 6.14 it is seen the nature of the depolarization current curve in Black Cellophane Tape with temperature variation. It is observed that the value of the depolarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature.

6.4.3 Estimation of Branch Parameters from DEBYE model

From the depolarization current curve of each sample, the branch parameters (resistance, capacitance and time constant of each branch) are determined by using the procedure as discussed in section 4.4.

Table 6.4 Derived Parameters of DEBYE model for Black Cellophane Tape

SL. No.	***Temperature*** **(°C)**	***Branch resistance***		***Branch capacitance***		***Time constant***	
		R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	τ_1 (s)	τ_2 (s)
1	30°C	5.17E+09	2.70E+11	9.23E-10	3.88E-11	4.772	10.476
2	40°C	4.98E+09	2.43E+11	*9.52E-10*	8.40E-11	4.740	20.412
3	50°C	4.82E+09	1.94E+11	*9.30E-10*	9.30E-11	4.482	18.042

6.4.4 Variation of Time Constant with Temperature

The insulation system of a power transformer consists of the various numbers of series R-C branches in parallel. This series R-C branch represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant τ_i=R_i*C_i can be estimated. For solid insulating material, the dielectric relaxation time is smaller than the oil or oil-paper insulation. Hence, the number of the branch parameter is lesser for solid insulating materials.

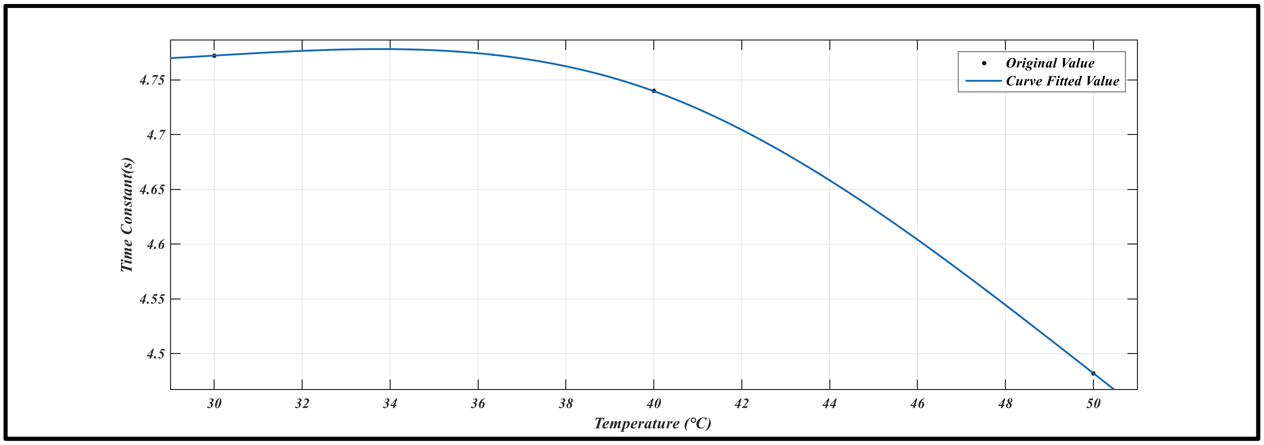
Fig. 6.15 (a) shows that variation of time constant of branch-I with temperature of thin black cellophane tape utilizing MATLAB bend fitting apparatus. The curve fitting function is:

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 0.68771737



(a)

In Fig. 6.15 (b) shows that variation of time constant of branch-II with temperature of thin black cellophane tape using MATLAB curve fitting tool. The curve fitting function is,

General model Gauss1:

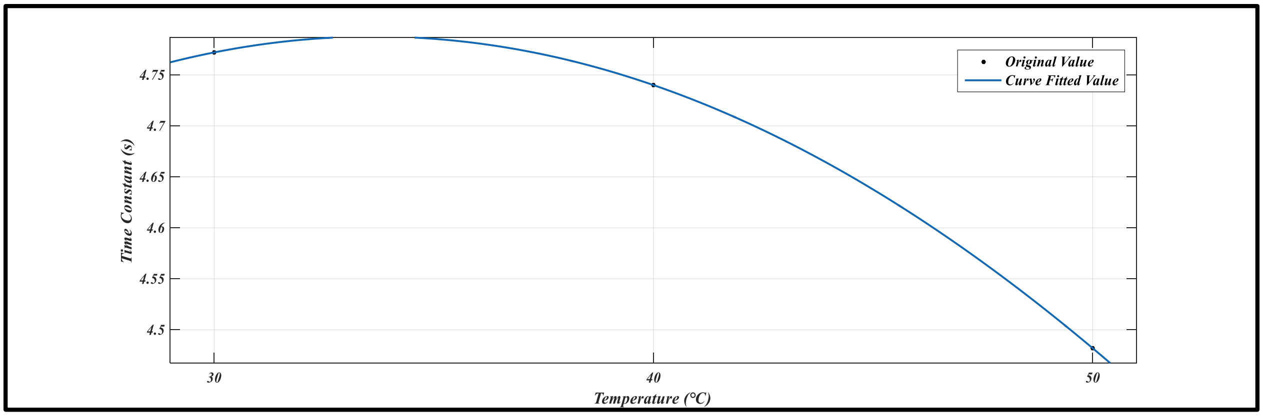
f(x) = a1*exp(-((x-b1)/c1)^2)

Coefficients:

a1 = 4.788

b1 = 33.63

c1 = 63.73



(b)

Fig. 6.15. (a) Variation of Time Constant for Branch-I and (b) Variation of Time Constant for Branch-II.

6.4.5 Variation of Dielectric Dissipation Factor with Applied Voltage

This section explains the dielectric dissipation factor with an applied voltage of Black Cellophane Tape. The experiment, determination of dielectric dissipation factors can be performed at room temperature with the help of ISA STS 300 LIGHT & TD5000. Fig. 5.16 demonstrates the variety of Dielectric Dissipation Factor with Applied Voltage in Black Cellophane Tape. The Fig. 5.16., is finished by utilizing the MATLAB bend fitting instrument. The curve fitting function is demonstrated as follows:

General model Exp:

$f(x) = a*exp(b*x) + c*exp(d*x)$

Coefficients (with 95% confidence bounds):

a = 0.01142 (-0.01512, 0.03795)

b = 0.001378 (-0.005232, 0.007987)

c = -0.004992 (-0.0139, 0.003915)

d = -0.01013 (-0.1175, 0.09725)

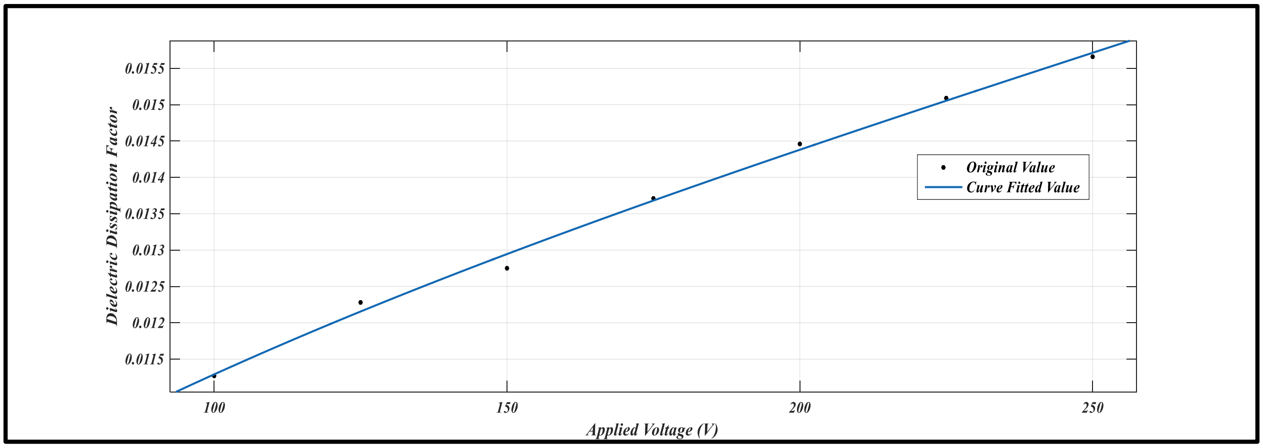


Fig. 6.16. Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of the Black Cellophane Tape increases with the increase in applied voltage.

6.5 Experimental parameters of Polarization and Depolarization Current of Blue Cellophane Tape

This section discusses about the various parameters of Polarization and Depolarization current of Blue cellophane tape.

The charging time (t_c) is kept at 220s throughout the experiment. The Input d.c. voltage (V_s) is set at 200V.

6.5.1 Sample Description

The sample description has explained in this section.

a) Dimension: The typical thickness of the sample is about 0.03mm.
b) Dielectric Strength: The dielectric strength of blue cellophane tape in the range 118 kV/mm to 236 kV/mm
c) Value of Insulation resistance (R_0)**:** 375 MΩ.
d) Value of Geometric Capacitance (C_0)**:** .428 pF.

6.5.2 Nature of Polarization and Depolarization Current

This section discusses about the nature of recorded PDC data. I n Fig. 6.17 it is seen the variation of the polarization current in blue cellophane tape insulation under different temperature.

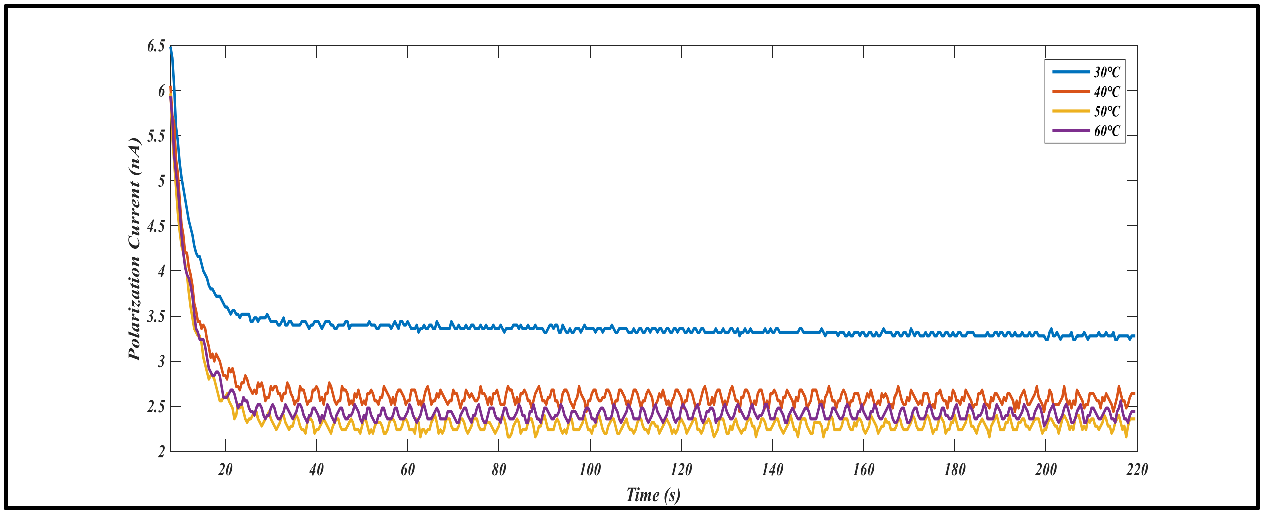


Fig. 6.17. Variation of Polarization current in Blue Cellophane Tape with temperature.

In Fig. 6.18 it is seen the variation of the depolarization current in Blue Cellophane Tapefor different temperature variation.

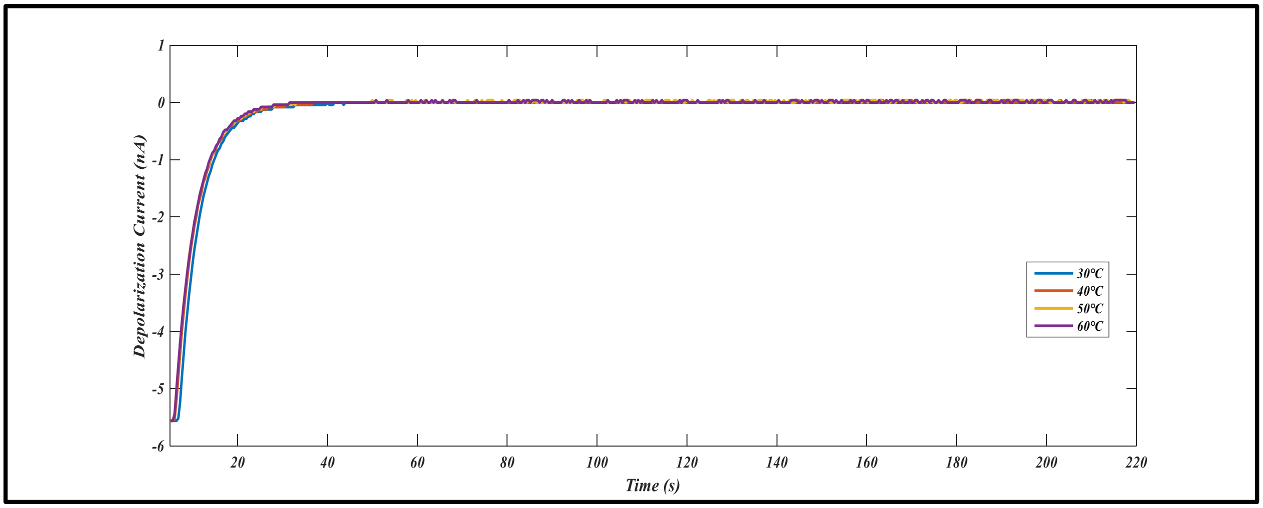


Fig. 6.18. Variation of Depolarization current in Blue Cellophane Tape with temperature.

In Fig. 6.17 it is seen the polarization current is recorded in the temperature range of 30℃ to 60℃. It is observed that the value of the polarization current decreases with the increase of temperature, it’s happening due to the nonlinearity nature of insulation.

In Fig. 6.18 it is seen the nature of the depolarization current curve in Blue Cellophane Tape with temperature variation. It is observed that the value of the depolarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature.

6.5.3 Estimation of Branch Parameters from DEBYE model

From the depolarization current curve of each sample, the branch parameters like resistance, capacitance and time constant of each branch are dictated by utilizing the procedure as examined in area 4.4.

Table 6.5 Derived Parameters of DEBYE model for Blue Cellophane Tape

SL. No.	***Temperature* (℃)**	***Branch resistance***		***Branch capacitance***		***Time constant***	
		$\boldsymbol{R_1}$ (Ω)	$\boldsymbol{R_2}$ (Ω)	$\boldsymbol{C_1}$ (F)	$\boldsymbol{C_2}$ (F)	$\boldsymbol{\tau_1}$ (s)	$\boldsymbol{\tau_2}$ (s)
1	30℃	8.33E+09	1.97E+10	5.61E-10	7.41E-10	4.673	14.597
2	40℃	9.99E+09	2.94E+10	4.71E-10	6.29E-10	4.681	18.492
3	50℃	1.65E+10	2.13E+10	2.20E-10	2.55E-10	3.630	5.431
4	60℃	1.01E+10	5.62E+10	4.58E-10	2.69E-10	4.625	15.117

6.5.4 Variation of Time Constant with Temperature

The insulation system of a power transformer consists of the various numbers of series R-C branches in parallel. This series R-C branch represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant τ_i=R_i*C_i can be estimated. For solid insulating material, the dielectric relaxation time is smaller than the oil or oil-paper insulation. Hence, the number of the branch parameter is lesser for solid insulating materials.

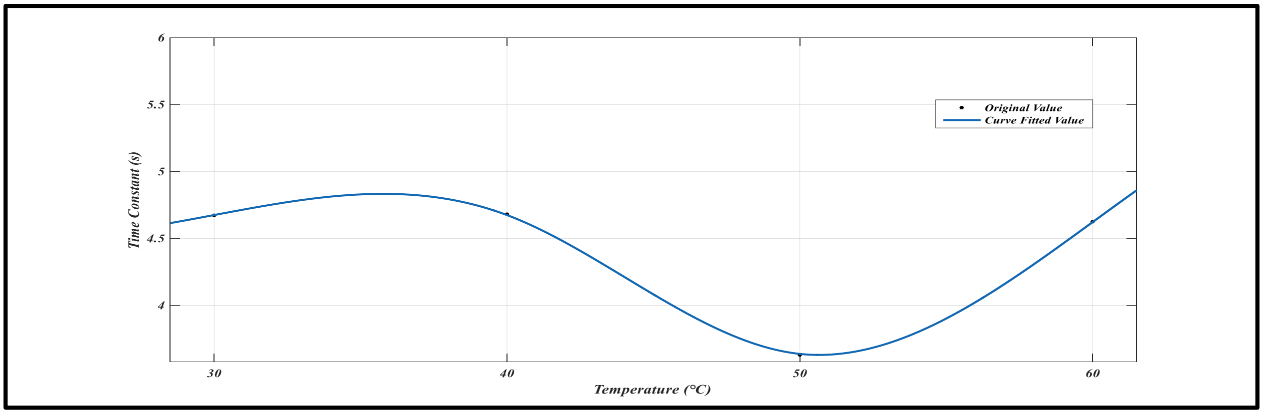
The Fig. 6.19(a) shows that variation of time constant of branch-I with temperature of thin blue cellophane tape using MATLAB curve fitting tool. The curve fitting function is,

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 0.5718662



(a)

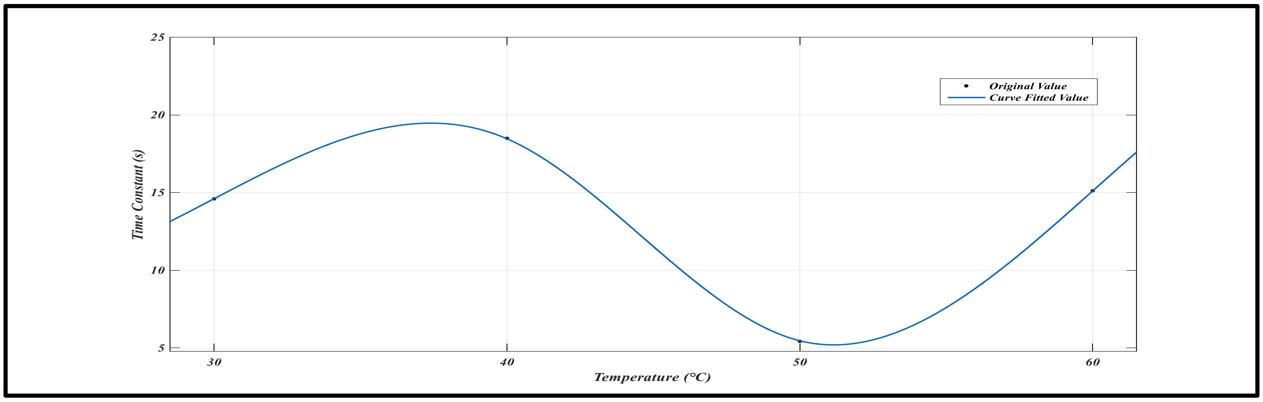
The Fig. 6.19(b) shows that variation of time constant of branch-II with temperature of thin blue cellophane tape using the MATLAB curve fitting tool. The curve fitting function is,

Smoothing spline:

f(x) = piecewise polynomial computed from p

Smoothing parameter:

p = 0.78405735



(b)

Fig. 6.19 (a) Variation of Time Constant for Branch-I and (b) Variation of Time Constant for Branch-II.

6.5.5 Variation of Dielectric Dissipation Factor with Applied Voltage

This section explains the dielectric dissipation factor with an applied voltage of Blue Cellophane Tape. The experiment, determination of dielectric dissipation factors can be performed in room temperature with the help of ISA STS 300 LIGHT & TD5000.In Fig. 6.20 it is seen the variation of Dielectric Dissipation Factor with Applied Voltage in Blue Cellophane Tape using the MATLAB curve fitting tool. The curve fitting function is shown below,

Linear model Polynomial:

*f(x) = p1*x^2 + p2*x + p3*

Coefficients (with 95% confidence bounds):

p1 = 6.705e-08 (-1.58e-08, 1.499e-07)

p2 = 1.422e-05 (-1.5e-05, 4.344e-05)

p3 = 0.01054 (0.00812, 0.01296)

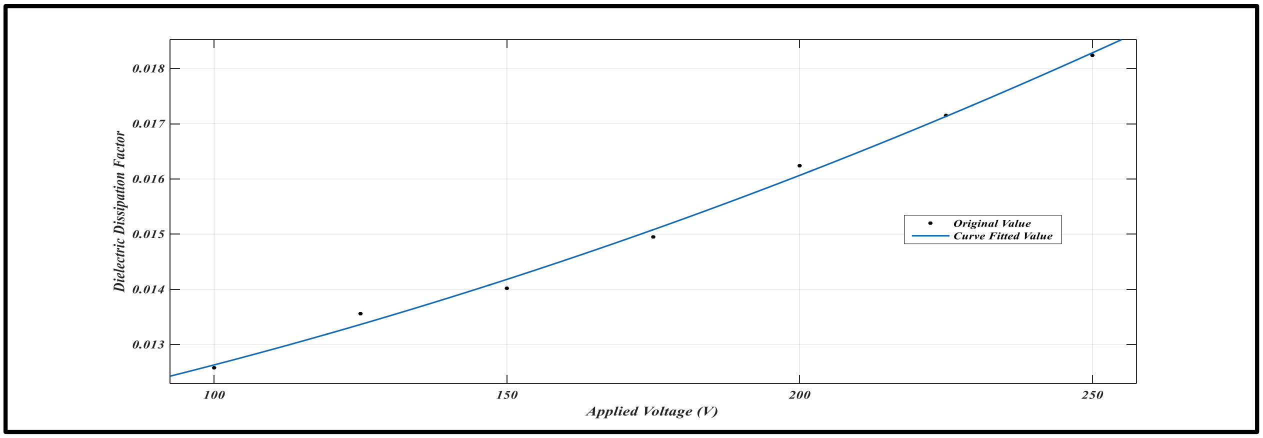


Fig. 6.20. Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of Blue Cellophane Tape increases with the increase in applied voltage.

6.6 Experimental parameters of Polarization and Depolarization Current of Epoxy resin (Pure) insulation

This section discusses about the various parameters of Polarization and Depolarization current of Pure Epoxy Resin.

The charging time (t_c) is kept at 220s throughout the experiment. The Input d.c. voltage (V_s) is set at 1000V.

6.6.1 Sample Description

This section explains the dimension and electrical properties of the sample.

a) Dimension: In this experiment circle shaped sample with 12cm diameter is used for PDC measurement. The thickness of the sample is about 5mm.
b) Dielectric Strength: The typical dielectric strength of epoxy resin insulation in the range 18 kV/mm to 34 kV/mm
c) Value of Insulation resistance (R_0)**:** 115 GΩ
d) Value of Geometric Capacitance (C_0)**:** .541 pF.

6.6.2 Nature of Polarization and Depolarization Current

This section explains the nature of PDC curve. In Fig. 6.21 it is seen the variation of the polarization current in pure epoxy insulation with different temperature.

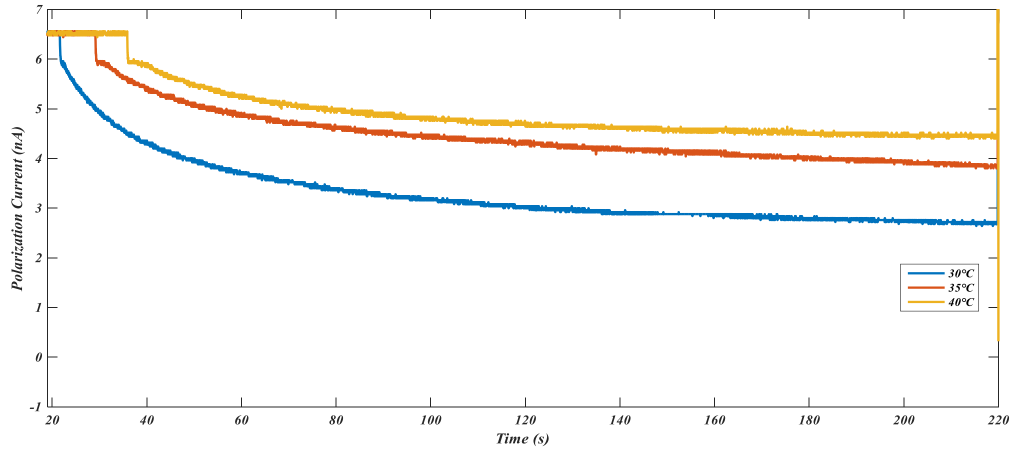


Fig. 6.21. Variation of polarization current in pure epoxy resin insulation with temperature.

In Fig. 6.22 it is seen the variation of the depolarization current in epoxy resin insulation with different temperature.

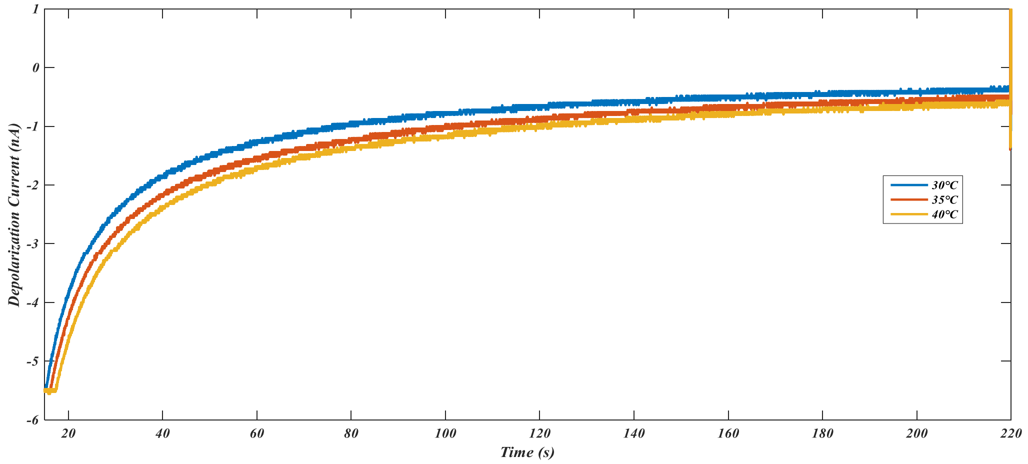


Fig. 6.22. Variation of depolarization current in pure epoxy resin insulation with temperature.

In Fig. 6.21 it is seen the polarization current is recorded in the temperature range of 30°C to 40°C. It is observed that the value of the polarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature. Due to increase in temperature, it can be observed from Fig. 6.21 that the conduction current also increases.

Fig. 6.22 shows that the nature of the depolarization current curve in pure epoxy resin insulation with temperature variation. The depolarization current decreases with an increment of temperature.

6.6.3 Estimation of Branch Parameters from Debye model

From the depolarization current curve of each sample, the branch parameters (resistance, capacitance and time constant of each branch) are determined by using the procedure as discussed in the previous section 4.4.

Table 6.6 Derived Parameters of DEBYE model for pure epoxy resin insulation

SL No	***Temperature* (℃)**	***Branch resistance***		***Branch capacitance***		***Time constant***	
		R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	τ_1 (s)	τ_2 (s)
1	30℃	5.56E+10	2.19E+12	1.79E-10	2.64E-11	9.952	57.816
2	35℃	5.89E+10	1.14E+12	3.06E-10	7.31E-11	18.023	83.334
3	40℃	5.41E+10	9.48E+11	6.19E-10	9.58E-11	33.487	90.818

6.6.4 Variation of Time Constant with Temperature

This section explains the time constant variation of pure epoxy resin insulation. The insulation system of a power transformer consists of the various number of series R-C branches in parallel. This series R-C branch represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant τ_i=R_i*C_i can be estimated. For solid insulating material, the dielectric relaxation time is smaller than oil or oil-paper insulation. Therefore, the number of the branch parameter is lesser for solid insulating materials.

Fig. 6.23 (a) shows that variation of time constant of branch-I with temperature of pure epoxy resin insulation using the MATLAB curve fitting tool. The curve fitting function is, Linear model Poly2:

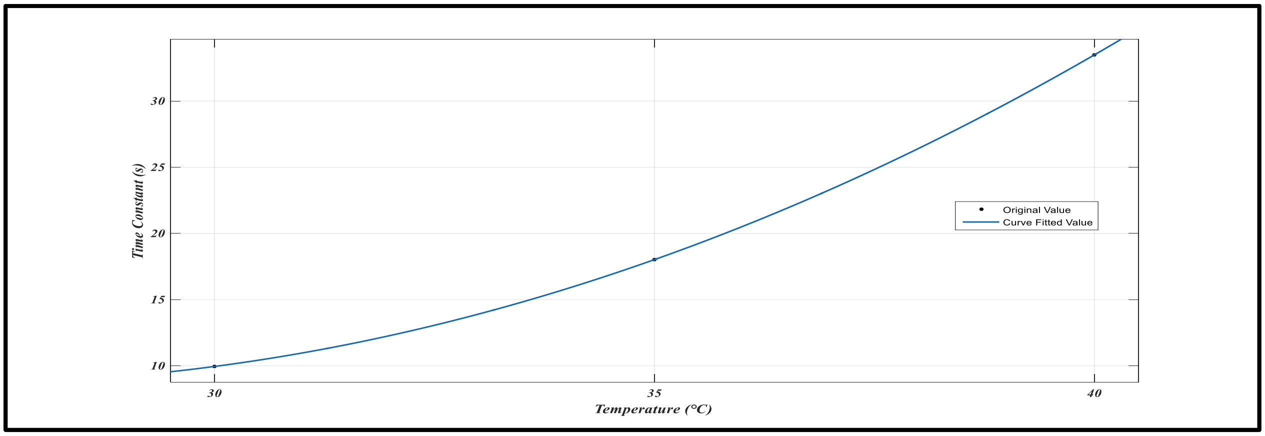
*f(x) = p1*x^2 + p2*x + p3*

Coefficients:

p1 = 0.1479

p2 = -7.997

p3 = 116.8



(a)

Fig. 6.23 (b) shows that Variation of Time Constant of Branch-II with temperature of thin of pure epoxy resin insulation using the MATLAB curve fitting tool. The curve fitting function is,

Linear model Poly2:

*f(x) = p1*x^2 + p2*x + p3*

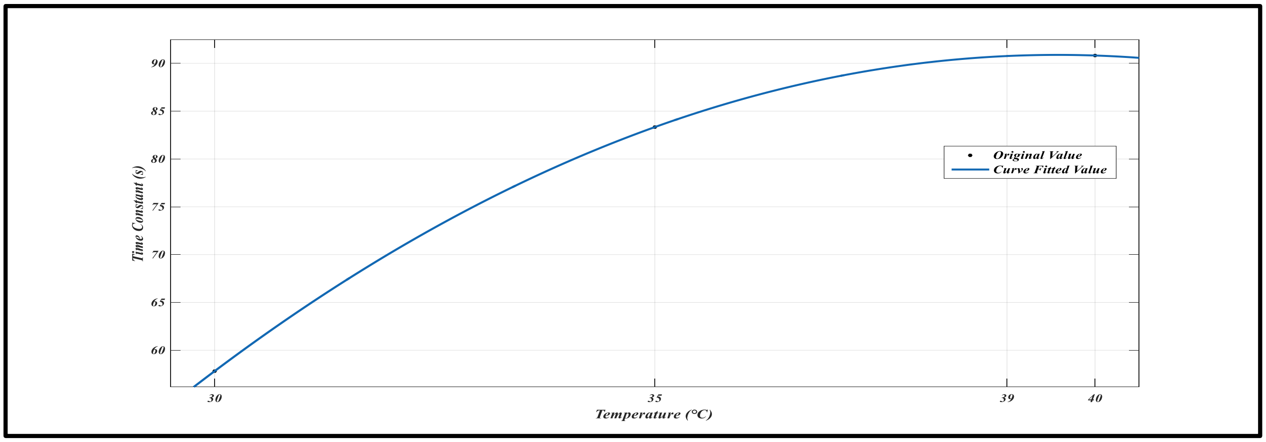
where x is normalized by mean 35 and std 5

Coefficients:

p1 = -9.017

p2 = 16.5

p3 = 83.33



(b)

Fig. 6.23 (a) Variation of Time Constant for Branch-I and (b) Variation of Time Constant for Branch-II.

Fig. 6.23(a) and Fig. 6.23(b) show that the value of time constant increases with the increases with temperature.

6.6.5 Variation of Dielectric Dissipation Factor with Applied Voltage

The experiment, determination of dielectric dissipation factors can be performed at room temperature with the help of ISA STS 300 LIGHT & TD5000. In Fig. 6.24 it is seen the variety of Dielectric Dissipation Factor with Applied Voltage in pure epoxy resin insulation. The dielectric dissipation factor plotted with respect to applied voltage in Fig. 6.24 using the MATLAB curve fitting tool.The curve fitting function is,

Smoothing spline:

$f(x)$ = piecewise polynomial computed from p

Smoothing parameter:

p = 5.1847179e-05

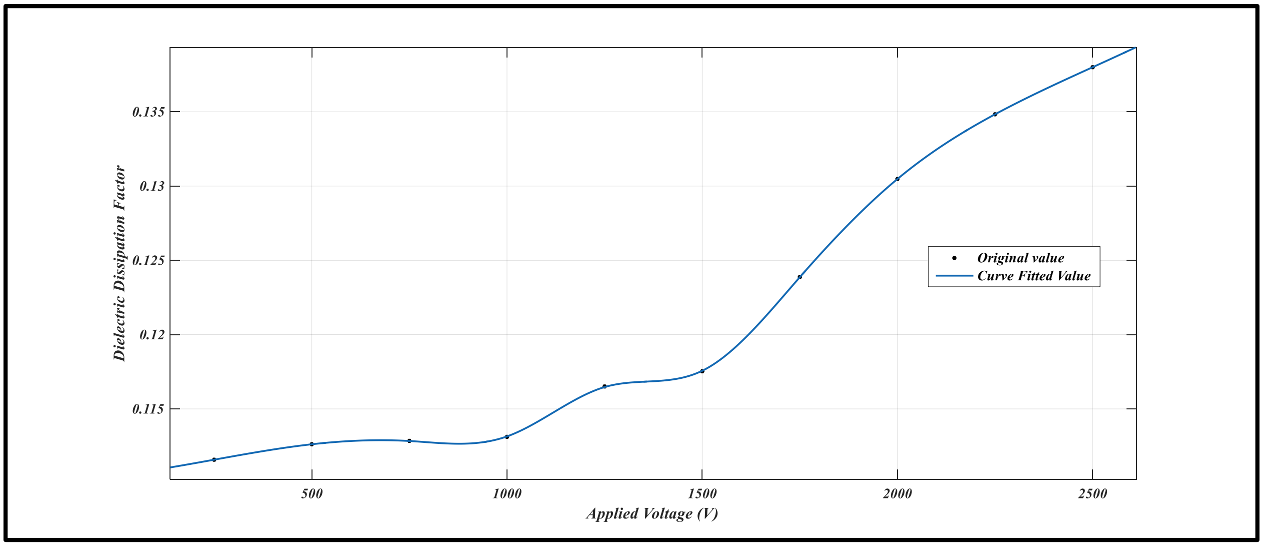


Fig. 6.24. Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of pure epoxy resin insulation increases with the increase in applied voltage.

6.7 Experimental parameters of Polarization and Depolarization Current of pure Epoxy Resin (with 1% carbon impurities) Insulation

This section discusses about the various parameters of the Polarization and Depolarization current of Epoxy Resin with 1% carbon impurities.

The charging time (t_c) is kept at 220s throughout the experiment. The Input d.c. voltage (V_s) is set at 1000V.

6.7.1 Sample Description

This section explains the dimension and electrical properties of the sample.

a) Dimension: In this experiment circle shaped sample with 12cm diameter is used for PDC measurement. The thickness of the sample is about 5mm.

b) Dielectric Strength: The typical dielectric strength of epoxy resin in the range 18 kV/mm to 34 kV/mm

c) Value of Insulation resistance (R_0)**:** 98.3 GΩ

d) Value of Geometric Capacitance (C_0)**:** .546 pF.

6.7.2 Nature of Polarization and Depolarization Current

This section explains the nature of PDC curve. In Fig. 6.21 it is seen the variation of the polarization current in Epoxy Resin with 1% carbon impurities insulation with different temperature.

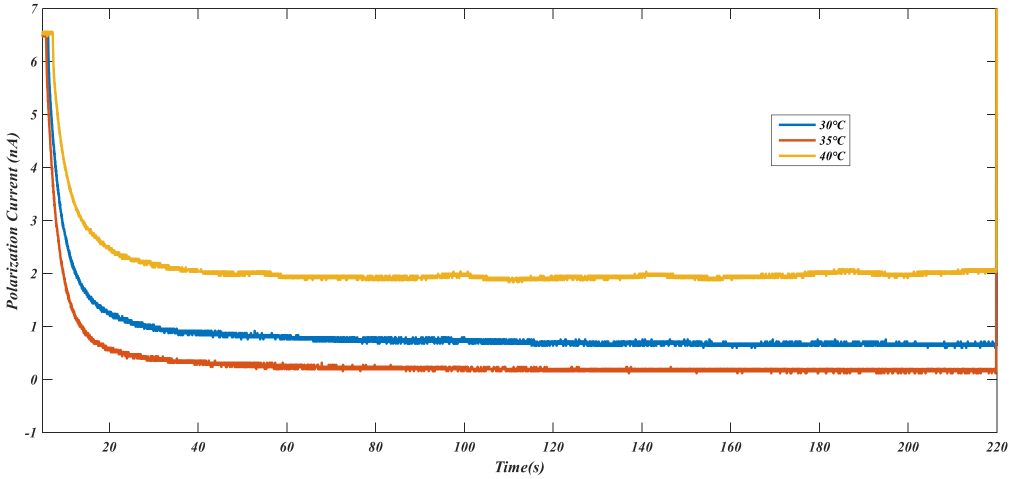


Fig. 6.25. Variation of the Polarization current in Epoxy Resin with 1% carbon impurities insulation with temperature.

In Fig. 6.26 it is seen the variation of the depolarization current in Epoxy Resin with 1% carbon impurities under different temperature.

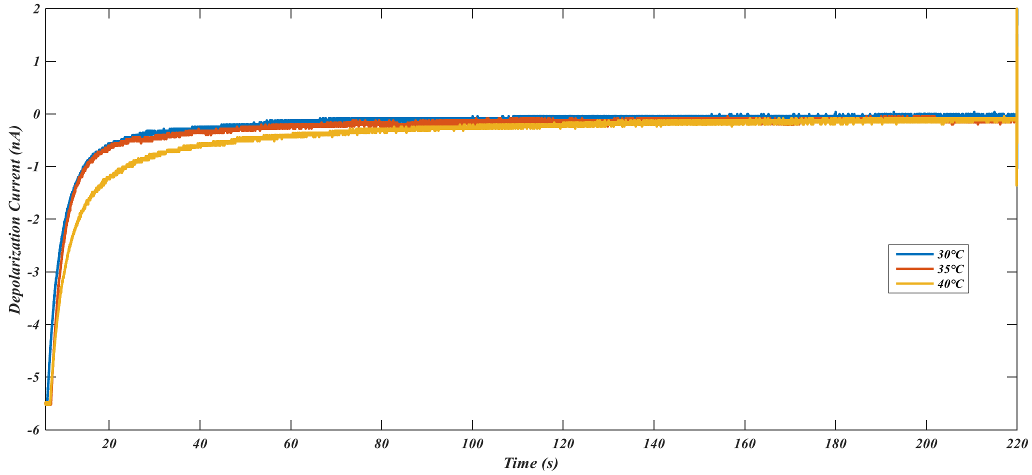


Fig. 6.26. Variation of the depolarization current in Epoxy Resin with 1% carbon impurities insulation with temperature.

In Fig. 6.25 it is seen the polarization current is recorded in the temperature range of 30℃ to 40℃. It is observed that the value of the polarization current increases with the increase of temperature, as it is known that resistance of insulation usually decreases with increase in temperature. Due to increase in temperature, it can be observed from Fig. 5.25 that the conduction current also increases.

In Fig. 6.26 it is seen the nature of the depolarization current curve in epoxy resin with 1% carbon impuritieswith the temperature variation. It is observed that the tail of depolarization current is same for all temperatures.

From Fig. 6.21 and Fig. 6.25, the value of depolarization current decreases by adding carbon impurities in epoxy resin.

6.6.3 Estimation of Branch Parameters from Debye model

From the depolarization current curve of each sample, the branch parameters (i.e. resistance, capacitance and time constant of each branch) are determined by using the procedure as discussed in the previous section 4.4.

Table 6.7 Derived Parameters of DEBYE model for Epoxy Resin with 1% carbon impurities

SL No	***Temperature*** **(℃)**	***Branch resistance***		***Branch capacitance***		***Time constant***	
		R_1 (Ω)	R_2 (Ω)	C_1 (F)	C_2 (F)	τ_1 (s)	τ_2 (s)
1	30℃	1.07E+12	2.04E+11	6.93E-12	1.49E-10	7.415	30.397
2	35℃	5.19E+11	1.08E+12	2.03E-11	3.42E-11	10.535	36.945
3	40℃	6.30E+11	5.41E+11	2.31E-11	8.37E-11	14.553	45.288

6.7.4 Variation of Time Constant with Temperature

This section explains the time constant variation of epoxy resin with 1% carbon impurities. The insulation system of a power transformer consists of the various number of series R-C branches in parallel. This series R-C branch represents the different dielectric relaxation process. By adjusting the depolarization current curve, the individual branch parameters (R_i-C_i) with the corresponding time constant τ_i=R_i*C_i can be estimated. For solid insulating material, the dielectric relaxation time is smaller than oil or oil-paper insulation. Hence, the number of the branch parameter is lesser for solid insulating materials.

Fig. 6.27 (a) shows that Variation of Time Constant of Branch-I with temperature of epoxy resin with 1% carbon impurities using MATLAB curve fitting tool. The curve fitting function is,

Linear model Poly2:

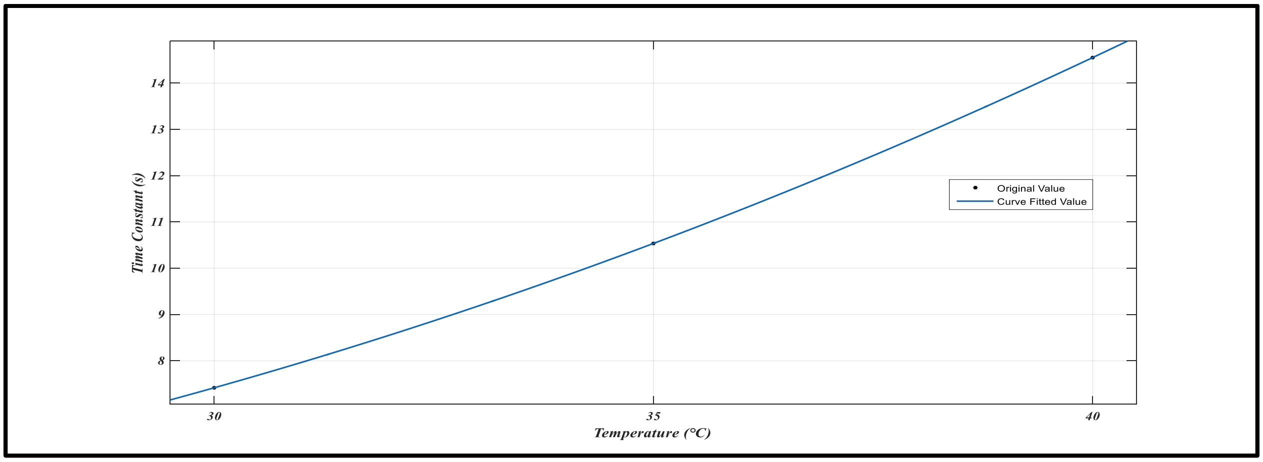
*f(x) = p1*x^2 + p2*x + p3*

Coefficients:

p1 = 0.01796

p2 = -0.5434

p3 = 7.553



(a)

The Fig. 6.27 (b) shows that the variation of time constant of branch-I with temperature of epoxy resin with 1% carbon impurities using MATLAB curve fitting tool. The curve fitting function is,

Linear model Poly2:

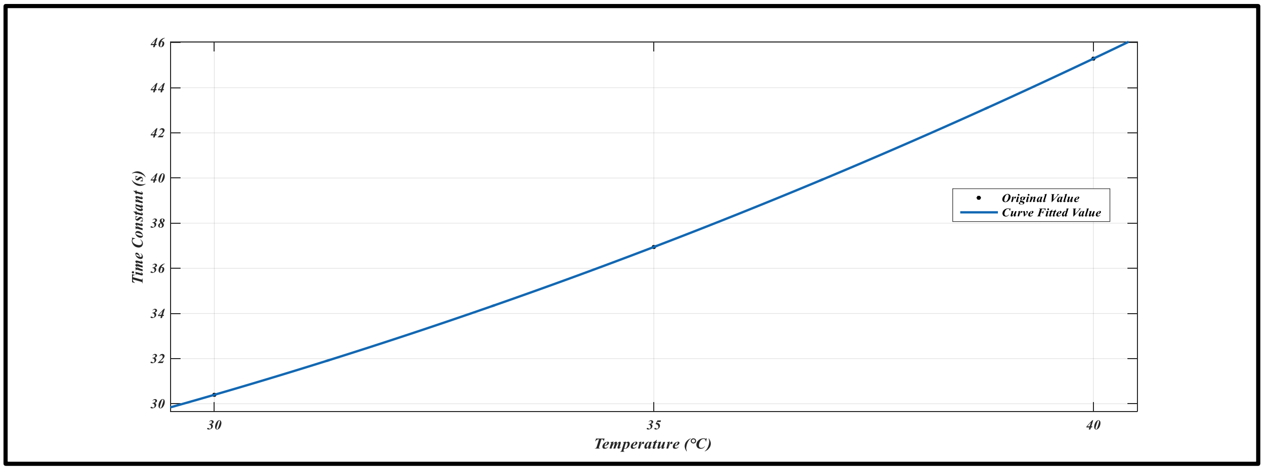
*f(x) = p1*x^2 + p2*x + p3*

Coefficients:

p1 = 0.0359

p2 = -1.024

p3 = 28.8



(b)

Fig. 6.27. (a) Variation of Time Constant for Branch-I and (b) Variation of Time Constant for Branch-II.

From Fig. 6.27(a) and Fig. 6.27(b), it is observed that the value of time constant increases with the increases of temperature.

6.7.5 Variation of Dielectric Dissipation Factor with Applied Voltage

The experiment, determination of the dielectric dissipation factors can be performed at room temperature with the help of ISA STS 3000 & TD5000. In Fig. 6.24 it is seen the variation of the Dielectric Dissipation Factor with an Applied Voltage in epoxy resin with 1% carbon impurities using the MATLAB curve fitting tool. The curve fitting function is,

Linear model Poly2:

$f(x) = p1*x^2 + p2*x + p3$

Coefficients (with 95% confidence bounds):

p1 = 2.819e-09 (6.409e-10, 4.997e-09)

p2 = 1.248e-05 (6.336e-06, 1.863e-05)

p3 = 0.1561 (0.1524, 0.1598)

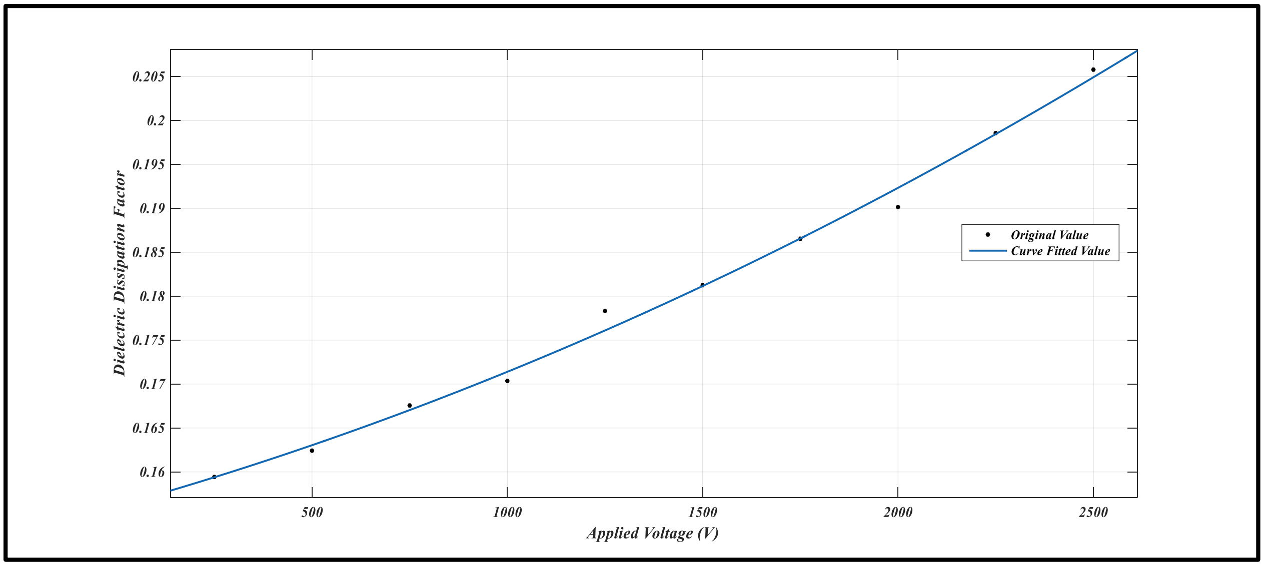


Fig. 6.28. Variation of Dielectric Dissipation Factor with Applied Voltage.

For any insulation, increase in dielectric dissipation factor is an indication of insulation aging. It can be inferred from the curvethat the value dielectric dissipation factor of epoxy resin sample with 1% carbon impurities increases with the increase in applied voltage.

6.8 Analysis of Activation Energy

This section explains about the activation energy of a dielectric sample. An estimation of activation energy of a dielectric samples signifies the barrier potential that the trapped charges would need to possess in order to carry conduction in the dielectric material.The process of polarization in an insulating material depends on different environmental factors, including predominant temperature [28,34]. As the insulation's thermal energy content varies, the time constant values of the dipoles change, resulting in the variation of the equivalent circuit parameters [29]. This variation of the parameter value with the temperature is related to the activation energy (E_g) of the insulating materials. It is reported in [28-29] that equations (6.1) and (6.2) respectively, can correlate the conductivity and resistance values with temperature change.

$$\sigma_{T2} = \sigma_{T1} e^{\frac{E_g}{K}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \qquad 6.1$$

The equation 6.1 can be rewritten as,

$$R_{T2} = R_{T1} e^{\frac{E_g}{K}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]} \qquad 6.2$$

Where,

$\sigma_{T1} and\ \sigma_{T2}$ are the conductivity of the dielectric at temperature $T_1\ and\ T_2$

$R_{T1}$and $R_{T2}$are the resistance of the dielectric at temperature $T_1\ and\ T_2$

'k' stands for the Boltzmann constant, the value of 'k' is 8.617385×10-5 eV/K

These equations (6.1) and (6.2) is applicable for both d.c. resistance R_0as well as branch resistances R_i

Table 6.8 Activation energy of different samples

Sl. No.	**Name of the Samples**	**Activation Energy (eV)**
1	LDPE	1.2301 eV
2	thick NOMEX	0.5428 eV
3	thin NOMEX	0.6235 eV
4	Black Cellophane Tape	0.7452 eV
5	Blue Cellophane	0.7521 eV
6	Pure Epoxy Resin	0.4783 eV
7	Pure Epoxy Resin with 1% carbon	0.5487 eV

CHAPTER-7

CONCLUSIONS AND FUTURE SCOPES

7.1 Conclusions

The experimental investigations of time domain dielectric response of all solid insulation were done in High Tension Lab, Jadavpur University. This experiment is used to measure the polarization and depolarization current data for seven samples. This measurement was done by a manual handler Dielectric Response Analyzer with variation of temperature.

The PDC analysis gives the information about the non-linearity of insulation via Debye model. Now, from the Debye model, the branch parameters of all the sample were calculated. It is observed that, the branch parameters of the equivalent model changes significantly with temperature.

The Dielectric Dissipation Factor of the seven samples under investigation was measured using ISA STS 300 LIGHT & TD5000. This test was performed at room temperature by varying the applied voltage.

The Activation Energy of the seven samples were determined from the recorded PDC data.

7.2 Future Scopes

In this present work was done by using time domain analysis. Some future scopes of the present work is mention below.

- To adapt a diagnostic method for condition monitoring of the insulation samples in the Frequency Domain.
- To investigate the variation of d.c. conductivity of the insulation samples with variation of temperature.

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