Condition Assessment of Power Transformer Using Polarisation and Depolarisation Current Measurement Technique

A Thesis report submitted in partial fulfilment of the requirements

for the award of the degree in

Bachelor of Technology in "Electrical Engineering" & Master of Technology in "Power Control and Drives"

Shivin Singh

(Roll No. 710EE2072)

May, 2015

Department of Electrical Engineering

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CERTIFICATE

This is to certify that the thesis entitled **"Condition Assessment of High Voltage Power Transformer Using Polarisation and Depolarisation Current Measurement Technique"**, submitted by **Shivin Singh (Roll No. 710EE2072)** in partial fulfilment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** & **Master of Technology** in **Power Control and Drives (Integrated Dual Degree)** during session 2014-2015 at National Institute of Technology, Rourkela.

The candidate has fulfilled all the prescribed requirements.

The Thesis is an authentic work, based on candidates' own work,.

To my knowledge, this thesis is up to the standard required for the award of a Bachelor of Technology in Electrical Engineering & Master of Technology in Power Control and Drives (Integrated Dual Degree) degree.

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ABSTRACT

Condition assessment is a process, which is used to monitor insulation condition in electrical machinery. Condition monitoring allows us to identify the insulation failure which would further lead to hardware failure. By using condition assessment, maintenance can be done in a scheduled manner or some other precautions can be taken up to avoid the failure. Moisture content and natural decay influence the dielectric characteristics of multi-layer insulation in a high voltage transformer. The observation and analysis of the dc conductivity and dielectric response function is a feasible way of diagnosis of a transformer main insulation condition. This research work, is focussed on polarization and depolarization current measurement which can be used for evaluating the quality of transformer insulation. This technique is a time domain based method for evaluating the conductivity of insulation and moisture content in solid insulation materials of a transformer. Prediction from this analysis provides a future course of action which include oil refurbishment, drying or changing the paper insulation in the transformer. This work presents a description of the PDC measurement technique with the quantitative modelling and simulation studies of PDC measurements on several power transformer having different dielectric material with different conductivity among the insulation configuration.

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LIST OF SYMBOLS

Symbol	Name of Symbol
C_0	Overall Geometric Capacitance of the insulation
U_0	Applied DC Step Voltage
C_{oil}	Capacitance of Oil duct
R_{oil}	Resistance offered by Oil Duct
C_{spacer}	Capacitance of Lumped Spacer
R_{spacer}	Resistance offered by Spacer Block
$C_{barrier}$	Capacitance of Pressboard Barrier Block
$R_{barrier}$	Resistance offered by Barrier Block
σ_{oil}	DC conductivity of transformer oil
σ_{paper}	DC conductivity of transformer paper insulation
σ_r	Average conductivity of insulation
ε_0	Vacuum permittivity
ε_r	Relative permittivity of material

CHAPTER 1

INTRODUCTION

- Motivation
- Literature Review
- Organisation of thesis

1. INTRODUCTION

1.1 Motivation

Many power transformers working today around the world are nearing towards the end of their expected design life. Power transformer is an expensive electrical machine thereby making it very costly to replace; however, few of these transformers until now are in good state and can be operated for a few more years. Determining the condition of the transformers would be of tremendous importance to the power sector. Well-coordinated maintenance by qualified personnel along with replacement planning is not possible in the current scenario. Condition assessment and online monitoring are gaining tremendous importance nowadays. A numerous number of techniques are available in electrical, mechanical and chemical domain for insulation testing of power transformers.

Insulation degradation is one of the major concern for the aged transformers. Material used in transformer insulation degrade at high temperatures in the presence of moisture and air. Degradation from thermal stress influences the electrical, mechanical, and chemical properties. Transformer insulation failure would eventually lead to transformer failure. Hence we require condition assessment of insulation. Most of the condition assessment techniques, namely, the dissolved gas analysis (DGA), measurement of insulation resistance (IR), partial discharges (PD), dielectric loss factor (DLF), interfacial polarisation, have been in use for quite a number of years.

In this decade, new diagnostic methods are given more emphasis contrary to the classical techniques like power frequency dissipation factor, insulation resistance and polarisation index measurement.

These new methods are based on either frequency or time domain polarisation measurements. Time domain measurements are carried out by applying dc voltage across the test object [1]. Polarisation and Depolarization current measurement and return voltage measurement are time domain techniques and have gained significant impetus in the last ten years.

Polarisation and Depolarisation current measurement (PDC) of transformer insulation is one of the best indicator of a transformer's insulation condition. Transformer Oil conductivity as well as moisture content in paper insulation can be found out by this method. This serves as a criteria for further actions.

1.2 Literature Review

Ageing of the power transformer insulation (oil/paper insulation) system is influenced by chemical, mechanical and thermal stresses. Thermal stress is one of the leading causes for degradation process of any insulation which include oil and paper dielectrics. Due to the presence of stresses, the paper insulation becomes fragile and the longevity capability of this material against mechanical tension is greatly reduced [2]. The process of breaking-down of chains of glucose molecules in cellulose gives rise to water molecules in the insulation, which acts as a incendiary for further breaking down of molecule chains. Furthermore, the breakdown voltage level of the insulation is decreased with increase in moisture content in the oil. The material conductivity is a property, by which it can be correlated to the moisture level and different by-products prevalent in the insulation. Thus valuable information about the conductivity of the dielectric insulation may serve as an important criterion for the condition assessment.

Although there are indirect methods to find out the moisture level in paper insulation. But these method require collection of samples from extremely critical locations (outer windings, leads) and then examining them in laboratories. Moisture in oil can be evaluated by collecting sample from oil-tank and analysing them by Karl-Fischer titration. Similarly moisture in paper insulation can be calculated by using Oommen's equilibrium method [3].

These indirect methods have a much larger error corresponding to the calculated values. Hence we require time or frequency domain relaxation current measurement for more accurate results. When an electric field is applied to a dielectric, a relative shift of charges occurs within the dielectric giving rise to dielectric polarization. Presently, there are three main types of dielectric response measurement techniques: (a) Polarisation and Depolarisation Current measurement (PDC), (b) Return Voltage Measurement (RVM) and (c) Frequency Domain Spectroscopy. PDC and RVM are DC voltage tests in which dielectric response is measured as function of time.

In Polarisation and Depolarisation Current (PDC) method, a step voltage of constant magnitude, is applied to the test sample for a long continuous period of time (e.g. 10000s) and the resulting polarisation current through the test sample is measured. This current arises from the dc conductivity and the various polarisation processes having different time constants pertaining to different insulating dielectric materials. The measurement of polarisation current is stopped when the polarisation current becomes either stable or very low. Subsequently, the test object is short circuited for a long continuous period of time and the depolarisation current is measured, which do not have any contribution from dc conductivity.

Gafvert et al. [4] reported observations on polarization/depolarization current measurements to calculate the quality of the insulation of various transformers. He recommends relaxation current measurements as a better method because the properties of oil and paper materials can be uniquely explained from the experimental observations.

Der Houhanessian et al. [5] demonstrated results of polarization current measurements of pressboard samples at various moisture content and temperature levels. Their results showed how the moisture present in pressboard samples could be quantified from calculation of the conductivity of the transformer.

1.3 Organisation of Thesis

Chapter 1: This chapter includes the brief introduction, motivation, and literature concept of polarisation and depolarisation current measurement technique for condition assessment of power transformer.

Chapter 2: This chapter deals with the detailed overview about the mechanism of dielectric response in the presence of an external electric field and also provides basic information about polarisation and depolarisation current measurement technique.

Chapter 3: This chapter deals with the modelling of insulation structure in a power transformer along with the details of RC model used to describe a linear dielectric. It also provides the equivalent circuit of the insulation in a transformer.

Chapter 4: This chapter deals with development of Simulink model of the insulation arrangement and a novel method by simplifying the equivalent circuit and calculating the transfer function of the equivalent circuit along with the simulation results.

Chapter 5: This chapter deals with the idea of estimating the dc conductivity and moisture level present in the paper insulation using the values obtained from the results. It also contains the results obtained from the research work.

Chapter 6: This chapter aims at the conclusion drawn from the results obtained and also provides insight into the future prospect of the work.

Chapter 7: This chapter provides the various references used in this research work.

CHAPTER 2

MECHANISM OF DIELECTRIC RESPONSE

- Polarisation Mechanism of a Linear Dielectric
- Theory of Dielectric Response
- Polarisation and Depolarisation Current Measurement Technique

2. MECHANISM OF DIELECTRIC RESPONSE

2.1 Polarisation Mechanism of a Linear Dielectric

When an electric field is applied to a dielectric, a relative shift of charges occurs within the dielectric giving rise to dielectric polarization. There are basically four different types of polarization mechanisms:

(a) Electronic Polarisation – In this mechanism, dipoles are induced by the displacement of the center of the negative charge of the electrons with respect to the positively charged nucleus due to the driving electric field. It is extremely fast with frequency up to 10^{15} Hz.

(b) Ionic Polarisation – In this case, the dielectric must have some ionic character, which cancel each other and cannot rotate. The applied electric field induces dipoles by displacing the ions from their original position. Frequencies can range up to 10^{12} Hz.

(c) Dipolar Polarisation – If the dielectric material contains permanent dipoles which can rotate freely, then on application of driving electric field there is an alignment of these dipoles thereby inducing polarization of the dielectric. In this case frequencies can lie up to 10^{8} Hz.

(d) Interfacial Polarization – In multi-dielectric medium, such as a transformer insulation. Under the application of electric field positive and negative charges may get deposited at the junction of the two media. This mechanism is slow and frequencies can range up to 10^{5} Hz [7].

On application of electric field some or all mechanism may act at the same time. Electronic Polarisation is always present in any dielectric. Presently there are three types of dielectric response measurement techniques.

(a) Polarisation and Depolarization Current Measurement Technique (PDC).

(b) Return Voltage Measurement Technique (RVM).

(c) Frequency Dielectric Response (FDS).

PDC and RVM are DC voltage tests and dielectric response is recorded as a function of time, whereas FDS is an AC voltage test and response parameters are measured as a function of frequency.

2.2 Theory of Dielectric Response

Applying a non-varying electric field E(t) across the dielectric, the current density flowing through the dielectric can be expressed as

$$J(t) = \sigma E(t) + \frac{dD(t)}{dt} \qquad (1)$$

The current density J(t) is the addition of two separate currents, conduction and displacement current [9], here σ is the dc conductivity and D(t) is the electric displacement and is given as below

$$D(t) = \varepsilon_0 \varepsilon_r \quad E(t) + \Delta P(t) \qquad (2)$$

Here ε_r is the relative permittivity and ε_0 is the vacuum permittivity. P(t) is called the dielectric polarization with dependency upon the response function f(t) of the dielectric material. The response function f(t) is used to describe the basic property of the insulating dielectric system and is provides valuable data about the dielectric[10].

Assuming the test object is totally discharged with no residual polarisation and that a dc step voltage is applied characterised by

$$U(t) = \begin{cases} 0 & t < 0 \\ U_0 & 0 < t < t_c \\ 0 & t > t_c \end{cases} \qquad (3)$$

It will yield no current for time before t=0, and polarisation current for time $0 < t < t_c$. The polarisation current flowing through the test object can be given as

$$i_p(t) = C_0 U_0 \left[\frac{\sigma}{\varepsilon_0} + f(t)\right] \quad (4)$$

After the removal of dc voltage source, depolarisation current builds up. The magnitude is given below

$$i_d(t) = C_0 U_0 [f(t) - f(t + t_c)] \quad (5)$$

We know that, for oil/paper insulation system, the dielectric response function can be modelled by the following equation [11].

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m} \quad (6)$$

2.3 Polarisation and Depolarisation Current Measurement (PDC) Technique

In PDC method, a DC step voltage of constant magnitude (~200V – 2000V), which is ripple free, is applied to the test object for a very long stretch of time (~10000s) and the obtained polarisation current flowing in the test sample is measured. Polarisation current comprises of dc conductivity and various polarisation processes each having different time constants corresponding to numerous insulating material and their different conditions. After a certain amount of time when the current becomes very small or zero, the measurement is stopped [12]. Furthermore, the test sample is shorted for a long interval of time and the resulting depolarisation current is recorded, which notably does not have any contribution from dc conductivity.

The findings reported in [13] indicate that the starting part of the curve is highly sensitive to higher mobility of charge carriers in insulating oils thereby proving that it is quite responsive to transformer oil. The steady part of the curve at longer times is because of the immobile charge dipoles in paper insulation.

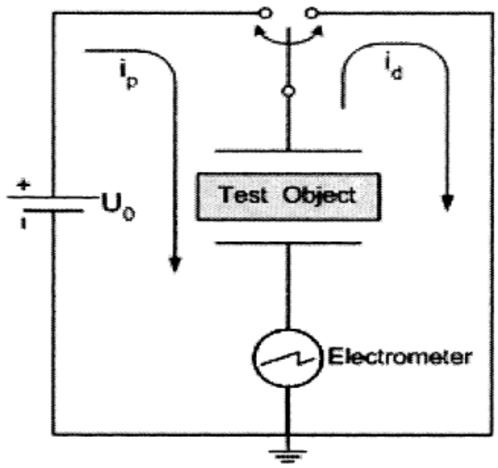

Figure 1: Basic Polarisation and Depolarisation Current (PDC) measuring circuit.

Fig above shows the basic PDC measuring circuit. For measuring the polarisation current the switch is in left position whereas while measuring depolarisation current switch is thrown on to the right side.

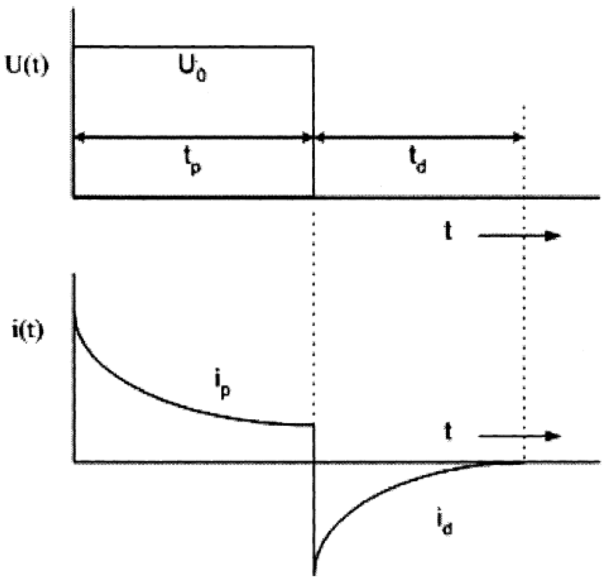

Figure 2: Typical waveforms of Polarisation and Depolarisation Current.

Figure 2 shows the typical nature of relaxation currents due to the application of step voltage U(t). U_0 is the applied dc step voltage. Here t_p and t_d are the charging and discharging periods of the process. i_p is the polarisation current whereas i_d is the depolarisation current. Relaxation currents are strongly influenced by the properties of insulating material as well as the geometric arrangement of the insulation.

CHAPTER 3

MODELLING OF TRANSFORMER MAIN INSULATION

- RC Model for Dielectric Response
- Elementary Theory behind the Model
- Modelling of Transformer Insulation
- Equivalent Circuit of the Main Insulation in a Power Transformer
- Estimation of DC Conductivity of Main Insulation in a Transformer

3. MODELLING OF TRANSFORMER MAIN INSULATION

3.1 RC Model for Dielectric Response

In the past decade, many researchers [3]–[6] have put forward numerous equivalent circuits for modelling the power transformer insulation system for a comprehensive understanding of the dielectric response. In reality, many of the proposed models until now have used conventional Debye model based on a complex RC model. Gafvert [3], has put forward the quantitative analysis of transformer insulation based upon the elementary equations of dielectric physics. Researcher [4]-[7], derived the formulation of a corresponding equivalent circuit from (PDC) relaxation current measurements. The modelling processes in the literature [3]–[8] were greatly dependent on the data of the geometry and positioning of dielectric insulation in the machine.

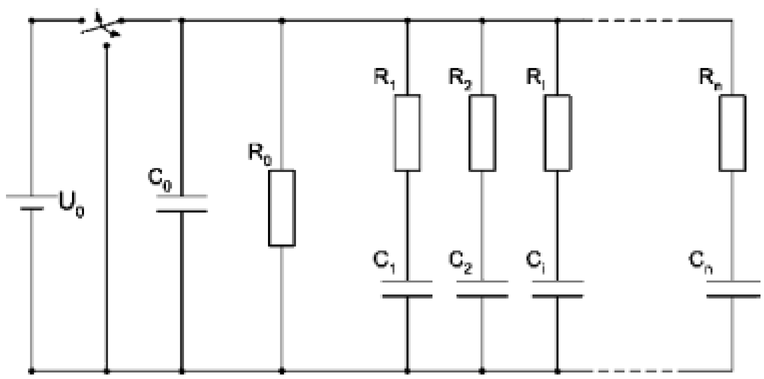

Figure 3. Equivalent RC circuit to model a linear dielectric.

3.2 Elementary Theory behind the Model

When an electric field is applied to a dielectric, a relative shift of charges occurs within the dielectric giving rise to dielectric polarization. When the field is switched off, the dipoles follow their normal tendency and return to their original state [14]. In a linear dielectric, every polar group has a different arrangement of neighbouring molecules. Thus, the response time of polar groups after the implementation of the electric field differs from each another [11]. These processes can be efficiently modelled by an arrangement of parallel RC branches each having resistor and capacitor connected in series as shown in the circuit of Fig. 3.

These dipoles, which are randomly distributed, are characterised by time constants given by $\tau = RC$. Conduction current flows in the insulating dielectric material along with polarisation current. This conduction current is prevalent due to the insulation dc resistance R_0, here C_0 is the geometric capacitance of the insulation.

3.3 Modelling of Transformer Insulation

The winding composition of a single phase of a power transformer is build on a primary winding (low voltage winding) closest to the limbs of the transformer core, covered by the secondary winding (high voltage winding), which is kept apart from the former by the main duct. This duct contains a series of paper insulator pressboards along with oil ducts in between to provide cooling and insulation. This arrangement also contains axial insulating paper material spacers to hold the barriers firmly. Figure 4 portrays a cross-section view of the major insulation between the windings. As the total length of the transformer windings is much more than the radial length between the transformer windings, the impact of the insulation between the windings and the yoke of the transformer is assumed to be negligible. To carry out assessment of the moisture level in the paper pressboard and the conductivity of oil in the power transformer insulation system data pertaining to the dimensions and the configuration of the insulation is needed.

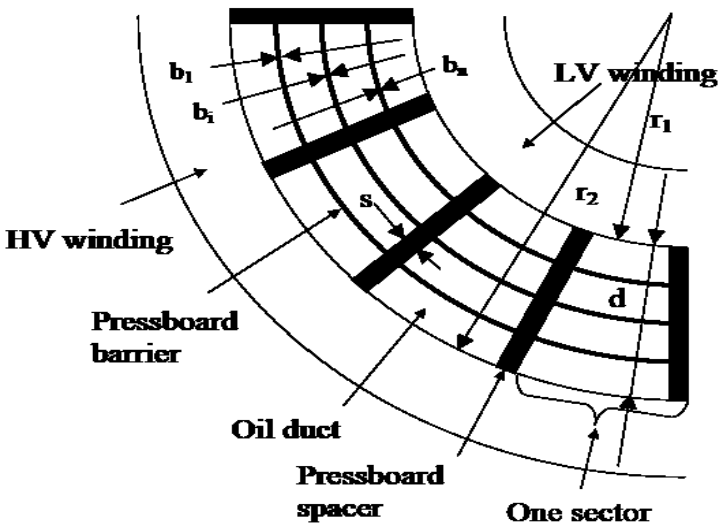

Figure 4: The cross-sectional view of the main insulation between primary and secondary windings of a power transformer.

Since the above description is too intricate to model, we can simplify the equivalent model by lumping all the spacers, barriers and oil ducts together to form a simpler insulation structure [18].

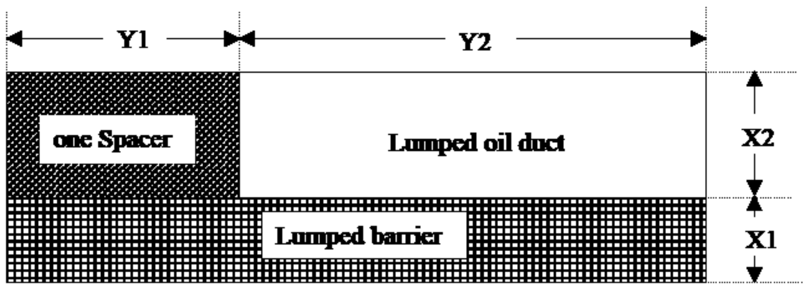

Figure 5: Lumped Insulation system in a single sector of the main insulation between windings.

If we consider a single phase of a transformer, its insulation between the low voltage and high voltage windings can be represented with the height h, the total number of sectors in the insulation depicted by N_{sec}, coincidentally, it is also equal to the number of the spacers in the periphery of insulation and the lumped arguments X_1, X_2, Y_1 and Y_2, which describe the configuration of the main insulation.

The height h is given by

$$h = \frac{(h_{LW}+h_{HV})}{2} \tag{7}$$

here, "h_{LW}" and "h_{HW}" are respectively the height of the primary winding and the height of the secondary winding. The parameters X_1, X_2, Y_1 and Y_2, are calculated as given below.

$$X1 = \sum b_{i,} \qquad for\ i = 1 \ldots .n, \tag{8}$$

Here b_i is the width of barrier i.

$$X2 = d - X1 \tag{9}$$

Also, $$d = r_2 - r_1 \tag{10}$$

The d, R_2, R_1 are width of the main duct, outer radius and inner radius respectively.

$$Y1 = s, \tag{11}$$

s is the spacer width

$$Y2 = \left(\frac{c}{nsec}\right) - Y1 \tag{12}$$

c is the median circumference of the main insulation duct and is described as

$$c = \pi[r_1 + r_2] \tag{13}$$

After successfully calculating the dimensions of the insulation model, geometric capacitance of all the lumped parameters can be calculated by considering insulation to be of cylindrical shape with height hwin.

3.4 Equivalent Circuit of the Main Insulation in a Power Transformer

Simplified lumped insulation model of the main insulation of a transformer can be used to model the equivalent circuit of the insulation.

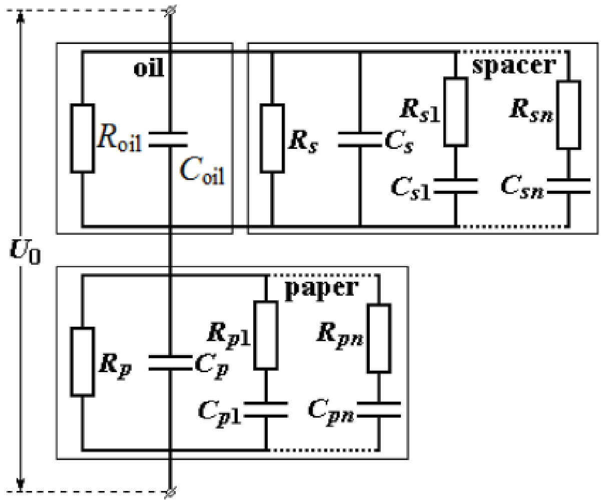

Figure 6: Equivalent circuit of the main insulation of a power transformer.

Here, the oil duct is represented by its resistance R_{oil} and the capacitance C_{oil}. The reason for such an assumption is that transformer oil shows no polarisation phenomenon within the power frequency range. Geometric capacitance of the oil duct can easily be calculated from the geometry of the insulation system, the values for R_{oil} and C_{oil} can be determined by using the following equations.

$$R_{oil} = \frac{\varepsilon_0}{\sigma_{oil}\, C_O} \qquad (14)$$

$$C_{oil} = \varepsilon_{roil} C_o \qquad (15)$$

Here, ε_0 is the permittivity of vacuum, σ_{oil} and ε_{roil} are the dc conductivity and relative permittivity of oil.

The barrier and the spacers are also modelled (Fig. 6) in a similar way by their resistances, R_B and R_S, along with their power frequency capacitances, C_B and C_S calculated from their DC conductivity σ_{pb} and relative permittivity ε_{rpb}. The dispersion phenomenon in dielectric material of pressboard is represented by number of parallel RC chains. These can be calculated from previously conducted PDC measurement on homogeneous pressboard material only. Usually ε_{roil} = 2.2 whereas ε_{rpb} = 4.9.Using these values we obtain the following.

Table 1: Calculated Geometric Capacitance of 4 test Transformers

Transformer Sample	Hwin (mm)	X1 (mm)	X2 (mm)	Y1 (mm)	Y2 (mm)	C_{0D} (F)	C_{SD} (F)	C_{BD} (F)
A	1597	18	54	30	120.1	$6.63E^{-9}$	$2.57E^{-9}$	$4.11E^{-8}$
B	1820	28.5	49.5	20	123.9	$7.98E^{-9}$	$1.71E^{-9}$	$2.9E^{-8}$
C	2585	65	55	15	75.27	$1.24E^{-8}$	$2.45E^{-9}$	$2.27E^{-8}$
D	2270	8	29	12	11.77	$4.74E^{-9}$	$7.8E^{-9}$	$3.54E^{-8}$

Table 2: Calculated R and C of lumped parameters

Test Sample	σ_{oil} (pS/m)	σ_{pb} (pS/m)	R_{Oil} (Ω)	C_{Oil} (F)	R_B (Ω)	C_B (F)	R_S (Ω)	C_S (F)
A	0.29	0.0025	$4.6E^{12}$	$1.46E^{-8}$	$86E^{12}$	$2E^{-7}$	$1.4E^{15}$	$12.5E^{-9}$
B	2.4	0.3	$4.6E^{11}$	$1.756E^{-8}$	$1.02\ E^{12}$	$1.42\ E^{-7}$	$1.72E^{13}$	$8.4E^{-9}$
C	1.65	0.06	$4.32E^{12}$	$2.728E^{-8}$	$6.5\ E^{12}$	$1.12\ E^{-7}$	$6E^{13}$	$12E^{-9}$
D	0.3	0.003	$6.22E^{12}$	$9.83E^{-8}$	$83.3\ E^{12}$	$1.73\ E^{-7}$	$3.8\ E^{14}$	$38E^{-9}$

The polarisation dispersion of pressboard made up of paper material, which is an important quantity in these analysis, is represented by a number of parallel connections of RC chains, which demonstrate the dielectric response function. The exact quantity of these RC chains can be evaluated from previously conducted polarisation and depolarisation current experiment on dielectric paper test samples, again taking into account the geometrical capacitance of the sample. The individual R_i-C_i with corresponding time constant τ_i can be determined by curve fitting the depolarisation current with the following equation [19].

$$i_d = \sum_{i=1}^{n}(A_i . e^{\left(-\frac{t}{\tau i}\right)}) \tag{16}$$

The process initiates with the greatest time constant RC chain. The value of depolarization current at the end time is assumed to be only due to the contribution from greatest time constant RC chain, the effect of branches with smaller time constant is negligible because its effect dies down before this time. Henceforth, the end region of the depolarization current is essential to calculate the value of largest time constant RC chain by using an exponential curve-fitting approach.

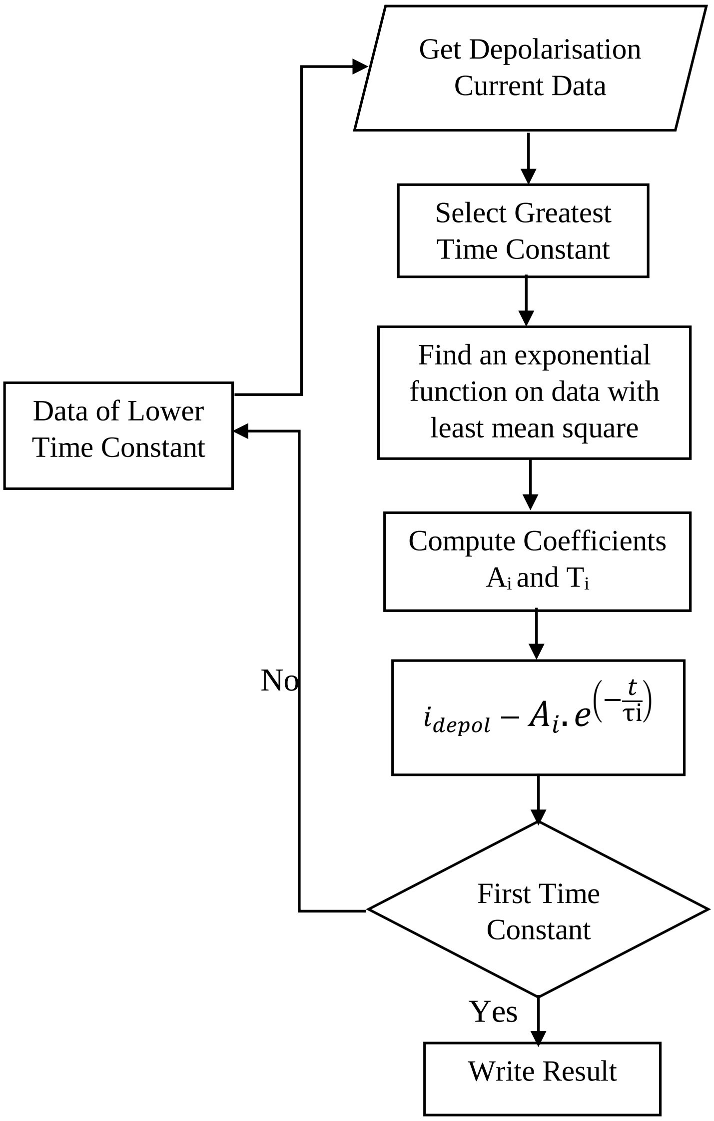

Figure 7: Flowchart for calculation of parallel RC parameters of RC insulation model.

Polarisation and Depolarisation results on pressboard samples provide the following data [9].

Table 3: Calculated Values of RC elements of paper sample through curve fitting technique.

Coefficient (A_i)	Time Constant (τ_i)	R_i (GΩ)	C_i (nF)
$2.384E^{-8}$	20842	55	378
$9.527E^{-8}$	2891.8	20	138
$3.346E^{-7}$	569.15	5.9	95
$1.214E^{-6}$	91.57	1.46	55.5
$3.475E^{-6}$	22.722	6.57	39.5
$4.608E^{-6}$	3.98	41.6	9.6

These calculated values are used in the insulation model, which are simulated in different environments.

3.5 Estimation of DC Conductivity of Main Insulation in a Transformer

From measurements of relaxation currents (PDC), we can easily compute average conductivity σ_r, of the sample in question (oil-paper insulation) [4], [10], and [11]. If the sample object is diagnosed with PDC technique for sufficient charging time then, (4) and (5) can be recombined in such a way to eliminate the response function and find the conductivity of the oil-paper insulation system as

$$\sigma_r = \frac{\varepsilon_0}{C_0 U_0}\left(i_{pol}(t) - i_{depol}(t)\right) \qquad (17)$$

The average conductivity of a power transformer insulation is found to be proportional to the difference of polarization and depolarization current. The average conductivity, is a mixture of the conductivities of oil dielectric and paper material that together form the insulation model. For the purpose of modelling, it is quite often to show the insulation arrangement by a lumped spacers, oil ducts and barriers, known as the X-Y model, as shown in Fig. 21 [22]. This model, comprises of a parameter X, which is defined as the ratio of the total width of all barriers, fused together to form a single entity, to the duct width [13]. The spacer coverage, Y, is described as the ratio of the total thickness of every spacers to the total periphery of the duct.

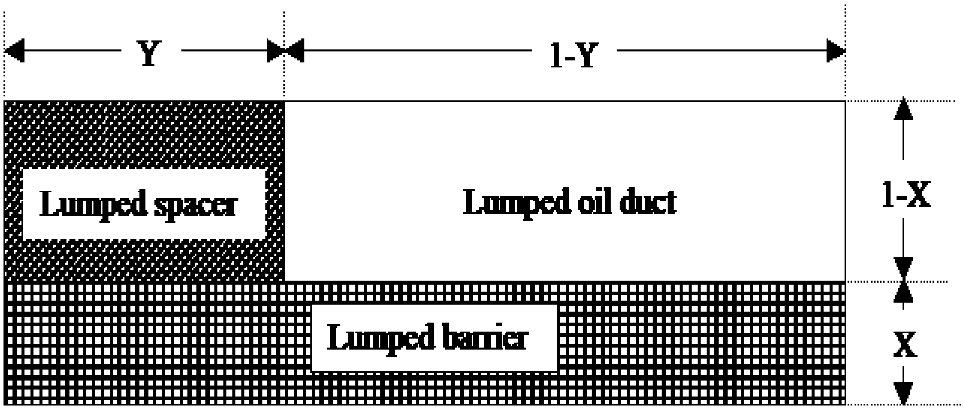

Figure 8: X-Y model of Main Insulation in Power Transformer.

According to the figure 21, “X” and “Y” are defined as follows [13].

$$X = B_{Total}/d \quad (18)$$

$$B_{Total} = \sum b_{i,} \qquad for\ i = 1 \ldots .n, \quad (19)$$

$$Y = S_{Total}/c \quad (20)$$

$$S_{Total} = m \times s \quad (21)$$

Here d and c, are already defined by equations (10) and (13)

Table 4: Calculated X-Y parameters

Transformer Sample	d (mm)	X1 (mm)	X	Y1 (mm)	Y2 (mm)	Y
A	72	18	0.25	30	120.1	0.25
B	78	28.5	0.36	20	123.9	0.16
C	120	65	0.46	15	75.27	0.2

For the X-Y model (as shown in Fig. 21), the equivalent conductivity of the insulation is written in terms of paper and oil conductivities as,

$$\sigma_r = \frac{Y}{\frac{1-X}{\sigma_{spacer}} + \frac{X}{\sigma_{barrier}}} + \frac{1-Y}{\frac{1-X}{\sigma_{oil}} + \frac{X}{\sigma_{barrier}}} \tag{22}$$

We know that,

$\sigma_{barrier} = \sigma_{spacer} = \sigma_{paper}$

$$\sigma_r = \frac{Y}{\frac{1}{\sigma_{paper}}} + \frac{1-Y}{\frac{\sigma_{paper}(1-X)+X\sigma_{oil}}{\sigma_{oil} \times \sigma_{paper}}} \tag{23}$$

Similarly, the effective relative permittivity of the insulation can also be evaluated as

$$\varepsilon_r = \frac{Y}{\frac{1}{\varepsilon_{paper}}} + \frac{1-Y}{\frac{\varepsilon_{paper}(1-X)+X\varepsilon_{oil}}{\varepsilon_{oil} \times \varepsilon_{paper}}} \tag{24}$$

The oil conductivity can be represented in terms of polarization current just at start of the experiment.

$$\sigma_{oil} = \frac{\varepsilon_0 . \varepsilon_{oil}}{\varepsilon_r . C_0 . U_0} \times i_{pol}(0+) \tag{25}$$

Using these equations we can find the average conductivity of the mail insulation in a power transformer.

CHAPTER 4

SIMULATION OF THE MAIN INSULATION OF POWER TRANSFORMER

- Simulink Model for Polarisation and Depolarisation Current Measurement Technique

4. SIMULINK MODEL OF THE MAIN INSULATION OF POWER TRANSFORMER

4.1 Simulink Model for Polarisation and Depolarisation Current Measurement Technique

We have successfully evaluated all the branch parameters, these parameters are used to model the insulation system of a power transformer. Simulink software is used to simulation.

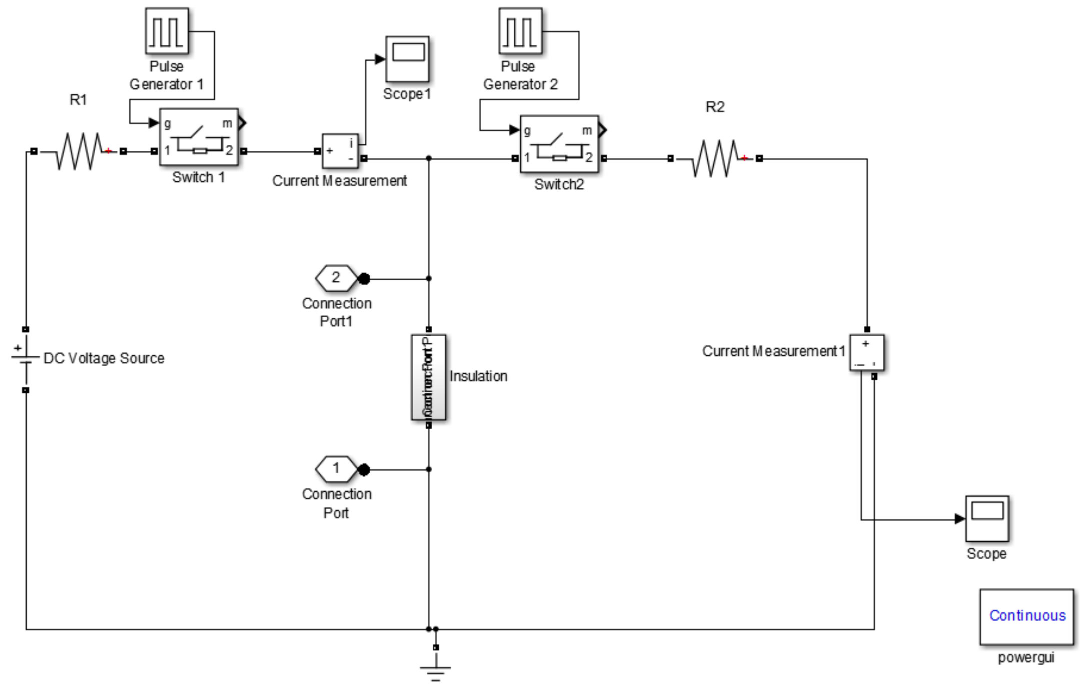

Figure 9: Simulink Model of PDC measuring circuit for transformer insulation.

Figure 8 shows how the PDC circuit is formulated in the software environment. A constant DC voltage source is applied across the test sample. Here the test sample is main insulation of the power transformer. Two pulse generators are connected respectively to switches which control the charging and discharging time. Two current measurement blocks are also connected to measure the polarisation and depolarisation current through the sample.

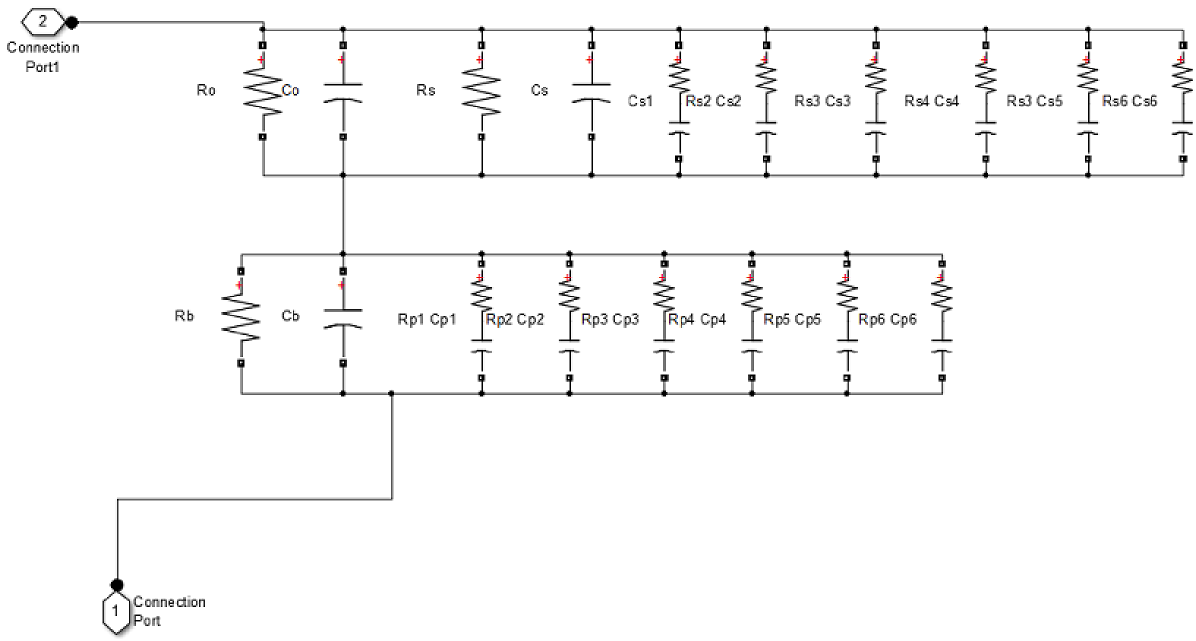

Figure 10: Main insulation model used as test sample in polarisation and depolarisation current measurement technique.

As already discussed in section 3.4, the main insulation is simulated through R and C elements of oil, spacer and barrier blocks. Since both pressboard barrier and spacer blocks are assumed to be made of same paper material, data from Table 3 is used in parallel RC chains to simulate dielectric response function.

CHAPTER 5

RESULTS AND DISCUSSION

- Simulation Results
- Influences of Oil and Paper Conductivities on Polarisation and Depolarisation Current.
- Investigation of Temperature Effects on Polarisation and Depolarisation Current Measurement
- Estimation of average conductivity of the insulation
- Discussion

5. RESULTS AND DISCUSSION

5.1 Simulation Results

Transformer A (7MVA, 66/11kV, Y/Δ connected) of dimensions given in Table 1 is simulated with its calculated insulation parameters using this model. DC voltage source applied is of the magnitude 1000.5 V and charging and discharging time of 10000 seconds is used.

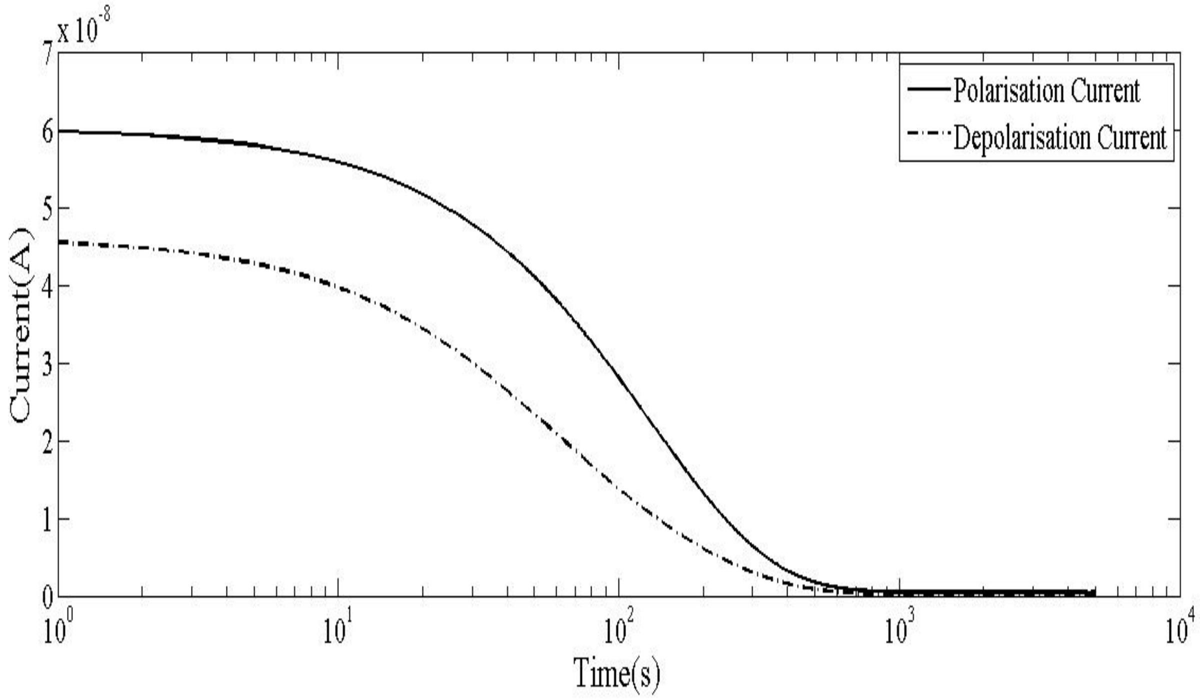

Figure 11: Polarisation and Depolarisation Current curves obtained for Transformer A.

Transformer B (30 MVA, 132/33kV, Y/Δ connected) of dimensions given in Table 1 with its calculated insulation parameters was simulated using this model and the obtained curves are shown below.

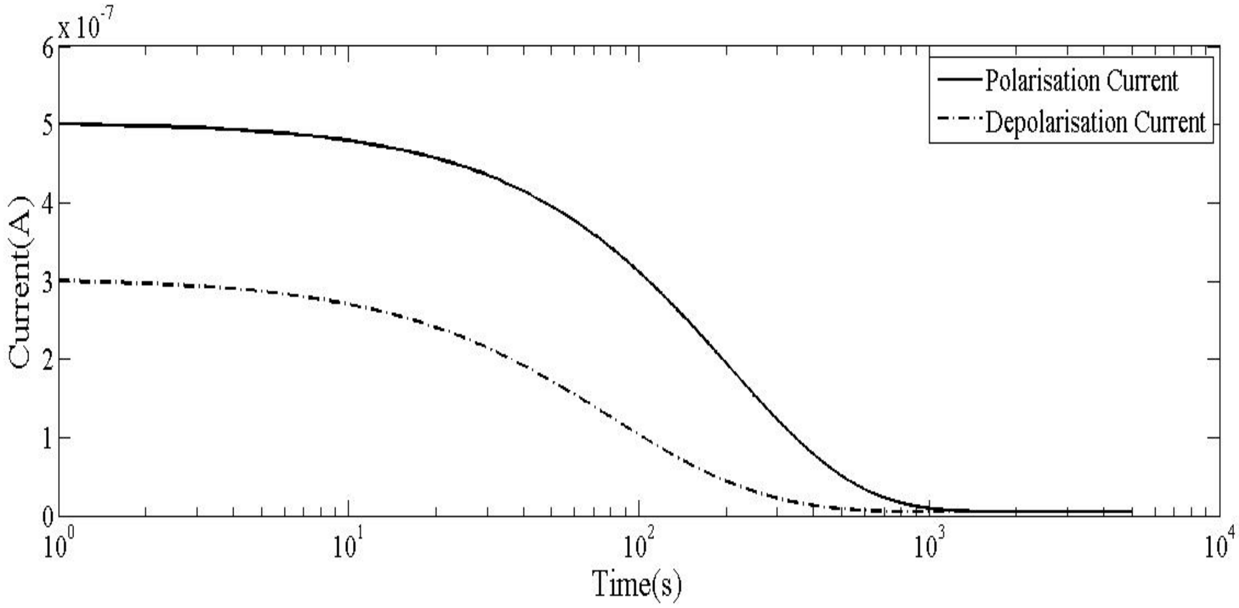

Figure 12: Polarisation and Depolarisation Current curves obtained for Transformer B.

5.2 Influences of Oil and Paper Conductivities on Polarisation and Depolarisation Current.

To understand the relationship of the paper and oil conductivities on the relaxation currents, a simulation is done with the already created Simulink model. Researcher [8] proved that the response function f (*t)* as given in equation (6), is greatly affected by the 2 dominant time-constants *n* and *m*. The time constant *n* affects the curvature of the dielectric response function at small times, whereas the characteristics of response function at larger times is heavily dependent upon counterpart time-constant *m*. Meanwhile, it was previously pointed out [20] that the curvature of the relaxation currents (polarisation and depolarisation current) at smaller times are affected by the conductivity of the oil used, likewise the end parts of the relaxation currents are determined by paper dielectric conductivity of the system. Time-constants namely, *n* and *m* are, therefore associated with the conductivities of oil dielectric material and paper material. To know more about the effects of the changing of oil and paper conductivity on the relaxation currents (PDC), these currents are simulated through the Simulink model, with various values of conductivities. Figures 12 to 14 show the effect of variation in paper and oil conductivities on relaxation currents. Variation in conductivity of oil and paper would lead to variation in resistance and capacitance of the lumped parameters according to the equation (14) and (15).

Table 5: Variation in Resistance due to change in conductivity.

σ_{oil} (pS/m)	σ_{pb} (pS/m)	R_{Oil} (Ω)	C_{Oil} (F)	R_B (Ω)	C_B (F)	R_S (Ω)	C_S (F)
1.5	0.015	$0.89E^{12}$	$1.46E^{-8}$	$14.35E^{12}$	$2.01E^{-7}$	$2.3E^{14}$	$12.5E^{-9}$
3	0.15	$1.78E^{11}$	$1.46E^{-8}$	$1.43E^{12}$	$2.01E^{-7}$	$2.3E^{13}$	$12.5E^{-9}$
6	1.5	$3.56E^{12}$	$1.46E^{-8}$	$1.43E^{11}$	$2.01E^{-7}$	$2.3E^{12}$	$12.5E^{-9}$

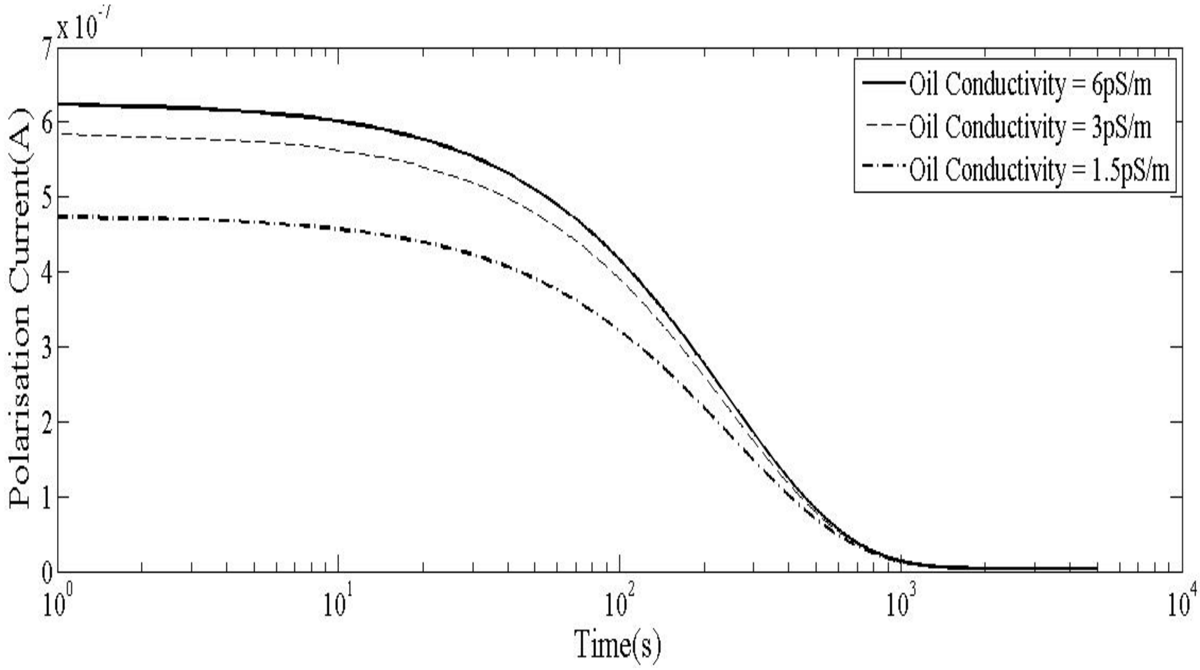

Figure 13: Variation of Polarisation Current with change in oil conductivity.

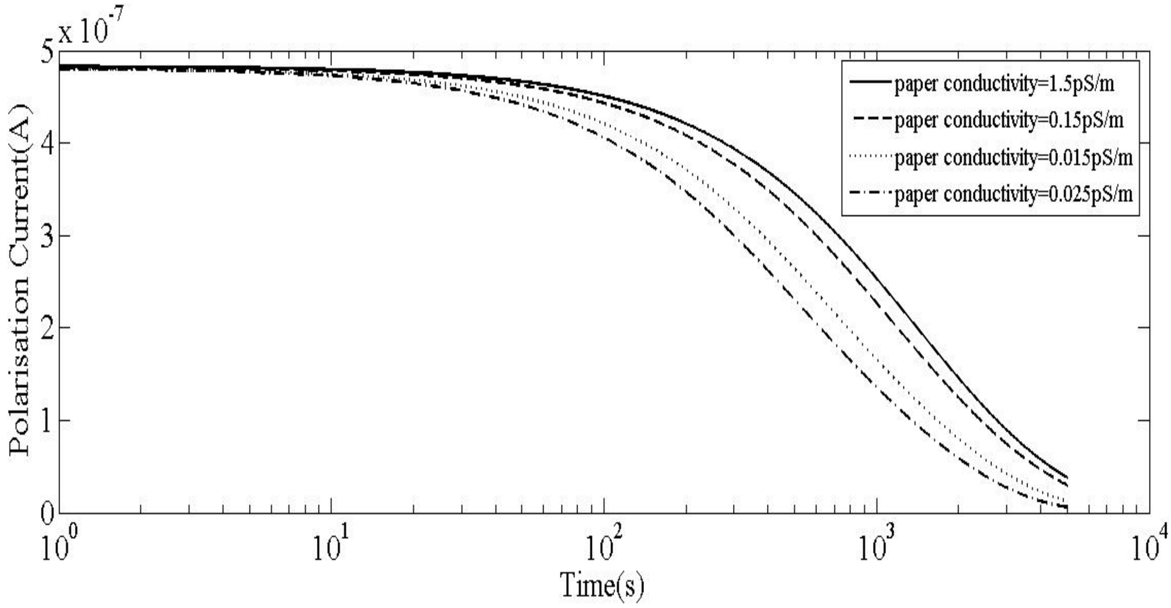

Figure 14: Variation of Polarisation Current with change in paper conductivity.

Figure 12 and 13 shows the effect of changing the paper and oil conductivity. The variation in oil conductivity targets the curvature at the starting region whereas on the contrary paper conductivity changes the end regions of the curve. This is due to the not so mobile charge carriers in paper dielectric which become dominant when quite a period of time has passed by.

5.3 Investigation of Temperature Effects on Polarisation and Depolarisation Current Measurement

In a power transformer insulation, both the oil and paper conductivities were found dependent on temperature. Further studies show that it increases exponentially with temperature [21].As reported by [11], the conductivity can be describes through an exponential function.

$$\sigma(T) = A.e^{(-E_{ac}/kT)} \quad (26)$$

Where T is the absolute temperature with standard unit as Kelvin (K), A is a constant used to refer the mobility of dipoles, k is the *Boltzman* constant and E_{ac} is the activation energy of the insulator. If we take Logarithm on both the right and left hand side of the equation, it can be shown that conductivity of the insulator has an inverse relationship with the absolute temperature.

$$\ln\big(\sigma(T)\big) = \ln(A) - \frac{E_{ac}}{kT} \qquad (27)$$

For the transformer oil used, we have	E_{ac} = 0.5eV
For paper Insulation used, we have	E_{acp} = 1.10eV
And we know that Boltzman constant	k = 8.62E^{-5} eV K^{-1}
For Transformer C we have	σ_{oil} = 1.65pS/m

Table 6: Variation of Oil Conductivity with Temperature.

Absolute Temperature (K)	Oil Conductivity (pS/m)	Resistance R_{oil} (Ω)
293	1.65	4.32E^{12}
313	4.3	1.66E^{12}
333	13.5	5.28E^{11}
353	41.03	1.73E^{11}

Table 7: Variation of Paper Conductivity with Temperature.

Absolute Temperature (K)	Paper Conductivity (pS/m)	Resistance R_p (Ω)
293	6.03E^{-2}	6.5 E^{12}
313	2.19E^{-1}	1.87 E^{12}
333	3.16	1.24E^{11}
353	22.85	1.7 E^{10}

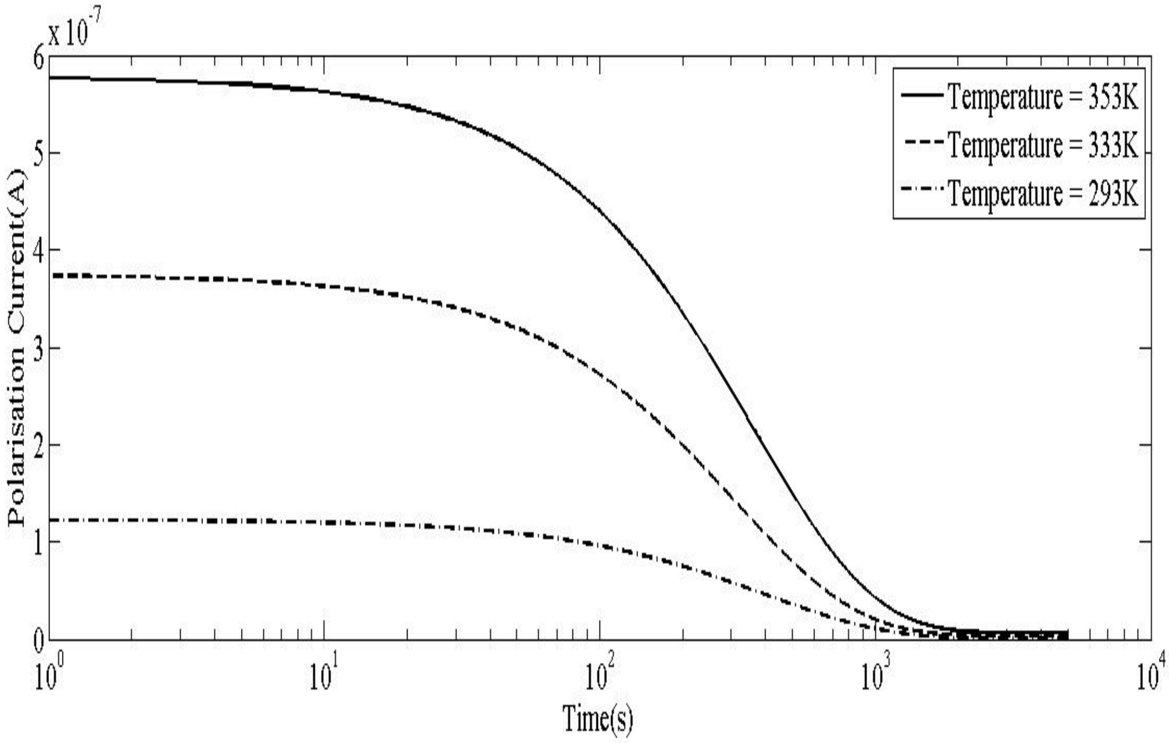

Figure 15: Effect of Temperature on Polarisation Current in insulation of transformer D.

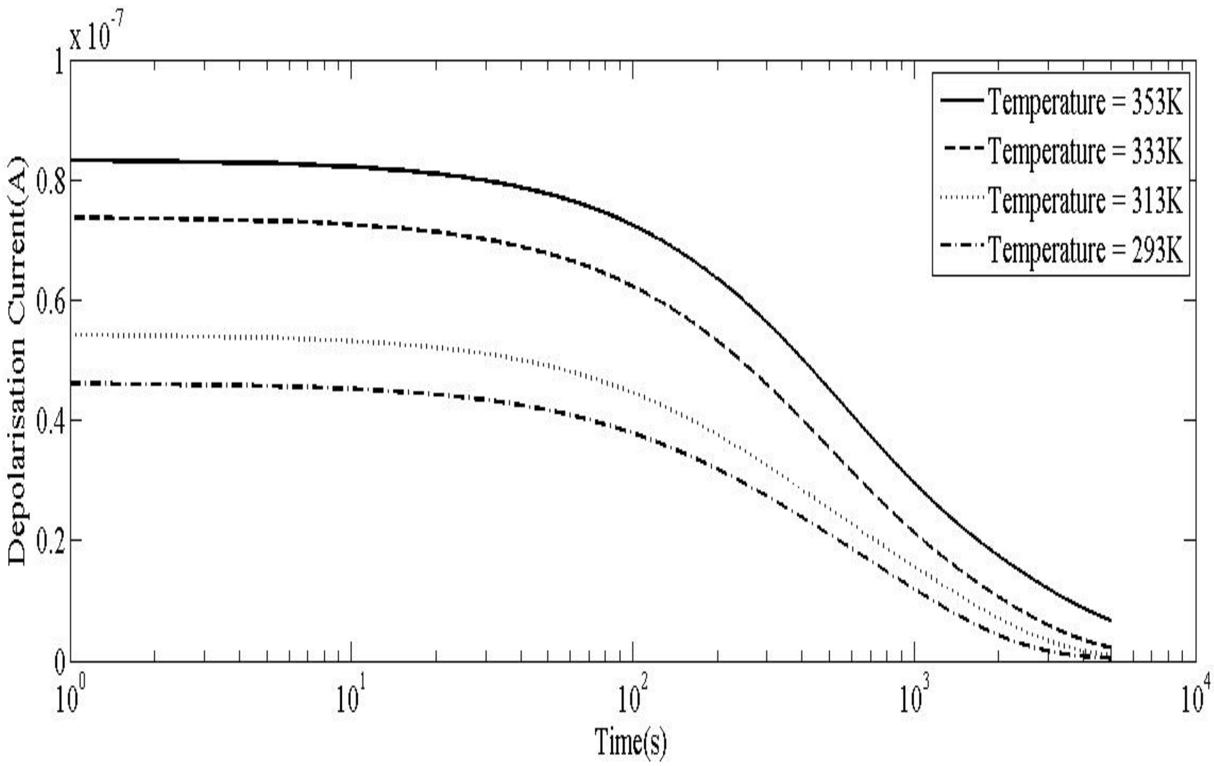

Figure 16: Effect of Temperature on Depolarisation Current in insulation of transformer.

Figure 18 and 19 show the variation in polarisation and depolarisation current with changes made in temperature. The temperature measured here is absolute temperature and the unit is in

Kelvin (K). According to the data obtained in Table 7 we observe that conductivity is dependent on temperature. With increase in temperature the conductivity shoots up, which thereby increases the dc conductivity of both oil and paper dielectrics used in main insulation of a power transformer.

5.4 Estimation of Average Conductivity of the insulation

Using equations (22)-(25), it can be shown that average conductivity depends upon the difference of relaxation currents. Calculated values are shown below.

Table 8: Calculated values of oil, paper and average conductivities.

Transformer	i_{pol} - i_{depol} (A)	$I_{pol}(0+)$ (A)	σ_r (pS/m)	ε_r	σ_{oil} (pS/m)	σ_{paper} (pS/m)
A	$2.89E^{-8}$	$6.13E^{-8}$	$6.3E^{-15}$	3.14	0.31	0.00021
B	$2.12E^{-7}$	$5.09E^{-7}$	$0.572E^{-12}$	3.012	2.51	0.27
C	$1.04E^{-8}$	$7.013E^{-8}$	$8.87E^{-14}$	3.28	1.71	0.054

5.5 Discussion

MATLAB Simulink program was used to simulate the transformer insulation system to obtain the polarisation and depolarisation curves for analysis of four transformers. From the simulation results it is evident that we can find out the dc conductivity of the dielectric test sample, in this study it is power transformer insulation. Furthermore, the effects of changing the conductivities of oil and paper dielectrics have been studied. The oil conductivity plays a dominant role in the starting of the polarisation and depolarisation current while changes in dielectric paper conductivity affects the latter end of the PDC curves. Using the simplified equivalent circuit, we find that there is more than 90 % correlation with the Simulink model results. Also, using the equations from basic dielectric response theory we can easily find out the conductivity of the transformer insulation. In this study, for transformer A (7 MVA, 66/11kV, Y/Δ connected) the average conductivity was estimated to be around 0.0063 pS/m, transformer B (50 MVA, 132/66kV, Y/Δ connected) insulation conductivity was found out to be 5.72 pS/m.

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

- Conclusion
- Scope for Future Work

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this research work, PDC method has been discussed in detail and a simplified equivalent circuit has been presented and the equations have been derived to describe the insulation of power transformers. By using this method, we have analysed four power transformers. The effect of changing the oil and paper conductivities is also studied in this work, along with the effect of temperature on relaxation currents. We have obtained the physical parameters of the transformers and the moisture level. The linear correlation coefficient between the Simulink data and the theoretical curves is of the order of 0.9 or greater, proving the accuracy of the model. The oil resistance is about three to ten orders of magnitude smaller than that of the paper, seemingly due to the increased content of copper ions with respect to the new transformers. Their activation energy was estimated to be = 0.5 eV, justifying the above supposition.

6.2 Scope for Future Work

There is a huge potential for future work in this area. Hardware implementation is of the utmost priority. Results from the simulated data can be compared with the experimental values to obtain the percentage error in the proposed model. An expert system can also be implemented which could provide fast and more accurate results based on the previously conducted assessment on power transformer. Furthermore, conventional Debye model approach can be replaced with a much more efficient Modified Debye Model [14].

CHAPTER 7
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7. REFERENCES

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