Relaxation studies on oil, pressboard and oil impregnated pressboard

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**RELAXATION STUDIES
ON OIL, PRESSBOARD AND OIL
IMPREGNATED PRESSBOARD**

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School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

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Statement of Originality

I hereby certify that the content of this Ph.D. thesis is the result of work done by me at NTU and has not been submitted for a higher degree to any other University or Institution.

30 -12-2005

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Cao Hongyan

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Abstract

Oil, paper and oil-impregnated insulation system is used extensively in electricity supply industry for high voltage power apparatus, such as transformers, capacitors and cables. Aging rate of such apparatus is a time function of electrical loading and corresponding operating temperature, moisture content, oxidation byproducts and acid content. Intrusive tensile strength and degree of polymerization measurements are the well established techniques to determine the aging level. Non-intrusive low-voltage electrical techniques based on relaxation measurements are finding their way to determine remaining life of aged apparatus. Three promising relaxation techniques are frequency domain spectroscopy (FDS), recovery voltage measurement (RVM) and polarization/depolarization current measurement (PDC). In this thesis, a laboratory relaxation study with FDS and RVM was carried out for a period of 3 years with the fabricated oil (OIL), pressboard (PB), oil-impregnated pressboard (OIP) samples and oil-filled single-phase transformer (SPT). The variation of relaxation parameters with equilibrium time, temperature change and the added polarizing impurities were studied on individual and composite dielectrics. It was found that all the studied dielectric materials require a minimum equilibrium time of 144 h in which the fluctuation in responses for a particular setting was minimum. Temperature increased oil and oil-impregnated paper conductance and capacitance while it reduced the above parameters with paper. Effect of oxidized impurities was also an increase in conductance and capacitance. In RVM, significant increase in peak voltage was obtained with temperature in oil-impregnated paper and paper. The results were interpreted by mathematical models. A new developed model, frequency dependent RC (FDRC) model was able to explain the different observations in comparison with extended Debye model (EDM). The study suggested the role of individual dielectric to composite dielectric. Aging studies in SPT before, during and after aging indicated that significant changes in relaxation could be obtained and maximum changes were observed during the end of aging at 100 °C. Measured water content indicated that it could increase from 20 ppm before aging to more than 50 ppm after aging for a period of 1100 h. The relaxation study suggested that relaxation measurements could be used as a reliable tool for estimating the aging condition of oil and paper insulation when enough database on dielectric responses of the defined insulation samples are available. The study showed that a simpler quantitative interpretation could be made using the newly developed FDRC model parameters.

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List of Symbols and Abbreviations

a, b	Fitted coefficients for $C_s(f)$
c, d	Fitted coefficients for $R_s(f)$
C	Capacitance
C_0	Geometrical capacitance of dielectric material
C_p	Parallel capacitance
C_s	Series capacitance
D	Electric displacement
$D(\omega)$	Complex electric displacement in frequency domain
E	Electric field
ε	Relative permittivity
ε_0	Permittivity of free space
ε_s	Static permittivity at $t = \infty$
ε_{∞}	Instantaneous (high frequency) relative permittivity
$\varepsilon^*(\omega)$	Complex relative permittivity in frequency domain
$f(t)$	Dielectric response function
i_{pol}	Polarization current
i_{depol}	Depolarization current
$j, j(\omega)$	Current density
K	Boltzman's constant
P	Polarization vector which is the dipole moment per unit volume
P_{∞}	Instantaneous (high frequency) polarization
P_0	Steady state orientation polarization
P_i	Interfacial polarization
ρ	Charge density
R	Resistance
R_p	Parallel resistance
R_s	Series resistance
$R_{so}(f)$	Series resistance of OIL in FDRC model
$C_{so}(f)$	Series capacitance of OIL in FDRC model
$R_{sp}(f)$	Series resistance of PB in FDRC model

List of Symbols and Abbreviations

$C_{sp}(f)$	Series capacitance of PB in FDRC model
$R_{sop}(f)$	Series resistance of OIP in simple series RC model
$C_{sop}(f)$	Series capacitance of OIP in simple RC model
t_0	Beginning of charging time in RVM
t_c	Charging time in RVM
t_d	Discharging time in RVM
t_p	Maximum (Peak) recovery voltage time
t_m	Measured time in RVM
τ, τ_s	Time constant of series RC of dielectric in frequency domain
τ_p	Time constant of parallel RC of dielectric in frequency domain
τ_i	Time constants of polarization elements of EDM in time domain
U_0	Applied DC voltage
U_r	Recovery voltage
W	Activation energy of material
ω	Angle frequency
χ	Dielectric susceptibility
χ_s	Steady state susceptibility
χ_∞	Instantaneous (high frequency) susceptibility
$\chi^*(\omega)$	Complex susceptibility in frequency domain
σ_{dc}	Conductivity of the dielectric
ATA	Accelerated thermal aging
CBM	Condition based maintenance
DGA	Dissolved gas analysis
DP	Degree of polymerization
EDM	Extended Debye model
FDRC	Frequency dependent RC model
FDS	Frequency domain spectroscopy
HV	High voltage
IDA	Insulation diagnosis analyzer
LHS	Left hand side
LV	Low voltage
RHS	Right hand side

List of Symbols and Abbreviations

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m.c.	Moisture content
OIL	Oil capacitor, oil insulation
OIP	Oil impregnated pressboard
PB	Pressboard capacitor
PD	Partial discharge
PDC	polarization and depolarization currents
RV	Recovery voltage
RVM	Recovery voltage method (measurement)
SPT	Single phase transformer
TBM	Time based maintenance

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Chapter 1

Introduction

1.1 Motivation

With the increasing demand for reliable power supply in the competitive restructured energy market of 21st century, effective delivery of electric power is of prime concern to utilities throughout the world. The traditional individual power utilities are moving towards greater competition after restructuring which means that consumers can buy energy from any power producer who offers the most favorable conditions like the cost, reliability and power quality. This has put the utilities under severe stress to reduce costs in order to be competitive.

The contradiction between the reduced cost in maintenance, operation and reliable supply of electricity to demanding customers forces the utilities to move from traditional time-based maintenance (TBM) programs to condition-based maintenance (CBM) [1] [2] [3] [4]. The cost can be reduced if the maintenance is only carried out if the condition of the equipment requires it instead of doing maintenance at a regular interval at a high cost.

Many power system operators now find that they have a large proportion of their critical and expensive assets operating beyond their design life. The average age of power transformers in Australian and New Zealand power system in 1995 was 28.6 years [4] [5] [6], the majority of large power transformers in Switzerland and most other countries in central Europe were installed in 60's and 70's [7]. Remaining life of these apparatus has to be established by some condition indicators.

Although many new materials like polymeric insulation [8] are proposed to the manufacture of power apparatus for high temperature operation, a huge number of transformers, bushings, circuit breakers and cables are still using cellulose and oil, such as oil impregnated paper and paper pressboard. The cellulose and oil insulation used in power apparatus degrade with time, operating temperature and other environmental stresses. The degradation depends on thermal, oxidative, hydrolytic,

electrical and mechanical condition which the apparatus experiences during its lifetime.

The aging and life expectancy of the oil based insulation system are predominantly dependent on the condition of the cellulose (winding insulation) and oil insulation. So many techniques of monitoring the health of insulations are developed. Each technique has some advantages on one hand and has other drawbacks on the other hand [5] [9] [10] [11]. New on-line condition monitoring techniques are continually being developed by using new relaxation techniques to overcome some of the drawbacks. Table 1-1 lists some of the commonly used diagnostic techniques for oil-based insulation system and their classification based on intrusive, on-/off-line, electrical, chemical and optical methods.

In general, the techniques can be classified into electrical, mechanical and chemical diagnostic techniques. The electrical techniques are breakdown, polarization and depolarization current measurements (PDC), loss factor, partial discharge (PD), recovery voltage measurement (RVM), frequency domain spectroscopy (FDS) measurements and transfer function analysis or frequency response analysis (FRA). The chemical techniques are measurement of moisture content in oil and paper by Karl Fischer titration, dissolved gas analysis (DGA), degree of polymerization in paper (DP), Furan content in oil, acidity, color and other oxidation products. The mechanical tests can be tensile strength of paper, viscosity and surface tension measurements. Again they can be classified as intrusive method if the sample is taken from operating apparatus. They are laborious, costly and time consuming methods [5] [12] [13]. Using non-intrusive on-line methods, like PD and hot-spot monitoring, the operating apparatus is not disturbed. Some of the tests are done in on-line or off-line modes.

In electrical methods, they may be tested at low voltage of AC/DC or at rated or above the rated voltage and the tests are classified by the test voltage [10] as destructive tests (such as voltage withstand tests, PD by an external HV source) and non-destructive tests (such as RVM, PDC, FDS and FRA). The destructive test can expose the serious defects in the insulation. However, it also might damage the insulation simultaneously. The non-destructive method can test the various relaxation characteristics of the insulation without causing damage by using lower voltage [13]

[14]. This test measures the changes of the relaxation properties of the insulation with aging.

Dielectric properties are dependent on many factors, such as on frequency/time, temperature, chemical composition of the dielectric and the geometrical structure of an insulation system [1]. The classical electrical tests such as insulation resistance (IR) and polarization index (PI) from PDC measurement using DC, and loss factor ($\tan\delta$) at 50 Hz provide very little information about transformer insulation. These tests are used as 'Go' and 'No Go' indicators. To get the information on slow degradation, dielectric relaxation measurements are used more widely. They are verified to be valid in the laboratory [1] and they find their route for condition monitoring in the industrial world as RVM [15], FDS [16] and PDC [17] commercial instruments.

Table 1-1 Typical diagnostic techniques used for oil paper insulation

Classification methods Diagnostic techniques	Destructive	Intrusive	Electrical	Chemical	On-line	Overall
DGA [2] [11] [23] [24]		Yes		Yes	Yes	
DP [11] [25]		Yes		Yes		
Tensile strength [26]		Yes				
Furfural analysis [11] [27] [28]		Yes		Yes		
Karl Fischer titration [11] [29] [30]		Yes		Yes		
Oxidation products[31]		Yes				
Acidity [31]		Yes				
Hot-spot monitoring [5] [11]					Yes	
RVM[2] [5] [6] [7] [9] [32]			Yes			Yes
PDC [1] [5][7] [17] [33]			Yes			Yes
FDS [1] [6] [32] [34]			Yes			Yes
Transfer function analysis [2] [5] [7]			Yes			Yes
PD[5] [7] [35]	Yes		Yes		Yes	
Breakdown [2] [10] [36]	Yes		Yes			
$\tan \delta$ at 50 Hz [3] [5] [6] (High voltage)			Yes			Yes

"Yes" means that the test technique in row belongs to the test method indicated at the top of that column.

Even though these relaxation methods such as RVM, FDS and PDC can be used as condition monitors, no detailed research is done here to fully understand the physics of relaxation changes in individual dielectric to the composite insulation, due to the temperature of operation and aging. Reliability of these tests is not still established and they are not still recommended by International Standards. No simple model is available to explain the relaxation phenomena relating individual dielectric to composite dielectric. This unexplored research area motivated me to take some simple studies in laboratory conditions.

1.2 Objectives

There are many unanswered questions in the relaxation studies on the power apparatus especially in oil-paper insulation by RVM, FDS and PDC techniques.

- a) RVM and FDS are used to make an estimation of the water content of the paper in transformers based on laboratory measurements [13] [18]. For correct estimation of water content in oil-filled apparatus, the method needs the constructional details to quantify the volume and arrangement of each used dielectric material. In all practical field measurements, it is not possible to get the geometrical details of different insulation. Hence, this method of analysis needs to be improved without depending on the geometrical dimension.
- b) The measured response with field apparatus depends on a number of ambient factors like the ambient temperature and humidity [19]. Also, the measurement time using these techniques takes long time in the range of 8 to 12 h [15]. In that period, ambient parameters may change. Reference [20] suggests that any leakage may affect RVM and it recommends making the measurements between 20 °C to 30 °C and at relative humidity less than 70% if the ambient fluctuation is more. The role of temperature, humidity and time interval on RVM and FDS measurements have to be explored.
- c) The relaxation characteristics of oil, paper and impregnated paper are different. Their behavior with time, temperature and humidity are not studied individually and the relationship of individual dielectric to composite dielectric is to be evaluated. The relaxation behavior due to aged products is not studied.

d) The moisture movement between oil and paper in the oil-filled transformer can be estimated by the moisture equilibrium curves [21] [22]. But there are many questions with that equilibrium curves which have been developed based on small samples in controlled laboratory conditions. In a complicated transformer construction, the diffusion of moisture through oil ducts in fluctuating oil temperature is very complicated and the moisture equilibrium time is very difficult to predict. In that case, the use of the standard curves for predicting the moisture content is difficult. Hence a simpler method is to be developed for the practical system.

With those unanswered questions, the research objectives are planned with the limited facilities in the laboratory. The investigations are mainly concentrated only on OIL, PB and OIP in a homogeneous state and not arranged as a two or multi component layered practical insulation system. To understand the relaxation behavior in oil-filled insulation, the following five objectives are formulated:

- (1) To find the relationship of relaxation parameters measured by time domain RVM polarization spectrum and frequency domain FDS measurements on laboratory samples. This can highlight the advantages and disadvantages associated with each technique for field measurement.
- (2) To evaluate the relationship of relaxation properties of individual dielectric like oil and paper on the relaxation property of composite oil impregnated paper. This may identify the dominant dielectric contributing to the relaxation behaviour of composite dielectric.
- (3) To evaluate the role of equilibrium time, operating temperature changes and polarizing impurities on the relaxation characteristics of individual and composite insulation. This study may evaluate the sensitivity of RVM and FDS techniques to follow any changes in relaxation behavior.
- (4) To quantify the change in relaxation behavior due to aging of transformer insulation.
- (5) To come up with a simple model with few parameters to study the change in relaxation characteristics.

1.3 Major contributions of the research work

The major contributions by this research work are summarized below.

- (1) For the first time, the relaxation relationship between individual mineral oil (OIL) and pressboard (PB) with oil impregnated pressboard (OIP) is studied in frequency and time domains. It clearly suggests that the relaxation behavior is dominant in low frequency/long time and it is a function of frequency/time. The behavior of individual dielectric in composite insulation does not obey a simple arithmetic.
- (2) RVM and FDS relaxation techniques measure the responses due to change of an environment, temperature of operation and the injected polar contaminants. The study emphasizes the need for equilibrium time in the order of at least 120 h to measure the relaxation responses with the tested laboratory samples in sealed tank.
- (3) A novel and simpler relaxation model known as frequency dependent RC (FDRC) model is developed for OIP. For EDM fitting, a new mathematical optimization method based on time constants is proposed to determine the parameters. This method is found to give a better fitting as the range of time constants is not wide like the range of fitted R and C values. The determined parameters by a model explain the polarization and conduction phenomenon in OIP under different test conditions.
- (4) The accelerated thermal aging relaxation studies are carried out in oil-filled SPT. The significant variation of relaxation behavior before, after and during aging is noticed after the equilibrium time. The aging phenomenon generates more water and other polarizing impurities.

1.4 Organization of the thesis

This thesis is organized into seven chapters with the contents described below:

Chapter 1: Introduction

The motivation for this research, the objectives, and the major contributions of this project and the layout of this thesis are presented.

Chapter 2: Literature Survey on Relaxation Phenomenon in Oil Related Insulation

This chapter presents the literature survey on the existing concepts of relaxation phenomenon in time and frequency domains, dielectric response function, relaxation phenomenon in two-component system, properties of oil, paper and composite insulation. It briefs the aging

phenomenon and the generated byproducts. It reviews the existing electrical techniques such as FDS, RVM and PDC for relaxation studies.

Chapter 3: Experimental Set Up

This chapter describes the details on the studied samples, two measurement systems, test layout for temperature rise and aging and three programs of relaxation study.

Chapter 4: Relaxation Studies in Frequency Domain

This chapter presents the experimental FDS results on OIL, PB and OIP with time to reach equilibrium range and temperature. The effect of oxidised impurities on OIP relaxation responses is also investigated. Based on the results, a novel and simple FDRC model is developed to relate the relaxation responses. The determined variation in parameters a, b, c and d reveal the trend of equilibrium, temperature dependence and effect of polarizing impurities. Using that, the model of OIP is built with individual dielectric FDRC network of OIL and PB.

Chapter 5: Relaxation Studies in Time Domain

This chapter presents the experimental RVM results on OIL, PB and OIP with time to reach equilibrium range and temperature. The results are analyzed by RV spectrum and the time at which peak response is obtained. The results are fitted to EDM. A new optimized method using time constants is proposed to evaluate the parameters of EDM by fitting the experimental results. The determined variation in parameters reveals the trend of equilibrium and temperature dependence. Using the parameters, FDS responses are predicted and similar trend of variation as measured in Chapter 4 is observed.

Chapter 6: Relaxation Studies on Thermally Aged SPT

This chapter reports about the FDS and RVM results before and after accelerated thermal aging of SPT. During aging, only RVM results are obtained. The analysis is made using EDM and FDRC models to understand the aging process.

Chapter 7: Conclusions and Recommendations

This chapter summarizes the findings of this project and presents new recommendations for future research work.

Chapter 2

Literature Survey on Relaxation Phenomenon in Oil Related Insulation

This chapter presents the literature survey on the existing concepts of relaxation phenomenon in OIL, PB and OIP used in transformer insulation, the variation of relaxation characteristics with temperature, and the techniques to measure relaxation phenomena and relate aging with relaxation responses.

The objective of this thesis is focused on oil-filled transformer insulation with oil and oil impregnated cellulose materials. The literature uses the following words to represent transformer oil as oil, transformer oil and insulation oil, and the different cellulose materials as pressboard, paper, Kraft paper, transformer board and cellulose.

2.1 Relaxation phenomena

The dielectric insulating material consists of negative and positive charges balancing each other in microscopic and macroscopic scales [8]. When a DC electric voltage is applied to a dielectric for a sufficiently long duration, the different kinds of dipoles (atoms, molecules, ions and hopping charge carriers, etc.) in the dielectric become excited to align in the direction of the applied field; the charge balance in the dielectric will be disturbed. This phenomenon is called polarization. The build up of polarization takes a finite time interval before the maximum value is reached. When the applied voltage is suddenly removed, the dipoles will naturally relax and return to original random balanced state and this process is called depolarization. The two polarization phenomena are described by a general term, dielectric relaxation. The decay of polarization to zero is not instantaneous but takes a finite time. This is the time required for the dipoles to revert to their random distribution from a field oriented alignment. This time is sensitive to the operating temperature of the dielectric [1] [8] [37] [38]. The polarization of a dielectric [1] [8] may be classified into:

- (1) Electronic or optical polarization

- (2) Orientation or dipolar polarization
- (3) Atomic or ionic polarization
- (4) Interfacial polarization and
- (5) Hopping of charge carriers

Among these polarizations, electronic and ionic polarizations are much faster than others; the polarization time will be in the range of 10^{-13} s [1]. The interfacial polarization and hopping occur in composite dielectric materials such as oil impregnated paper and pressboard. It is slow and may take about 10^{-3} - 10^4 s. Dipolar polarization response is in between these two in the order of μ s.

2.1.1 Expression of the polarization

The interaction between the electromagnetic fields and dielectric material is described by Maxwell equations [8] [39]. The relationship between dielectric displacement $\mathbf{D}$ and electric field $\mathbf{E}$ of the dielectric is expressed by (2-1).

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} \quad (2-1)$$

where ϵ_0 is the permittivity of free space and polarization vector $\mathbf{P}$ is the dipole moment per unit volume. It can be written as

$$\nabla \cdot \mathbf{P} = -\rho \quad (2-2)$$

where ρ is the charge density. The relation between the dielectric displacement $\mathbf{D}$ and the applied field $\mathbf{E}$ often is linear and can be expressed with a simple proportionality relative dielectric constant ϵ (≥ 1), as

$$\mathbf{D} = \epsilon_0 \epsilon \mathbf{E} \quad (2-3)$$

The vector of polarization $\mathbf{P}$ of the material and the electric field $\mathbf{E}$ lie in the same direction and interrelated by

$$\mathbf{P} = \epsilon_0 (\epsilon - 1) \mathbf{E} = \chi \epsilon_0 \mathbf{E} \quad (2-4)$$

$\chi = \epsilon - 1$ is the dielectric susceptibility of the material which is zero in free space. The susceptibility χ accounts for all kinds of dielectric polarization process. From (2-4), it can be seen that the polarization $\mathbf{P}$ will change if the electric field $\mathbf{E}$ is changed. A decrease and removal of $\mathbf{E}$ will lead to depolarization process. The relaxation speed is

not instantaneous and there is some delay in time. As stated in the beginning of Section 2.1, the first three polarizations are much faster than the others. This fast polarization can be considered as an instantaneous polarization P_∞ . When a DC voltage is applied to a material, the total polarization P can be expressed as the sum of P_∞ , the steady orientation polarization P_o and interfacial polarization P_i . It can be regrouped as rapid polarization process, P_∞ , and slow polarization process as $(P_o + P_i)$ [39].

$$P(t) = P_\infty(t) + (P_o(t) + P_i(t)) = P_{rapid}(t) + P_{slow}(t) \quad (2-5)$$

After a long time, the polarization becomes finite and static as shown in Fig. 2-1 and $P(t \rightarrow \infty) = P_s$. At the same time, the permittivity values at $t \rightarrow \infty$ and $t=t_0$ are defined as ϵ_s and ϵ_∞ which are the static and instantaneous (high frequency) permittivity respectively. χ_∞ is the susceptibility at initial time when the electric field is applied and χ_s is the value at the steady state. The various polarization phenomena have a certain inertia, which can be defined by time constants in time variable fields [1]. As shown in (2-5), polarization is classified as two processes only. In practice, the polarization process is a continuous function of time/frequency and temperature. This relaxation process can be studied in time and frequency domains.

Under the assumption that the dielectric material is linear, homogeneous, and isotropic, the information obtained in either the time or frequency domain is the same and the results can be transformed from the time to frequency domain and vice versa [1] [38]. The validity of linear dielectric response needs to be studied.

Fig. 2-1 Build up of polarization in a dielectric when a step field is applied

2.1.2 Relaxation studies in time domain

In time domain, it is assumed that the dielectric was initially discharged completely and a constant direct voltage U_0 is applied for a period of t_c as defined in (2-6). The relaxation phenomena are studied in terms of polarization and depolarization currents (PDC) and recovered voltage (RVM) after open-circuiting [1] [15] [33] [39-43] [45]. Fig. 2-2 illustrates the measured responses. The applied DC voltage $U(t)$ is varied as

$$U(t) = \begin{cases} = 0, & t < 0 \\ = U_0, & 0 \leq t < t_c \\ = 0, & t_c \leq t \leq t_d \end{cases} \quad (2-6)$$

The expression for current is derived by following the polarization equation. When the voltage $U(t)$ is applied to a dielectric for a time t_c at time $t_0 = 0$, the polarization process with reference to Fig. 2-1 may be written as follows:

$$P(t) = P_\infty + (P_s - P_\infty)g(t - t_0) \quad (2-7)$$

where $g(t)$ is a dielectric polarization function. Normally it is monotonically increasing function like an exponential function [1] [8] [34] [39]. It satisfies the following condition:

$$g(t) = \begin{cases} 0 & \text{if } t \leq t_0 \\ 1 & \text{if } t \rightarrow \infty \end{cases} \text{ and } g(t) \geq 0 \text{ \& } \frac{dg(t)}{dt} \geq 0 \text{ for } t \geq t_0$$

Fig. 2-2 Illustration of the relaxation responses of PDC and RVM in time domain [1]

Expressing in terms of electric stress, $\mathbf{E}(t)$ is constant as $\mathbf{E}_0$ and U_0

$$\mathbf{P}(t) = \varepsilon_0 [\chi_\infty + (\chi_s - \chi_\infty)g(t - t_0)]\mathbf{E}_0 \quad (2-8)$$

For any other time dependent excitation $\mathbf{E}(t)$, $\mathbf{P}(t)$ is expressed by Duhamel's integral and superposition principle [2] [4] as

$$\mathbf{P}(t) = \varepsilon_0 \chi_\infty \mathbf{E}(t) + \varepsilon_0 \int_{-\infty}^t f(t - \tau) \mathbf{E}(\tau) d\tau \quad (2-9)$$

$$f(t) = (\varepsilon_s - \varepsilon_\infty) \frac{dg(t)}{dt} = (\chi_s - \chi_\infty) \frac{dg(t)}{dt} \quad (2-10)$$

$\frac{dg(t)}{dt}$ is proportional to the dielectric decay or dielectric response function $f(t)$. As per Maxwell (2-1), the electric field $\mathbf{E}(t)$ generates a total current density $\mathbf{j}(t)$. It is written as the sum of conduction, vacuum and polarization displacement currents.

$$\mathbf{j}(t) = \sigma_{dc} \mathbf{E}(t) + \frac{\partial \mathbf{D}(t)}{\partial t} = \sigma_{dc} \mathbf{E}(t) + \varepsilon_0 \frac{\partial \mathbf{E}(t)}{\partial t} + \frac{\partial \mathbf{P}(t)}{\partial t} \quad (2-11)$$

where σ_{dc} is the conductivity of the dielectric. If $\mathbf{E}(t)$ is step field, (2-11) reduces to (2-12) after substituting (2-9).

$$\mathbf{j}(t) = \sigma_{dc} \mathbf{E}(t) + \varepsilon_0 [\varepsilon_\infty \delta(t) + f(t)] \mathbf{E}(t) \quad (2-12)$$

Integrating (2-12), the polarization current $i_{pol}(t)$ is derived.

$$i_{pol}(t) = C_0 U_0 \left[\frac{\sigma_{dc}}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t) \right] \quad (2-13)$$

(1)   (2)   (3)

where C_0 is the geometric capacitance of the dielectric material and $\delta(t)$ is the delta function contributing only at $t=t_0$. The polarization current is due to three phenomena.

- (1) Current due to conductivity of the material;
- (2) Instantaneous current due to fast polarization processes ; and
- (3) Current due to slow polarization processes.

After the voltage is applied for specified time, the depolarization current i_{depol} can be measured after isolating the voltage source and short-circuiting the dielectric as shown in Fig. 2-2. Following the superposition principle and neglecting the very short current pulse, the expression for depolarization current becomes as

$$i_{depol}(t) = -C_0 U_0 [f(t) - f(t + t_c)] \quad (2-14)$$

The depolarization current has the opposite polarity and is proportional to the dielectric response function.

After short-circuiting the dielectric for some time $t_d (< t_c)$, recovery voltage with leftover slow polarization process can be measured under open-circuiting conditions by voltmeter with very high input impedance. Under finite conductivity condition, it satisfies that

$$U_r(t) = \begin{cases} 0 & \text{at } t = t_d \\ 0 & \text{at } t \rightarrow \infty \end{cases}$$

During the recovery voltage period, the current density $\mathbf{j}(t)$ in (2-12) is zero. Rewriting (2.12),

$$\sigma_{dc} \mathbf{E}(t) + \varepsilon_0 \varepsilon_\infty \frac{\partial \mathbf{E}(t)}{\partial t} + \varepsilon_0 f(0) \mathbf{E}(t) + \varepsilon_0 E_0 [f(t) - f(t - t_c)] + \varepsilon_0 \int_{t_2}^t \frac{df(t - \tau)}{d\tau} \mathbf{E}(\tau) d\tau = 0 \quad (2-15)$$

Integrating (2-15), (2-16) is obtained to interpret the RVM results [39] [43].

$$\sigma_{dc} U_r(t) + \varepsilon_0 \varepsilon_\infty \frac{dU_r(t)}{dt} + \varepsilon_0 f(0) U_r(t) + \varepsilon_0 U_0 [f(t) - f(t - t_c)] + \varepsilon_0 \int_{t_d}^t \frac{df(t - \tau)}{d\tau} U_r(\tau) d\tau = 0 \quad (2-16)$$

It can be seen that in time domain the dielectric material is characterized by the DC conductivity σ_{dc} , the high frequency component of the relative permittivity, ε_∞ , and the dielectric response function $f(t)$ which will be explained in Section 2.1.4.

2.1.3 Relaxation studies in frequency domain

The response function $f(t)$ of (2-10) in frequency domain can be determined by the Fourier transform. The complex susceptibility [1] [34] [37] $\chi^*(\omega)$ is the Fourier transform of the dielectric response function $f(t)$.

$$\chi^*(\omega) = \chi'(\omega) - j\chi''(\omega) = \int_0^\infty f(t) e^{-j\omega t} dt \quad (2-17)$$

From (2-12),

$$\mathbf{j}(\omega) = \left\{ \sigma_{dc} + \varepsilon_0 \omega \chi''(\omega) + j\omega \varepsilon_0 [1 + \chi'(\omega)] \right\} \mathbf{E}(\omega) \quad (2-18)$$

The main part of this current is created by the complex electric displacement $\mathbf{D}(\omega)$ which is proportional to the complex dielectric permittivity, $\epsilon^*(\omega)$ with the relation:

$$\mathbf{D}(\omega) = \epsilon_0 \epsilon^*(\omega) \mathbf{E}(\omega)$$

where $\epsilon^*(\omega) = \epsilon'(\omega) - j\epsilon''(\omega) = [1 + \chi'(\omega)] - j\chi''(\omega)$. The real component of the complex permittivity gives the capacitive dielectric constant while the imaginary component determines the power dissipation (loss) in the dielectric; and the frequency dependent dielectric susceptibility, $\chi^*(\omega)$ which refers to delayed polarization processes is a complex number [37].

$$\chi^*(\omega) = \chi'(\omega) - j\chi''(\omega) = (\epsilon^*(\omega) - \epsilon_\infty) / \epsilon_0 \quad (2-19)$$

(2-18) is simplified to

$$\mathbf{j}(\omega) = j\omega\epsilon_0 \left\{ \epsilon_\infty - j\frac{\sigma_{dc}}{\epsilon_0\omega} + [\chi'(\omega) - j\chi''(\omega)] \right\} \mathbf{E}(\omega) \quad (2-20)$$

The current density in the frequency domain is a sum of the high frequency component of the relative permittivity ϵ_∞ , DC conductivity σ_{dc} , and the complex dielectric susceptibility $\chi^*(\omega)$.

2.1.4 Dielectric response functions

It is shown that the dielectric response function $f(t)$ defined in (2-10) controls the polarization process in both the domains. Many theoretical response functions are proposed to explain the behavior of the dielectric polarization in solids. Any dielectric response function must satisfy the condition (2-21). The reference [18] summarizes the different proposed dielectric response functions. In general, $f(t)$ should satisfy (2-21).

$$\int_0^\infty f(t) dt = 1 \quad (2-21)$$

2.1.4.1 Debye's response function [18]

In Debye classical equation, the polarization is assumed to increase exponentially with a single relaxation time, τ as shown in Fig. 2-1.

$$P(t) = 1 - e^{-\frac{t}{\tau}} \quad (2-22)$$

In that case, the dielectric response function can be derived as

$$f_D(t) = \frac{\epsilon_s - \epsilon_\infty}{\tau} e^{-\frac{t}{\tau}} \quad (2-23)$$

Debye's response function is the simplest function and few dielectrics satisfy it.

2.1.4.2 Jonscher's response function [18]

The dielectric response function was proposed by Jonscher [18] [37] after observing two types of polarization processes in many dielectrics.

$$f_J(t) = \frac{A_J(m, n, \omega_0)}{(\omega_0 t)^n + (\omega_0 t)^{m+1}} \quad (2-24)$$

where

$$A_J(m, n, \omega_0) = \omega_0 \frac{(1+m-n)}{\pi} \sin \left[\frac{(1-n)\pi}{1+m-n} \right]$$

where m and n are the parameters to control the polarization rates, and ω_0 is the maximum loss frequency. The values of m and n are constrained in the range $0 < (m, n) < 1$.

2.1.4.3 The Dissado-Hill response function [18]

The Dissado-Hill theory states the dielectric response function as

$$f_D(t) = A_D(m, n, \omega_p) (\omega_p t)^{-n} e^{-\omega_p t} {}_1F_1(1-m; 2-n; \omega_p t) \quad (2-25)$$

where m and n are parameters which lie in the same range as Jonscher's function. ω_p can be interpreted as the maximum loss frequency, ${}_1F_1$ is the confluent hypergeometric function and

$$A_D(m, n, \omega_p) = \omega_p \frac{\Gamma(1+m-n)}{\Gamma(m)\Gamma(1-n)\Gamma(2-n)}$$

The value of m , n and ω_p can be obtained by experiments [18].

2.1.4.4 The Kohlrausch-Williams-Watts response function [18]

The Kohlrausch-Willimams-Watts's response function:

$$f_K(t) = \frac{\beta}{\tau_0} \left(\frac{t}{\tau_0} \right)^{\beta-1} e^{-\left(\frac{t}{\tau_0} \right)^\beta} \quad (2-26)$$

where the parameters β and τ_0 can be found experimentally, and β lies in the range $0 < \beta \leq 1$ [29].

2.1.5 Debye equations of dielectric properties in frequency domain [39] [40]

Debye's equations describe the behavior of polar dielectrics with frequency. With the assumption that the polarization increasing exponentially with a single relaxation time, τ , (2-27) and (2-28) can be derived [37] [39] as,

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2 \tau^2} \quad (2-27)$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty) \omega \tau}{1 + \omega^2 \tau^2} \quad (2-28)$$

After using the Fourier transform of the response function [39], the complex dielectric susceptibility, χ^* reduces to (2-29)

$$\chi^*(\omega) = \frac{\Delta \epsilon}{1 + \omega^2 \tau^2} - i \left[\frac{\Delta \epsilon \omega \tau}{1 + \omega^2 \tau^2} + \frac{\sigma}{\epsilon_0 \omega} \right] \quad (2-29)$$

In a given dielectric, a Cole-Cole diagram is plotted by the measured values of ϵ'' as a function of ϵ' at various frequencies. If the Cole-Cole diagram's points fall on a semi-circle, it can be concluded that the material exhibits Debye relaxation. In practice, very few materials agree with Debye's exponential equation. It is attributed to distribution of relaxation times. For the eccentric elliptic Cole-Cole plots, an empirical equation for the complex dielectric constant is given as (2-30).

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega \tau_{c-c})^{1-\alpha}}, 0 \leq \alpha \leq 1; \quad (2-30)$$

$\alpha=0$ for Debye relaxation. τ_{c-c} is the mean relaxation time and α is a constant for a given material. In more general functional form [39]

$$\chi(\omega) = \int_0^{\infty} \frac{\Delta \varepsilon F(\tau)}{1 + (j\omega\tau)} d\tau + \frac{\sigma}{j\omega\varepsilon_0} \quad (2-31)$$

where $\Delta \varepsilon \equiv \varepsilon_s - \varepsilon_{\infty}$ and $F(\tau)$ is considered as a distribution function of the relaxation time.

2.1.6 Dielectric relaxation in two-component system

Electrical power apparatus use more than one type of insulating materials. In oil-filled transformer, paper insulation with oil is used widely. Such insulation system is called composite dielectric. When two materials are put into contact (forming an interface) and an electric field is applied, charge polarization occurs at the interface due to the difference in the conductivity. Few people have modeled the relaxation phenomena of two-component system using different structures.

Assuming a layered structure, the effective dielectric permittivity of the composite insulation is expressed as a function of intrinsic electrical properties of the components, $\sigma_1, \sigma_2, \varepsilon_1, \varepsilon_2, \varepsilon_{\infty 1}, \varepsilon_{\infty 2}$ and their volume fraction q [39] [44].

$$\begin{aligned} \varepsilon_1(\omega) &= \varepsilon_{\infty 1} + \frac{\sigma_1}{j\omega\varepsilon_0} \\ \varepsilon_2(\omega) &= \varepsilon_{\infty 2} + \frac{\sigma_2}{j\omega\varepsilon_0} \end{aligned} \quad (2-32)$$

The effective complex permittivity of the mixture can be expressed as

$$\varepsilon_e(\omega) = \frac{\varepsilon_1(\omega)\varepsilon_2(\omega)}{q\varepsilon_1(\omega) + (1-q)\varepsilon_2(\omega)} \quad (2-33)$$

2.1.7 The various arrangements of two-component system

Following Section 2.1.6, various arrangements of the two-component system are explored in [44]. The simplest arrangements of the two-component system are the series and parallel arrangements shown in Fig. 2-3 (a) and (b), where θ_f is the volume fraction of the cellulose, and θ_a is the volume fraction of the fluids (air, oil or vacuum). The subscripts “s” and “p” refer to series and parallel components. Other arrangements are the pillar and the series/parallel arrangements shown in Fig. 2-3 (c) and (d).

Fig. 2-3 Possible arrangements of two-component system (a) series; (b) parallel; (c) pillar; (d) series/parallel [44]

The real part of the complex permittivity for two dielectrics in series [44] is

$$\epsilon' = \frac{\epsilon'_f \epsilon'_a}{\epsilon'_f \theta_a + \epsilon'_a \theta_f} \quad (2-34)$$

For dielectrics in parallel [44], it is derived as

$$\epsilon' = \epsilon'_f \theta_f + \epsilon'_a \theta_a \quad (2-35)$$

The imaginary part of the permittivity is obtained by

$$\epsilon'' = \epsilon' \tan \delta \quad (2-36)$$

where $\tan \delta$ is the dielectric loss tangent.

For series dielectrics, it is derived as

$$\tan \delta = \frac{\theta_f \epsilon'_a \tan \delta_f + \theta_a \epsilon'_f \tan \delta_a (1 + \tan^2 \delta_f)}{\theta_f \epsilon'_a + \theta_a \epsilon'_f (1 + \tan^2 \delta_f)} \quad (2-37)$$

For parallel dielectrics, it is derived as

$$\tan \delta = \frac{\theta_f \epsilon'_f \tan \delta_f + \theta_a \epsilon'_a \tan \delta_a}{\theta_f \epsilon'_f + \theta_a \epsilon'_a} \quad (2-38)$$

2.2 Components and properties of oil and paper insulation system

The main components of transformer insulation are cellulose papers of various grades immersed in transformer oil. Normal recommended loss factor [38] is <0.005 at 50 Hz and measured insulation resistance should be greater than 1000 M Ω depending on MVA and voltage rating.

2.2.1 Transformer oil

The transformer oil functions as a heat transfer medium as well as a dielectric material [21] [22] [29] [46]. The most commonly used insulating oil is mineral oil and the insulation strength is much higher than air. The main purpose of using the oil in addition to heat transfer is to fill any voids in cellulose structures with oil that has high dielectric strength. This procedure of impregnation in oil under vacuum reduces significantly internal partial discharges due to voids in cellulose/solid insulating materials. Oil transfers the heat out of conductors and core to heat exchangers in large power transformers. The grounded transformer tank keeps the transformer outer metal body at ground potential apart from transferring heat.

Mineral transformer oils are refined from predominantly naphthenic crude oils [46]. The refining processes include acid treatment, solvent extraction, dewaxing, hydrogen treatment, or combinations of these methods to yield mineral insulating oil meeting the specification [46]. The insulating oil is mainly a mixture of hydrocarbons which include paraffin, alkenes, naphthenes, and aromatic hydrocarbons. Although, polar and ionic species are a minor part of the constituents which may greatly influence the chemical and electrical properties of the oil.

To obtain better performance as a cooling medium and as electrical insulation, transformer oil must have high electric strength, low viscosity, high heat capacity and low expansion coefficient. It should also be free from moisture, gases, chemical impurities and other physical solid contaminants to avoid unnecessary electrical discharges. With aging in the presence of moisture and heat, the oil turns darker due to the formation of acids, resins and sludge in the liquid. Some of the acids are

corrosive to the solid insulating materials and metal parts in the transformer. Deposits of sludge on the transformer core, on the coils and inside the oil ducts reduce circulation of oil and thus its heat transfer capability gets considerably reduced. Monitoring and removing these polarizing impurities is an important part to maintain a reliable operation [29] [35]. The loss angle of good oil [46] is <0.005 with conductivity less than 0.7 pS/m [21].

2.2.2 Paper and pressboard

Kraft paper is obtained from wood pulp with outstanding mechanical and electrical properties. Paper is composed of 90% cellulose, 6% - 7% hemi-cellulose and 3% - 4% lignin. Generally, if the thickness of paper is 0.8 mm or higher, it is called paper board. Pressboard is produced by compressing several thin paper layers in a wet condition, without using any cementing or bonding material. The thinner the individual layers the better will be the quality of the pressboard. Pressboard is used in transformers and bushings as supporting materials and insulating barriers [25] [27] [31] [35].

An important mechanical property of the paper is its tensile strength [26]. The tensile length is the length of a suspended paper tape of uniform thickness and width with tensile force equal to its dead weight to cause rupture. This length lies in the range of 6 to 8 km. Other electrical specifications of the paper are dielectric strength, dielectric permittivity ϵ , and loss factor $\tan\delta$ and conductivity σ . Dielectric strength at 50 Hz on a dry and thin layer of paper should be about 100 to 150 kV/cm [26]. The permittivity of dry paper varies from 1.5 to 3.5 and loss factor is in the range of 0.003 to 0.004. Dry paper has a very high volume resistance between 10^{15} and $10^{17} \Omega\text{-cm}$. The density of pressboard is more than paper due to its low porosity and the permittivity of pressboard is higher than that of paper, around 4.5 [26].

2.2.3 Oil impregnated paper pressboard

Paper itself shows modest dielectric performance due to its porous structure. When air is present, the dielectric strength of paper is predominantly determined by the gaseous

ionization within the air space. Heat, water and oxygen accelerate the degradation of paper insulation. Paper is highly hygroscopic and moisture degrades the paper. Therefore it is dried and impregnated in vacuum with insulation oil to maintain good dielectric properties [31] [34] [35].

The dielectric strength of paper impregnated with oil is considerably above that of either of the two individual components [35] [38]. The dielectric strength of the oil and paper combination depends mainly on how perfect is the impregnation of the paper with oil, and also how successful is the elimination of the effects of moisture and gases which reduce the strength of the insulation. The dielectric strength of oil impregnated pressboard insulation of new transformer is 200 to 400 kV/cm, and its permittivity is about 3.5 at power frequency. The loss factor is less than 0.003.

The dielectric strength of oil-impregnated paper insulation is affected by the moisture content. The complicated process of water movement between oil and paper mainly in higher temperature is discussed in detail in Section 2.3. The reported investigation of relaxation studies in these materials is discussed in Section 2.4.

2.3 Aging studies of oil and paper insulation system

Aging is defined as the irreversible changes of the properties of an electrical insulation system due to action of one or more factors of influence.

2.3.1 Main factors influencing the aging of oil and paper insulation

The aging factors of oil and paper insulation of transformer in service are electrical, thermal, mechanical and environmental elements that eventually lead to failure. When aging is dominated by one aging factor, this is referred to as single-factor aging. Multifactor aging occurs when more than one aging factor affects the performance of the insulation. Aging of oil and paper insulation can be complex and failure is usually caused by a combination of aging factors. But among these factors the thermal aging is the dominant aging mechanism [10] [49].

2.3.2 Aging products

The aging products of oil and paper insulation are water, gases, furan, acids and oxidation byproducts forming sludge. Since water is the most important catalyst of aging the oil and paper insulation, diagnostic techniques based on relaxation techniques are explored in this decade. It was found that relaxation response varied significantly with the moisture content (m.c.) [25] [26] [27] [31]. Their main objectives are to use the relaxation phenomena to predict the water content in frequency and time domains. In this section, the water, its sources and behaviors are discussed in detail.

2.3.2.1 Water, the sources and its behaviors

The presence of moisture in a transformer deteriorates transformer insulation by decreasing both the electrical and mechanical strength. In general, the mechanical life of the insulation is reduced by half for each doubling in water content [38]; the rate of thermal deterioration of the paper is proportional to its water content. Electrical discharges can occur in a high voltage region due to a disturbance of the moisture equilibrium causing a low partial discharge inception voltage and higher partial discharge intensity [38].

There are two sources of water in oil and paper insulation system [29] [21]:

- (1) A small quantity of water may enter the transformer oil throughout its working life as a result of free breathing through silica cell.
- (2) As the transformer ages, the moisture content will increase steadily due to chemical reactions at operating temperatures [29]. Aging breaks down the hydrocarbon chains in the cellulose causing the length of the molecular chains to reduce. The released hydrogen and oxygen atoms will then form H_2O . This process is accelerated by the hot spots and other localized defects in operating transformer.

Moisture in oil is measured in parts per million (ppm) using the weight of moisture divided by the weight of oil ($\mu g/g$). The unit for moisture concentration in pressboard is expressed in %, which is the weight of the moisture divided by the weight of the

dry oil-free pressboard. A new transformer would normally contain less than 0.5% moisture by weight in its paper but this would increase to as much as 4% after some years in service [29]. Insulating oils have less affinity for water. However, the solubility increases sharply with temperature for normally refined naphthenic transformer oil. Water gets distributed in the oil in three different ways [29]: in dissolved states, finely distributed (forming emulsion), and coarsely distributed (forming droplets).

Water is expected to be present in the oil in the non-dissolved state when the oil is saturated with moisture. It happens when the oil cools down. As the transformer heats up on load, water held in the paper will migrate into the oil. A new transformer normally contains less than 0.5% moisture by weight in its paper but this may increase to as much as 4% after some years in service. However, the solubility of water in aged transformer oil increases by around 800% between 20 °C and 80 °C [29].

The time to get water distribution equilibrium between the paper and oil for any disturbance at a specific temperature is called water equilibrium time constant. Some researchers [22] stated that this time constant may be about 1600 h for oil at room temperature, and about 20 h at 60 °C based on mobility studies in laboratory samples. It suggests that during daily transformer thermal cycling, equilibrium is never fully attained.

Industry measures the moisture in oil by Karl Fischer titration coulometer to a level of ppm [53]. The moisture distribution between oil and paper can be estimated through a set of moisture equilibrium curves [21] [22] [29] at various temperatures. Therefore, one of the methods to estimate water content in paper pressboard is using the equilibrium curves. Oommen's curves [18] shown in Fig. 2-4 is accepted by different researchers. For paper with moisture level lower than 1%, Oommen's curves are preferred. For high moisture concentration in oil up to 800 ppm, other curves [18] are suitable.

The polarization based dielectric diagnostic techniques such as recovery voltage measurement (RVM), polarization and depolarization current measurement (PDC)

and frequency domain spectroscopy (Dielectrometry) (FDS) are also currently used to investigate the moisture content in oil and paper insulation [1] [14] [24] [25] [41].

Fig. 2-4 Oommen's moisture equilibrium curves on oil and paper system [18]

2.3.2.2 Gases

Insulating oils under abnormal electrical and thermal stresses break down to liberate small quantities of gases. The composition of these gases is dependent upon the type of fault [23]. The thermal decomposition of oil impregnated cellulose insulation produces oxides of carbon (CO , CO_2) and some hydrogen. Oil decomposition leads to the production of H_2 , CH_4 , C_2H_4 and other hydrocarbon series [2] [23] [24] [48].

2.3.2.3 Furan analysis and degree of polymerization analysis

In addition to gases, the aging process of the paper produces several oil soluble byproducts, the furan compounds. By using high performance liquid chromatography (HPLC) and sampling of the oil, the furan compounds can be monitored and analyzed. However, the relationship between the generation of the furan compounds and the condition of paper has not been well established [27] [28].

During degradation, chain scissions take place in the paper leading to lowering of degree of polymerization (DP). This results in the depletion of the mechanical properties of the material. The DP proves to be the most informative parameter and standard indicator for assessing the aging or the progress of aging of cellulose in

transformer. The correlation between the quantity of furan dissolved in the oil and DP of the paper are established [28]. But there are a number of practical problems in determining the value of DP [28] [48]. They can be as follows: (1) Taking a sample of paper at the desired winding location from an operating transformer and (2) DP determined by means of viscosimetric method gives us only an approximate estimate of the average chain length of the cellulose.

2.3.2.4 Acids and oxidation

The acidic contamination may range from naphthenic acids to organic acids which are formed by oxidation during the refining process [46]. Other products of the breakdown of oils are alcohols, organic acids, aldehydes, ketenes, peroxides, polymerized hydrocarbon and the peroxides. They react with cellulose to cause its decomposition [36].

2.4 Reported relaxation techniques for oil and paper insulation diagnosis

Aging of insulation materials can be monitored from the variation of dielectric responses measured in any of the time and frequency domains [1] [9] [10] [40] [34] [48] [69]. The water content of the oil and paper is sensitive to the operating temperature. The three most discussed electrical relaxation techniques to determine the moisture content and aging of the oil and paper insulation are FDS, RVM and PDC [40] [51]. Although different measurements are made, they all reflect the fundamental polarization phenomena in oil and paper transformer insulation. The mathematical modeling provides a link between the responses of the three methods and the responses are affected by oil conduction, moisture content and object geometry [40].

2.4.1 Frequency domain spectroscopy (FDS)

The variation of dielectric impedance with frequency is called frequency domain spectroscopy [1] [34] [50]. Many parameters like complex permittivity, capacitance and $\tan\delta$ can be derived to identify the relaxation behavior. In laboratory, this technique is used to determine the water content and aging condition of oil and paper insulations [34] [39]. The advantage of this technique is that it is non-destructive low voltage AC test in the frequency range from 0.0001 Hz to 1 kHz.

FDS and RVM methods are used as condition monitoring tools [15] [16] using laboratory “sampling comparison”. A data base of dielectric responses of well-defined insulation samples with known water content is built. It measures the dielectric response with frequency of oil and paper insulation whose water content and other parameters are unknown. By using the calibration data base and varying the geometrical parameters, moisture content is predicted at a known temperature using the developed software. In all the practical measurements, the environmental conditions introduce some error in the measurement [16].

2.4.1.1 Temperature and moisture effects on FDS

Operating temperature affects the solubility equilibrium of moisture between cellulose and oil insulation and it influences the conductivity. A mass transfer process of water results from the equilibrium imbalance for a change in operating temperature. At high temperature, moisture leaves the cellulose to enter the oil. The oil initially establishes moisture equilibrium around the interfacial zone of the surface of the pressboard. The steady state will be reached when moisture from deep inside the pressboard diffuses to the surface to establish a uniform moisture distribution. It is experimentally found with FDS measurements that the complex permittivity and $\tan\delta$ are increasing with temperature and moisture, and decreasing with frequency on oil impregnated paper insulation [3] [54] [55] [58].

However, for most of the materials, the trend of the spectra shape does not change with temperature as shown [34] [39] [55] in Fig. 2-5. It slides to LHS for lower temperature and to RHS for higher temperature. This means that the behavior of temperature dependence can be shifted to obtain a single master curve shown in Fig.

2-5(b). Accordingly, a response at absolute temperature T_1 can be obtained by shifting the frequency of response at absolute temperature T_2 by an Arrhenius factor as [34] [39] [55],

$$\omega_{T_2} = \omega_{T_1} e^{-\frac{W}{K} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)} \quad (2-39)$$

In (2-39) W is the activation energy and K is Boltzman's constant. The researchers from MIT found that the dielectric spectra shifted horizontally with frequency and the shift was a function of temperature and moisture [55] [65]. This characteristic is used to predict the moisture content of the oil and paper insulation at another temperature if a FDS measurement is got on a sample under known temperature and moisture content. This is expressed by (2-40) and (2-41).

$$\log \left(\frac{\epsilon' - \epsilon_\infty}{\epsilon_0} \right) = F' \{ \log \omega - [f_T(T) + f_M(m)] \} \quad (2-40)$$

$$\log \left(\frac{\epsilon''}{\epsilon_0} \right) = F'' \{ \log \omega - [f_T(T) + f_M(m)] \} \quad (2-41)$$

where $f_T(T)$ is a function varying with temperature and $f_M(m)$ is another function varying with moisture content of paper.

Fig. 2-5(a) shows the real and imaginary parts of dielectric spectra of an OIP at five temperatures with 2.3% moisture content. Fig. 2-5(b) shows the master curves of permittivity using (2-40) and (2-41) by taking 50 °C reading as reference.

Other researchers [58] studied FDS on paper samples from mass-impregnated cable having different moisture contents at different temperatures. Their results shown in Fig. 2-6 show that increase in moisture content increases the real and imaginary dielectric constants. For ϵ'' , the shift of the dielectric response with moisture content is seen in Fig. 2-6(b). While for ϵ' , apart from horizontal shift in frequency vertical variation is also observed in Fig. 2-6(a). Loss factor shown in Fig. 2-7(a) decreases with frequency and increases with water content. The frequency shift in loss factor responses with temperature is seen in Fig. 2-7(b) while its shape remains unchanged with moisture content less than 0.5%.

Fig. 2-5(a) FDS on OIP at five temperatures with 2.3% moisture content in paper [55]

Fig. 2-5(b) Temperature shifted master curves at five temperatures using (2-40) & (2-41) [55]

Fig. 2-6(a) Real part of complex permittivity of OIP samples for different moisture contents [58]

Fig. 2-6(b) Imaginary part of complex permittivity of OIP samples for different moisture contents [58]

Fig. 2-7(a) Loss factor of OIP for different moisture contents [58]

Fig. 2-7(b) Loss factor of OIP for different temperatures [58]

2.4.1.2 Drawbacks of FDS

FDS uses lower voltage and lower frequencies to measure the dielectric properties. For field apparatus with large volume of oil and paper insulation, the current will be very small and the measured signal will be modulated with the ambient electromagnetic noise to affect the accuracy of measurement. In addition, 0.1 mHz measurement may take around 3 h and during that period environmental condition may interfere with the polarization phenomenon. The linearity of polarization responses with different operating voltages is to be explored. This is only a comparative measurement for different apparatus as the measured results can not reflect the moisture content directly. A data base with the operating history and other condition monitor parameters may be useful to relate the operational condition of oil-filled apparatus. The instrumentation used for this is expensive and is developed after 1970s. For field studies, time domain based recovery voltage measurement is used for longer period [1] [37] to study the polarization condition of insulation and a constant improvement is made on the measured results.

2.4.2 Recovery voltage measurement (RVM)

In Section 2.1.2, the theory of RVM was explained. It is a non-destructive low voltage DC test in time domain. This time domain technique is done in two ways [1] [33]. The first oldest method is known as “Single Return or Recovery Voltage Measurement” [1] described in Fig. 2-2. A DC voltage of known amplitude U_0 is applied to the test object which was completely discharged. It is charged to a time t_c which should be very long so that after-effects produced by the application of U_0 have dispersed completely. After a short for a defined short-circuiting period, a return or recovery voltage $U_r(t)$ is measured. Some improvements on it were done by measuring peak by changing the charging voltage [33] and it was called “DR” or “Discharge Method”. The second method [15] [45] is known as “Polarization Spectra” or “RVM-technique”. In this method, spectrum relating peak recovery voltage with t_c is produced by taking a series of recovery voltages by varying t_c , t_d and short-circuiting

the test object after each set of measurement. This method is described below. The completely discharged dielectric is charged for a known time t_c and is discharged for a known time of $t_c/2$. The dielectric is left in open-circuited condition and the left-over polarized charge recovers and charges the dielectric geometrical capacitance. In this thesis, the RVM refers to the latter technique.

This charging time t_c is varied from 1 s to 10,000 s and a characteristic curve –“the polarization spectrum” relating the peak response and charging time is obtained. The peak recovered voltage, the corresponding time of charging and the initial slope are the derived parameters describing the RVM relaxation processes. By fitting the results to theoretical extended Debye model shown in Fig. 2-16, the relaxation time constants are determined. It is found that there exists many RC time constants and they vary and increase with aging of insulation system [12]. Laboratory studies [4] [9] [52] [56] [60] conducted on fabricated OIP laboratory model transformer show the variation of RVM by thermal aging at 120 °C in Fig. 2-8. The shift in left direction of the peak of RVM spectrum is interpreted as the formation of water due to thermal aging [56]. When the oil impregnated paper ages due to heating at 120°C, the water and the oxidized impurities due to the decomposition of oil and paper increase. The formation of water content and oxidized impurities shifts the time of the RVM peak polarization spectrum to short charging time. It is suggested that the polarization materials with fast polarization time constants get formed due to aging. The peak value also increases marginally with time of aging. This phenomenon can be used to evaluate the aging condition of the oil-paper insulation apparatus.

Fig. 2-8 Variation of RVM spectra with aging on transformer model [56]

2.4.2.1 Temperature and moisture effects on RVM

Fig. 2-9 shows the temperature dependent characteristics of RVM polarization spectra on an oil-filled transformer [3] [56] [57]. The peak occurs at charging time of around 200 s for 10 °C operations and it reduces to 1 s if the operating temperature is 101 °C. The rate of change in RVM with charging time also changes with temperature. Peak is reached fast at high temperature of operation.

Fig. 2-9 Variation of RVM spectra with operating temperature on 10/0.4 kV oil-filled transformer with moisture content of 2.14% [56]

The initial part of the polarization spectra is controlled by oil conductivity and the initial slope is used as an indicator of the condition of oil insulation. While the tail of RVM response is controlled by paper conductivity [59] and that rate of change is used to evaluate the condition of paper insulation. The RVM polarization spectra [56] are very sensitive to moisture content in paper as shown in Fig. 2-10. When the moisture in paper increases, the time at which RVM peak polarization spectrum occurs also shifts to lower charging time and the peak value also increases marginally.

Fig. 2-10 Variation of RVM spectra with moisture content in new state paper/oil insulation [56]

It should be noted that the test samples used in Figs. 2-8, 2-9 and 2-10 were different. Apart from operating temperature and water content in paper, ambient humidity affects RVM polarization spectra significantly [19]. Outdoor industrial practice is that RVM is done on a clear day with relative humidity less than 75%. The RVM polarization spectra [56] are very sensitive to moisture content in paper as shown in Fig. 2-10. When the moisture in paper increased, the time at which RVM peak polarization spectrum occurred also shifted to lower charging time and the peak value also increased marginally. Increased moisture content may induce fast polarization process resulting the peak to occur in lower charging time.

2.4.2.2 Drawbacks of RVM

(1) The old interpretation on RVM response was based on the Debye model which consists of a parallel RC or single series RC circuit [15]. That model relating the dominant time constant of the polarization spectrum and the water content in cellulose is not correct [40] [71] for all the field measurements.

(2) More research is to be done to relate with RVM polarization spectra and insulation condition [52]. At present, water content analysis in oil is related with RVM spectra as shown in Fig. 2-10. The moisture content of the cellulose evaluated from the

polarization spectrum is always higher than that obtained from other methods [12]. The error is attributed to their developed model which relates the moisture content and RVM polarization spectra.

(3) One set of RVM measurement takes up to 12 h if the charging is to be varied from 0.02 s to 10000 s. Any variation in ambient condition during that measurement may affect the measurement. RVM uses DC voltage in the range of 100 V to 2 kV for measurement and the polarization behaviors at 50 Hz with higher operating voltage may be different.

The required instrumentation is expensive and the person taking the measurement should be very knowledgeable about insulation as high impedance measurement is involved. The interpretation of the results in relation to polarization phenomena is not well studied. With that point of view, insulation resistance measurement with megger and polarization index measurement are extended to study the polarization phenomenon by polarization current measurement.

2.4.3 Polarization and depolarization current measurement (PDC)

When an electric field is suddenly applied to a dielectric, it interacts with the free and different kinds of bound charges within the dielectric. The initial in-rush polarization current decays fast and after a long time in the order of 10,000 s, it becomes steady. If the voltage generating the electric field is switched off by replacing the voltage source by a short circuit, an in-rush depolarization current of opposite polarity will flow and then it decreases to zero slowly [7] [14] [17] [68].

It is found that polarization current can be approximated to “n” number of exponents which stand for the different polarization time constants (τ_i) defined by (2-42) [14] and the leakage current of insulation due R_g .

$$i_{pol}(t) = U_0 \left(\frac{1}{R_g} + \sum_{i=1}^n \frac{e^{-\frac{t}{\tau_i}}}{R_i} \right) \quad (2-42)$$

While, depolarization current (2-43) [11] is also computed by adding “n” exponential terms.

$$i_{\text{depol}}(t) = U_0 \sum_{i=1}^n \frac{(1 - e^{-\frac{t_c}{\tau_i}}) e^{-\frac{t}{\tau_i}}}{R_i} \quad (2-43)$$

where t_c is the duration of the time during which the sample is charged.

Commercial instrument like PDC-analyzer [17] measures the current by applying a voltage in the range of 1000 V_{DC}. Using laboratory and field studies, software based on linear model of OIP transformer is developed to interpret the measured relaxation currents. It calculates the dc insulation resistance and polarization index. From PDC, the software can determine the dielectric response function and from that, RVM and FDS characteristics can be calculated.

2.4.3.1 Aging and moisture effects on PDC

The typical measured/calculated PDC by varying moisture content (m.c.) in the pressboard bar from 0.2% to 2.5% on a power transformer [46] is shown in Fig. 2-11. Up to 50 s, the current does not change much and the observed variation is attributed to the variation in oil conductivity. Beyond 50 s, the polarization and depolarization currents decrease significantly. The rate of variation is more if m.c. is low. It is attributed to the m.c. of paper.

Fig. 2-11 Measured and calculated PDC with m.c. in transformer [17]

T. Leibfield and A. J. Kachler [68] verified the validity of variation of PDC with the measured m.c. by Karl Fischer measurements on oil-filled paper insulation of transformer. Reference [58] used PDC technique to evaluate the effect of m.c. effects on OIP in cable as shown in Fig. 2-12. The PDC at 1s increases by 30 times when m.c. increases from 0.18% to 4.16%, and the increase in PDC at 10000 s is about 500 times. The references [63] [64] report that PDC for aged samples are significantly higher than the unaged 2% m.c. sample.

Fig. 2-12(a) Variation PDC of OIP with m.c. - Polarization current [58]

Fig. 2-12(b) Variation PDC of OIP with m.c. - Depolarization current [58]

2.4.3.2 Drawbacks of PDC

The difficulty in PDC measurement is that the measured current can vary from a few amperes to pA in duration from less than 1 s to 10000 s. Fast polarization information is buried at the starting time of measurement and slow polarization information is buried in the longer interval. Also, it can only reflect the integrated insulation condition of all connected apparatus, such as XLPE cable insulation and moisture content of OIP insulation together. One had to compare the field results with the database which was built with large amount of sample measurements in controlled laboratory conditions.

2.4.4 Summary

At present, three relaxation techniques use the “trend assessment” to assess the condition of insulation of different apparatus. It needs the initial healthy fingerprint of

new or aged apparatus which is difficult to get in a connected power network. Many laboratory studies on small samples and damaged transformer indicate that the above techniques can be used to diagnose the condition of insulation by trend assessment and the measurement gives a lot of polarization information with m.c., temperature and aging. More systematic and quantitative studies have to be done to relate the relaxation measurements with m.c., temperature and aging for field application. The relaxation electrical indicators like variation of complex dielectric constant with frequency, RVM and PDC spectra in time domain can be measured and it may vary with different apparatus and geometry for the identical insulation conditions. To overcome this difficulty, model studies are introduced and the parameters of the model are related to m.c., temperature and aging. A survey on the different reported models on OIP is reported below.

2.5 Modeling of oil and paper insulation

Based on the relaxation measurements on dielectric under different operating conditions, models are developed to identify the dielectric responses for different perturbations and different combination of dielectrics, and to understand the basic relaxation mechanisms. The interaction of individual dielectric responses on a composite insulation can be evaluated to understand and identify the dominant dielectric role. The studied operating conditions are the effects of aging, temperature, relative humidity and geometry on the relaxation responses.

Reported models can be classified into three groups. One group uses the dielectric response function models [18] [37] [39] in which an analytical expression is fitted to the experimentally measured time or frequency dependent dielectric responses. The responses are modeled like exponential or power functions as indicated in Section 2.1.4. The other group uses equivalent circuits [1] [8] [12] with the RC elements to represent the different polarization time constants of the insulation. It is nothing but the circuit representation of exponential responses. Recently, modeling of composite insulation based on geometrical arrangement discussed in Section 2.1.7 and

dimension is explored [40] since practical oil-filled apparatus uses different quantities of oil and paper depending on power and voltage rating.

2.5.1 General response function model

The main purpose of the general response function model is to characterize the insulation system with determined dielectric response function from anyone of the above three measurements that measured conductivity and relative permittivity [62]. (2-21) to (2-26) in Section 2.1.4 presents the mathematical equations to satisfy the dielectric response function in different dielectric media. Mostly, they are fitted to single dielectric with PDC and RVM measurements [18] [50]. Basically it is reported that the response function of OIP can approximately follow multi exponential functions and universal response functions [61]. References [61] and [62] use (2-24) and (2-16) to predict OIP system response functions. The typical calculated dielectric

Fig. 2-13(a) General response function model - Calculated dielectric response function [62]

Fig. 2-13(b) General response function model - Measured and predicted RVM[62] function from two RVM results is shown in Fig. 2-13(a). Fig. 2-13(b) shows the measured and calculated RVMs. It can be seen that the fitting of RVM calculated from the dielectric response function is very good.

2.5.1.1 Drawbacks

Characterizing insulation in power apparatus for diagnostic purposes and for estimating the remaining operating life is an important research area. For long time, $\tan\delta$ and Megger methods are being used. Dynamic methods using RVM, FDS and polarization/depolarization current measurements are being used to determine the condition indicating parameters by mathematical modeling of the measured respective dielectric responses. The procedure to calculate the response function is complicated, and it is not unique as many types of mathematical fitting can be made. It is important to notice that the general response function is only curve fitting and the relationship of this with different polarization responses in composite insulation is to be researched [62].

2.5.2 Equivalent circuit models

Dielectric response on dielectric is studied widely and physical interpretation in the form of lumped circuit model is tried following the material researchers working in fundamental physics and chemistry.

2.5.2.1 Simple RC circuits

AC low voltage bridges are used and the responses are modeled following Debye and Cole-cole models. Fig. 2-14 shows a few simple equivalent circuits to model the observed responses. For homogeneous single dielectric (a) and (b) are always used [8]. They are known as Debye model [8] with one time constant and the relaxation response follows the exponential function. Based on that, apparatus is tested at rated voltage of 50 Hz to evaluate the loss component. (c) is the complex capacitance model representing the dielectric impedance as a complex capacitance where the imaginary part of the capacitance represents the loss [1] [16]. Two parallel RC circuits in series are used to model the interfacial polarization [8]. In addition models describing diffusion, series dielectric barrier and series solution resistance have been proposed based on Cole-Cole plots [8] [37]. In practical HV dielectric measurements, the relaxation responses do not fit very well with all the above described models [1] [12] [61].

Fig. 2-14 Simple equivalent circuits

2.5.2.2 Extended Debye model (EDM)

Attempts are made to model the responses by many time constants using extended Debye model (EDM) [12] [61]. For power apparatus with oil insulation, the extended Debye model shown in Fig. 2-15 is used to match the individual recovery voltage response curves obtained by varying charging time [1] [61]. With the fitted model, responses on RVM, PDC and FDS can be predicted and matched. Typical measured and calculated responses by reference [61] are shown in Fig. 2-16. It is found that the fitting error reduces by increasing the number of RC elements. The model is verified by PDC measurement also [61]. The role of RC elements on relaxation is to be researched.

Fig. 2-15 Extended Debye model (EDM)

Fig. 2-16 Measured and fitted RVM response of transformer with 7 RC elements [61]

2.5.2.3 Drawbacks

Prediction of unified parameters of extended Debye model is difficult with the measured RVM, FDS and PDC responses. The determined parameters should be reasonable to match the observed relaxation time constants and must be able to explain the physical relaxation process.

The arrangement of two or multi dielectrics in any power apparatus is complicated. Section 2.1.7 presented some possible arrangements with two dielectrics. Recent study by varying oil and paper ratio suggests that different dielectric responses can be obtained [40]. With that point of view, the role of geometry in building the dielectric response model is developed.

2.5.3 Volume model of composite insulation

Reference [44] studied the dielectric property of multilayer stack of dry Kraft paper in air by varying frequency, temperature and compression in the frequency range of

10 to 30 kHz. Derived empirical equations (2-37) and (2-38) with two components for series and parallel arrangements take into account the volume fraction of paper and air. For OIP, it is found that dielectric response varies with oil-paper ratio [40]. Hence, a model known as X-Y model taking into account the volume of used dielectrics is proposed and tested with dielectric responses.

2.5.3.1 X-Y model

Any oil-filled insulation uses cellulose spacer and barrier with oil. It is found that by changing oil-paper ratio, the dielectric property changes as shown in Fig. 2-17. Based on the dimension of used insulating dielectrics, this model is developed. CIGRE Task Force 15.01.09 [40] studied extensively using different laboratory transformer models. The 3 dimensional symmetrical distributions of used dielectrics are grouped to 2 dimensional area distributions as shown in Fig. 2-17. The thickness of total barriers is marked as “X” and the left-over is taken as the thickness of total oil and spacers in that duct. The width of spacer is taken as “Y” and the left-over is taken as the width of oil. In many of commercial transformers [40], the ratio X varies from 0.2 to 0.5 and the ratio Y varies from 0.15 to 0.25. The developed model using pancake structure is termed as pancake or X-Y model. After a lot of experimentation and fitting, it is found that the dielectric constant of composite insulation of the transformer can be equated to (2-50). That equation predicts that the composite dielectric constant is a function of X, Y, $\epsilon_{\text{barrier}}$, ϵ_{spacer} and ϵ_{oil} . It is found to be a function of frequency and temperature as the dielectric properties are a function of temperature and frequency. Such X-Y modeling may be useful for physical interpretation and to link the measured responses by all the three methods.

$$X = \frac{\text{Thickness of total barriers}}{\text{Width of the duct}}$$

$$Y = \frac{\text{Total width of spacer}}{\text{Periphery of the duct}}$$

$$\epsilon(\omega, T) = \frac{Y}{\frac{1-X}{\epsilon_{\text{spacer}}} + \frac{X}{\epsilon_{\text{barrier}}}} + \frac{1-Y}{\frac{1-X}{\epsilon_{\text{oil}}} + \frac{X}{\epsilon_{\text{barrier}}}} \quad (2-50)$$

where

$$\varepsilon_{\text{spacer}} = \varepsilon_{\text{barrier}} = \varepsilon_{\text{pressboard}}(\omega, T)$$

$$\varepsilon_{\text{oil}} = \varepsilon_{r,\text{oil}} - j \frac{\sigma(T)}{\varepsilon_0 \omega}$$

Fig. 2-17 Schematic representation of the transformer insulation

2.5.3.2 Drawbacks

This model is based on the data collected from fabricated laboratory transformer. It is possible to estimate the geometrical parameters, oil and paper volume in laboratory sample. The dielectric properties and m.c are measured and used in the developed model. When used in field, normally the complex impedance is measured. In addition oil conductivity and dielectric constant are given as input. Conversion of this complex impedance to (2-50) is done by the built-in database [16]. X, Y and m.c. are predicted by fitting the experimental results as it is difficult to estimate the X and Y values of a transformer insulation in service. The validity of this prediction is to be proved in the field measurements.

2.6 Needed research work

From the literature survey, it is found that many areas are to be explored in connection with composite insulation relaxation studies.

(1) Most of the current relaxation theories are based on one component dielectric. The interfacial experimental polarization behavior in OIP with transformers and fabricated OIP samples were well explored for diagnosing purposes. The relaxation studies of

OIP relating with the corresponding relaxation properties of the individual components - oil and paper are to be further investigated. It is important to know the contribution of individual dielectric to the composite dielectric responses under various conditions.

(2) Reported conditions under which OIP studied are m.c., temperature and aging. No definite relationship is established with model and dielectric properties. The main reason may be equilibrium of m.c. in oil and paper and reference [55] suggests from theory that moisture may reach equilibrium state in about 69 days at 70 °C and 15 years at 15 °C. The diffusion of water between the cellulose and oil is sensitive to ambient temperature as pointed out, and the dielectric properties are sensitive to water content. Two areas to be explored are the equilibrium status of OIP, oil and paper using dielectric measurements and the role of temperature on the above.

(3) The thermal aging of the oil and paper insulation is the main reason for transformer damage and failure [10]. It is necessary to study the relaxation phenomena before, during and after the thermal aging to understand the mechanism of failure. Reported studies do not explain the mechanism with the models.

(4) The influence of oxidation products on dielectric responses is not reported.

(5) The suggested three relaxation models discussed in Section 2.5 can be used to model OIL, PB and OIP insulation or any other dielectric materials. The model linking OIP with its individual dielectric component models is not explored completely. X-Y model discusses about this but it is not explained in the form of equivalent circuits and physical meaning of individual relaxation processes.

(6) Oil-filled transformer insulation life and aging rate [49] are a time function of temperature, moisture content, oxygen content and acid content. Tensile strength of PB and degree of polymerization are the two existing intrusive condition monitoring methods used by the industry. Relaxation electrical measurements using RVM, FDS and PDC techniques are an interesting alternative tool to evaluate the changes in the dielectric status of insulation. Even though, they offer some promising results with aging and temperature, the reproducibility and practicability of these measurements are not still established.

Chapter 3

Experimental Set Up

The main objectives of the study are to understand the relaxation phenomena of individual pressboard and transformer oil in comparison with oil-impregnated pressboard, and to evaluate the role of thermal aging on the relaxation behavior. Dielectric properties of insulation materials can vary with voltage, operating temperature, frequencies, moisture content, aging, mechanical and other combination of stresses [1] [8] [37] [38]. Diagnosis of the dielectric parameters of the apparatus may be useful to know the operating condition of the apparatus. Power apparatus consists of two or more insulation components. The dielectric properties like conductivity and complex permittivity of the complete insulation are influenced by the dielectric properties of the individual constituents and the geometrical configuration of the system.

This chapter describes the details of developed test samples and designed measurement set up for relaxation and aging studies. It includes the preparation of test samples, the test arrangements, the procedures of testing, and the developed software for data logging and analysis. Sample capacitors with dielectric materials of OIL, PB and OIP were fabricated in the laboratory and the relaxation behavior of them was studied in time and frequency domains using RVM and FDS techniques respectively. The test object was kept in a sealed tank so that the disturbance from the ambient was kept to a minimum level to identify the variation of dielectric behavior. To get reproducible results within a range, the experiment was conducted for long hours in the range of 240 h. After reaching the equilibrium range, the recorded data was analyzed to evaluate the role of equilibrium time in each dielectric media. Then the effects of temperature and polarizing impurities were evaluated on the fabricated sample capacitors. The relaxation behavior of an oil-filled single phase transformer (SPT) was studied before, during and after aging for a period of 1100 h at 100°C. The obtained results were analyzed using EDM and newly developed FDRC model. The evaluated parameters may be more useful for field application to identify the change in relaxation processes in relation to insulation remaining life and aging rate.

3.1 Preparation of the test samples

The test samples used were fabricated with industrial grade transformer oil – Shell Diala® “B”, paper pressboard - PUCARO®, oil-impregnated pressboard and an oil-immersed 220V/110V, 1 kVA rated, paper insulated single phase transformer (SPT). They are called as OIL, PB, OIP and SPT respectively in the thesis. The pressboard was cut to size and kept in between the two planar electrodes tightly. The sample was kept in an air-tight sealed grounded chamber to minimize the external ambient disturbance. Connection from two planar electrodes was Teflon insulated and the necessary measurement instrument was interfaced to those terminals. For transformer, all the single-phase LV terminals were shorted to one terminal while all the HV terminals were shorted to another terminal.

3.1.1 Test samples

The test samples were made in the form of parallel plate capacitors of area $50 \times 100 \text{ mm}^2$. Aluminum planar electrodes of 1.5 mm thick with screwed external metallic connection were used. The thickness of the PB and the spacing in oil capacitor between the electrodes was 5 mm. The electrodes and insulation of the capacitors were held together by PVC bolt and nut to provide necessary pressure and mechanical stability. Table 3-1 lists all the studied samples, their quantity to conduct the relaxation measurements and the types of measurement. The measurements included FDS and RVM measurements at various temperatures, before, during and after accelerated thermal aging (ATA).

Sample No. 1

“OIL” shown in Fig. 3-1 was assembled using two parallel Aluminum electrodes spaced at 5 mm with teflon spacers, and kept in oil filled air-tight grounded stainless steel tank.

Sample No. 2

“PB” shown in Fig. 3-2 was made by packing the paper pressboard in between aluminum electrodes. The pressboard extended at least 5 mm beyond the electrodes

giving a fringe distance. During the measurement, this sample was also kept in the air-tight grounded stainless steel tank without oil at atmospheric pressure.

Table 3-1 Test samples and their purposes

Sample No.	Name and Abbreviation	Quantity and Dimension in mm	Measurements
1	Oil capacitor (OIL)	2 (100×50×5)	FDS, RVM - moisture equilibrium time, temperature dependence and oxidized impurities studies. Karl Fischer titration to determine water content in OIL.
2	Paper pressboard capacitor (PB)	4 (100×50×5)	FDS, RVM - moisture equilibrium time and temperature dependence studies.
3	Oil impregnated pressboard capacitor (OIP)	4 (100×50×5)	FDS, RVM - moisture equilibrium time, temperature dependence and oxidized impurities studies. Karl Fischer titration to determine water content in OIL.
4	Oil immersed single-phase transformer (SPT) 1kVA, 220V/110V	1	FDS, RVM - before and after ATA test. RVM - during ATA test.

Sample No. 3

“OIP” shown in Fig. 3-3 was made by keeping “PB” into the oil-filled stainless steel tank. Before the impregnating process, the pressboard samples were dried and degassed.

Stainless steel tank

The stainless steel tank had a steel lid with a recessed gasket and the lid was secured air-tight with 6 screws. Insulated binding posts in the center of the cover were electrically connected to aluminum electrodes. The test sample was connected using the binding posts for the measurement. The dimension of the stainless steel tank is

shown in Fig. 3-1. The volume of the tank was 4181 cm^3 and could hold oil with the weight of about 3.72 kg (the density of the used oil at $23\text{ }^\circ\text{C}$ was 0.888 g/cm^3).

Fig. 3-1 PB in the tank (LHS) and the photograph of the stainless steel tank (RHS)

Fig. 3-2 PB capacitor with the leads

Fig. 3-3 OIP in the sealed tank with the external electrical connections

Fig. 3-4 SPT with the external electrical connections

Sample No. 4

A laboratory paper insulated SPT with two windings of rating 220V/110V 1 kVA was immersed in an open tank filled with fresh transformer oil. The insulation of the winding was enamel and impregnated pressboard in cylindrical structure. The insulated leads from shorted LV and HV windings were taken for measurements as shown in Fig. 3-4. The tank and the LV winding were shorted to ground when carrying out the measurements. All the connected wires were Teflon insulated coaxial cable.

3.1.2 Transformer oil

Commercial grade Shell Diala “B” transformer oil was used in this project. It was refined from naphthenic oil. Before the oil was used, it was dried and degassed to ensure that there was minimum moisture present in the oil.

The main dielectric properties of this kind of oil are:

Dielectric loss factor:	<0.005
Volume resistivity	>60 GΩm
Dielectric constant at 50 Hz:	2.3

Other physical and chemical properties of this kind of oil can be found in Appendix A.

3.1.3 Paper pressboard (PB)

The commercial PUCARO® PB from local transformer manufacturer was used for the studies. The PB samples were dried for 48 h at a temperature of 105 °C in vacuum condition before any measurements. This drying procedure could achieve a water content of <0.5% in the PB samples.

The main dielectric properties of PB are:

Dielectric loss factor:	<0.003
Conductivity:	6.0mS/m
Dielectric constant at 50 Hz:	3.4

Other physical and chemical properties of this kind of pressboard can be found in Appendix B.

3.2 Measurement systems

For the relaxation measurements, FDS and RVM techniques were used. Low frequency dielectric spectroscopy measurement (FDS) was done with a commercial instrument – Insulation Diagnosis Analysis system (IDA) - IDA 200 [16]. Recovery voltage measurement (RVM) system was developed for the research work. Both the measurement systems could record the data digitally and then the data was processed with the developed programs using Matlab® optimization and signal processing tool-boxes [66].

3.2.1 FDS

FDS is low frequency AC current measurement system to evaluate the relaxation spectra in frequency domain from 0.1 mHz to 1 kHz. Fig. 3-5 shows the layout of FDS measurement setup with Insulation Diagnostic System - IDA 200 [16]. It can test the insulation objects up to AC voltage of 140 V_{rms}. It can measure the impedance from 10 Ω to 10¹³ Ω in the entire frequency range. The outputs of the instrument were connected with the shielded coaxial cables to the terminals of the test object.

The system applies the programmed AC voltage with the desired frequency range over the sample connected at “LO” and “HI” terminals. This voltage will generate a current in the sample kept in the tank. By accurately measuring the AC voltage and the AC current, the complex impedance can be calculated. Depending upon equivalent circuit model of the sample, various dielectric parameters [16] like series/parallel capacitance (C_s/C_p), series/parallel resistance (R_s/R_p), and complex dielectric constants (ϵ' and ϵ'') and loss factor ($\tan\delta$) can be calculated from the impedance data. In sweep mode, frequency responses of the above parameters can be measured automatically.

The system is fully computerized and most of the measurement can be performed automatically. A command file in “C” language controls every step in the measurement. This file describes the measurement setting in detail and is interpreted by the system on a sequential basis. Certain types of frequency measurements can be pre-programmed by creating a specific C-file. The results of a measurement are stored in a data-file.

Fig. 3-5 FDS measurement setup

The frequency range and sampling points can be set up according to the requirements. For a cycle of FDS with 23 sampling points with frequency range from 0.0001 Hz to 1 kHz, it will take about 16 h to finish the measurement. At each frequency setting, the experiment is repeated 3 times to eliminate noise. For a cycle of FDS with 7 sampling points with frequency range from 0.01 Hz to 1 Hz, it will take 30 minutes to carry out the measurement.

For the temperature dependence relaxation study, the samples were put into an environmental chamber to control the temperature and humidity. The instrument

computes the following: the parallel model parameters (parallel resistance R_p and capacitance C_p), series model parameters (series resistance R_s and capacitance C_s), relaxation time (product of series model resistance and capacitance), loss factor ($\tan\delta$) and complex permittivity (real part ϵ' and imaginary part ϵ'') as function of frequency. All the dielectric response results come from the measured impedance and phase at the selected frequencies. The variation of these parameters with frequency is good indicators of relaxation behavior of the dielectric.

Normal setting for FDS measurement in this project was:

For moisture equilibrium process study: 0.01 Hz - 1 Hz

For measurements in accelerated thermal aging: 0.01 Hz - 1 kHz.

AC voltage: 50 V_{rms}.

Data was saved in text-format with an extension of .idf and it was changed to text format with extension .txt for Matlab® signal processing.

3.2.2 RVM

In RVM measurement, the so-called RVM polarization spectrum technique was adopted. The layout of the developed measurement system is shown in Fig. 3-6. DC source up to 200 V_{DC} was used as the charging source. The procedure for RVM polarization spectrum measurement was: first, the DC source was connected to the test sample for polarization using computer controlled switch S1 for a programmed duration. Then, open S1, DC source was isolated from the test sample and the test

Fig. 3-6 RVM measurement setup

sample can be shorted for depolarization using S2 for a programmed duration. Then S2 was opened and the recovered voltage was measured using two serially connected high impedance Keithley DMMs. The reason was that it could increase the range of the measured voltage with input impedance greater than $10^{13} \Omega$.

The RVM polarization spectrum measurement was controlled with PC and GPIB interfaced instruments. Necessary interfacing software was developed using LabVIEW® [67] to control the sequence of operation of instruments. The data can be recorded to a maximum sampling rate of 10 per second for a long period up to 20000 s. The data were stored in the computer and on-line graphs of measured RVM can be seen on the PC's screen to make any local decision on measurement. In all the measurements, single peak response was obtained. The user can set the desired charging and discharging times, sampling interval and sampling data number. The developed PC screen layout is shown in Appendix C. The RVM measurement consists of 4 to 10 cycles of charging and discharging depending on the program of study. The charging voltage was kept at 50 V DC for minimum perturbation level. The charging time (t_c) was varied from 1 s to 1000 s by keeping the discharging time equal to half of t_c . The program was developed to display the summary of the responses in the form of RV polarization spectrum showing the peak RVM with the corresponding t_c after the completion of measurement. Normally one measurement for the above setting will take about one hour for the above selected setting.

3.2.3 Karl Fischer titration

Moisture content in transformer oil was measured using the Karl Fischer titration test method [53] [63]. The commercial instrument with coulometer titrator was used in this project [68]. The range of measurement was from 1 ppm to 100% of water in OIL.

3.3 Temperature and accelerated thermal aging (ATA) test set up

3.3.1 The environmental chamber

An environmental chamber shown in Fig. 3-7 was used to control the ambient temperature and humidity conditions for temperature dependent relaxation studies and

accelerated thermal aging tests. One of the test samples described in Section 3.1.1 can be housed inside the chamber. The chamber can maintain the ambient temperature in the range from 20 °C to 110 °C $\pm$ 1°C. The relative humidity can be set up to 90% $\pm$ 1%. Using the Teflon coated shielded cables; external connection to the measuring instruments was made.

Fig. 3-7 Environmental chamber

3.3.2 Portable temperature and relative humidity meter

The portable humidity meter, Hygroskop A1, from rotronic® Instruments (UK) Limited, was used to measure the spot temperature and humidity in the measurement site of laboratory. It was also used to check and calibrate the setting in the environmental chamber. The accuracy of the calibrated instrument at 25 °C was $\pm$ 2% RH for humidity and $\pm$ 0.3 °C for temperature.

3.4 Plan of the relaxation measurement studies

According to the objectives of my research work as described in Section 2.6 of Chapter 2, the following relaxation measurements were done. This time consuming experimental study was done in three relaxation programs with the samples described in Table 3-1.

Relaxation program 1: As the first part of this study, the role of stainless steel tank was explored on the measured results. This program was done to evaluate the relaxation behavior in frequency domain at room temperature. Using FDS, the relaxation measurements were done on OIL, PB and OIP with equilibrium time and

temperature. Then for OIP, oxidized impurities were added to study its role. The measured results and analysis are discussed in Chapter 4.

Relaxation program 2: This program was done to evaluate the relaxation behavior in time domain at room temperature. Using RVM, the relaxation measurements were done on OIL, PB and OIP with equilibrium time and temperature. The measured results and analysis are discussed in Chapter 5.

Relaxation program 3: This program was done to evaluate the relaxation behaviors before, during and after aging on SPT. Both FDS and RVM measurements were done during before and after aging. RVM was done also during aging. The measured results and analysis are discussed in Chapter 6.

3.5 Developed software tools

Relaxation studies may be done in many ways as described in Chapter 2. In this project, frequency and time domain relaxation behaviors were measured. For interpretation, lumped circuit models were used to identify the energy storage and dissipation during relaxation processes. A number of programs were developed using Matlab® Optimization Toolbox [66].

The developed programs for three relaxation programs are:

- (1) The curve fitting of the FDRC model on OIL, PB and OIP.
- (2) The curve fitting of the coefficients α and β in the new parallel-series RC model.
- (3) The optimization methods for determining the parameters of extended Debye model (EDM).
- (4) Programs for instrument interfacing for FDS and RVM.

3.6 Summary

The experimental setup for relaxation studies connected with this project was developed and tested. The experimental programs according to the requirements of the project were defined, and the software tools for data acquisition, control and analysis of the relaxation measurement results in frequency and time domains were developed.

Chapter 4

Relaxation Studies in Frequency Domain

This chapter presents the relaxation measurement results of OIL, PB and OIP using FDS and their analysis. The main objectives of this study are as follows: (1) to evaluate the equilibrium time constants of three test objects under different constant ambient temperature; (2) to determine the role of change in ambient temperature on the relaxation responses in OIL, PB and OIP; (3) to understand the role of oxidized impurities in OIP relaxation behavior. The first part of this chapter presents the measured procedures and responses; the second part of this chapter discusses a novel model to represent the relaxation processes of individual and composite dielectrics with a provision to predict the composite dielectric response from the individual dielectric responses. Significant changes are observed in the lowest frequency range.

4.1 Introduction

Relaxation studies have been researched for the condition assessment of oil-filled power apparatus [1]. Under operational electrical and temperature stresses, moisture, gases and other oxidation products are formed and they degrade the insulation [23] [26] [28]. By taking either a cut paper or oil sample, the condition parameters can be evaluated using chemical and physical methods described in Chapter 2. This off-line method is laborious and expensive, and the results can reveal the moisture and properties of the small sample only. It is found that the relaxation behavior in lower frequency [1] can be used to evaluate the moisture content and the aging condition of the insulation system. In addition by laboratory studies, it is found that the properties of individual dielectric and its geometrical arrangement can control the dielectric responses in different frequency ranges [18]. The dominant influence of pressboard for a composite insulation system of a transformer is mainly in the frequency range below 1 Hz. The moisture movement in between oil and PB is a dynamic process and it is sensitive to temperature. The moisture equilibrium between oil and PB under different operating temperature range is studied in laboratory by

many researchers [22] [46] [65]. When the insulation is in moisture equilibrium, any temperature change will disturb this current equilibrium to reach a new equilibrium as per the moisture equilibrium curves. The time constants are different for OIL, PB and OIP because of their individual chemical properties [46].

Relaxation response time of the dielectric is studied with Debye's expression (2-22) and other response function models described in Sections 2.1.4 and 2.1.5. The response is modeled as either single, multi exponential or power law functions. Because of the presence of conduction due to electrons and current due to polarization in the dielectric, one is bound to get in-phase current due to electrons and capacitive current due to polarization. These currents are represented as pure resistance R_p and capacitance C_p respectively by taking single RC Debye model. The response time τ to reach 63% of final polarization level can be determined at a frequency from R_p and C_p

$$\text{as } \tau = \frac{1}{\omega^2 R_p C_p}.$$

Polarization can also be evaluated by the relative permittivity of a dielectric which can be represented by a complex quantity ϵ that has a real part ϵ' describing energy storage, and an imaginary part ϵ'' describing the energy losses. It also varies as a function of the frequency of the applied voltage. The imaginary part ϵ'' is the sum of a conductivity term and a relaxation term [34].

$$\epsilon(\omega) = \epsilon'(\omega) - j\epsilon''(\omega) \quad (4-1)$$

$$\epsilon''(\omega) = \frac{\sigma}{\omega\epsilon_0} + \epsilon''_{rel}(\omega) \quad (4-2)$$

where σ is the ionic conductivity expressed in S/m, ϵ_0 is the permittivity of free space ($8.854 \times 10^{-12} \text{ C V}^{-1} \text{ m}^{-1}$), and ϵ''_{rel} is the loss due to dielectric relaxation.

The variation of these parameters can occur with frequency and temperature. The main objectives of this study are to identify the sensitive electrical parameters which can indicate the moisture equilibrium status for any variation. The variation of these parameters R_p , C_p , τ , ϵ' and ϵ'' depends on polarization response and energy lost. Both depend on the available polar impurities and their response to frequency and temperature.

During these equilibrium processes, the conductivity and the relative permittivity of the insulation system may change and reach an equilibrium state. For OIL, PB and

OIP, it is found that the measured $\tan\delta$ is also a function of tested frequency. It can show significant changes for the same deterioration at lower frequency [1] than at 50 Hz. Hence low frequency measurement is preferred for diagnosis of degradation.

When the dielectric is represented by serial circuit, the R_s , C_s and time constant τ can be got by R_p and C_p .

$$\begin{cases} R_s = \frac{R_p}{1 + \omega^2 C_p^2 R_p^2} \\ C_s = C_p + \frac{1}{\omega^2 C_p R_p^2} \end{cases} \quad (4-3)$$

$$\tau = R_s C_s = \frac{1}{\omega^2 R_p C_p} \quad (4-4)$$

It is well known that moisture equilibrium is very temperature sensitive; any tiny change in ambient temperature will change the equilibrium response of the insulation kept in sealed metal tank. Therefore, it is difficult to get exact reproducible results during the equilibrium state. It should be noticed that the equilibrium time will be strongly dependent on the size of a test object. Therefore, the determined equilibrium time is only applicable to the measured three samples – OIL, PB and OIP.

A systematic FDS based relaxation study is undertaken to understand the equilibrium process affects of temperature and oxidized impurities on the different relaxation processes.

4.1.1 Procedures for relaxation program 1 – in frequency domain

To evaluate the role of grounded tank on the measured test samples kept in them, the first series of measurements was done with 2 terminal measurements. The constant error was evaluated before continuing with other measurements. Then FDS measurements were done to evaluate the equilibrium status at room temperature of 22 °C, the effects of temperature dependence and injected polar oxidized impurities. The following steps were followed.

(a) Contribution of tank on FDS measurements

Step 1: The measurements were carried out between the tank and one electrode with and without oil to quantify the role of stainless steel tank on measurement. The determined correction factors were used for other measurements.

(b) Moisture equilibrium experiments at 22 °C

Step 2: The relaxation behavior of PB was evaluated by keeping it in sealed stainless steel tank without oil at air-conditioned laboratory condition of 22 °C. FDS measurement was done regularly once in 24 h until there was minimum fluctuation in the consecutive dielectric spectrums.

Step 3: Step 2 was repeated by removing PB with OIL.

Step 4: Step 2 was repeated by keeping the tank with OIP immersed in OIL.

It took at least 120 - 240 h for each insulation of PB, OIL and OIP to reach equilibrium range with minimum fluctuation.

(c) Temperature dependent measurements at 30 °C and 40 °C

Step 5: The sealed stainless steel tank either with PB, OIL and OIP was kept into the environmental chamber. The temperature was set to 30 °C with humidity level of 60% in the environmental chamber. Measurements described in steps 2 to 4 were repeated.

Step 6: Step 5 was repeated at 40 °C.

(d) Effect of oxidized impurities on OIP by FDS

Step 7: After the above studies, the stainless steel tank was emptied and cleaned dry, a fresh load of oil was filled to the tank with new OIP sample and FDS measurements were carried out at temperatures 22 °C and 30 °C. After that series of measurements, the tank was cooled down to room temperature of 22 °C. Opening the lid, the tank was emptied to half volume of the oil and then the top-up of tank was done with aged oil. The aged oil was taken from accelerated thermal aging experiments done for 1100 h at 100 °C. After stirring well, FDS measurements were carried out at temperatures 22 °C and 30 °C.

4.2 Experimental results

According to the relaxation program 1, FDS measurements were carried with OIL, PB and OIP. Since the samples were kept in sealed tank, the error in measurement due to enclosed tank was first investigated.

4.2.1 Contribution of tank on FDS measurements

The simplified schematic of the measurement system is shown in Fig. 4-1. The measured FDS results include the impedance of samples and the impedance between the high voltage electrode and tank. FDS measures R_p and C_p . For each setting, two measurements were done as described in Step 1 of Section 4.1.1. The measurement with one electrode to tank gives C_{pt} and R_{pt} . While the second measurement with two electrodes and grounded tank gives the parallel combination of sample between two electrodes and the tank. By simple parallel subtraction the individual R_p and C_p of sample and tank can be determined using (4-5).

$$\begin{cases} C_{ps} = C_p - C_{pt} \\ R_{ps} = \frac{R_{pt} R_p}{R_{pt} - R_p} \end{cases} \quad (4-5)$$

where C_p, R_p : the measured simple parallel RC value with tank,

C_{pt}, R_{pt} : the measured simple parallel RC value with one electrode and tank filled with air or oil, and

C_{ps}, R_{ps} : the simple parallel RC value of sample (OIL, PB and OIP).

Fig. 4-1 Simplified schematic of the measurement system

For the tank filled with air at 22 °C, the tank parallel resistance R_{pta} satisfies (4-6).

$$R_{pta}(f) = 9.52 \times 10^8 e^{-0.055f} \quad (4-6)$$

The tank parallel capacitance C_{pta} satisfies (4-7).

$$C_{pta}(f) = 1.16 \times 10^{-10} f^{-0.047} \quad (4-7)$$

If the tank is filled with oil at 22 °C, the tank parallel resistance R_{pto} satisfies (4-8).

$$R_{pto}(f) = 8.04 \times 10^8 e^{-0.066f} \quad (4-8)$$

The tank parallel capacitance C_{pto} satisfies (4-9).

$$C_{pto}(f) = 1.21 \times 10^{-10} f^{-0.048} \quad (4-9)$$

Fig. 4-2 shows the typical variation of R_p and C_p due to tank effects on OIP at 22 °C. The “Tank” stands for the tank alone measurement, the “OIP+Tank” stands for the measurement with 2 electrodes encompassing OIP in oil filled tank and the “OIP” stands for the determined OIP. From the above, we can understand that a maximum error in R_p and C_p will be 16% and 18% respectively. This correction is taken into account in all the future calculations.

Fig. 4-2 The effect of tank with OIP

4.2.2 Moisture equilibrium studies by FDS

It was reported from numerical calculation based on moisture diffusion coefficients in OIL and PB that the equilibrium time may vary from 7 days to hundreds days depending on the operating temperature [65]. A systematic study was undertaken by keeping PB, OIL and OIP in a stainless steel tank under various conditions.

Relaxation parameters in terms of R_p , C_p , relaxation time constant (τ) = $R_s \times C_s$, real dielectric constant (ϵ') and imaginary dielectric constant (ϵ'') were measured and plotted with respect to frequency. The reason for the selection of the relaxation time constant, (τ) = $R_s \times C_s$ in stead of (τ') = $R_p \times C_p$, is for the convenience of identifying series time constant range to be used for the developed new FDRC model described in the Section 4.3.

4.2.2.1 OIL alone

With two electrodes arrangement, periodic measurement was made on the relaxation behavior of OIL in sealed tank at 22 °C. Figs. 4-3 and 4-4 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and time of measurement. Indicated number beside the curves is the time in “h” of conducting the measurements.

Fig. 4-3 Variation of R_p , C_p and τ with time and frequency in OIL

Fig. 4-4 Variation of ϵ' and ϵ'' with time and frequency in OIL

4.2.2.2 PB alone

The next series of equilibrium studies were done in the stainless steel chamber without oil. Across the two electrodes, PB was mounted. Figs. 4-5 and 4-6 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and time of measurement at 22 °C.

Fig. 4-5 Variation of R_p , C_p and τ with time and frequency in PB without oil

Fig. 4-6 Variation of ϵ' and ϵ'' with time and frequency in PB without oil

4.2.2.3 OIP in oil

The next series of equilibrium studies were done in the stainless steel chamber with OIL and PB immersed in oil. Across the two electrodes, PB was mounted. Figs. 4-7 and 4-8 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and time of measurement.

Fig. 4-7 Variation of R_p , C_p and τ with time and frequency in OIP

Fig. 4-8 Variation of ϵ' and ϵ'' with time and frequency in OIP

Equilibrium time – The samples OIL, PB and OIP were brought in the sealed test chamber from storage conditions. The distribution of polar water impurity in these media can remain in different forms and the determination of exact water content and its distribution is not a practicable exercise with the existing technology. Dielectrometry measurement [58] at low frequency was identified as the best tool to evaluate the dynamic responses in non-invasive mode. The experiment was conducted for a continuous period of 240 h for each sample and after that period, the variation of these parameters at 0.01 Hz was found to be small. In OIL, PB and OIP the variation of R_p in equilibrium time of 240 h in Figs. 4-3, 4-5 and 4-7 were 70%, 63% and 27% respectively. Rate of change was decreasing with equilibrium time. This may be due to the migration and redistribution of dissolved and suspended water molecules in the test chamber reducing the conductivity. In OIP, it was minimum due to slow diffusion rate and may have stabilized in earlier experiments.

It is well known that moisture equilibrium is sensitive to temperature. Any tiny change in ambient temperature will change the equilibrium response of the insulation kept in sealed metal tank. Therefore, it was difficult to get reproducible results during the equilibrium state. All the responses in Fig. 4-3 to Fig. 4-8 were found to have a huge variation in the beginning of equilibrium time and then they fluctuated around a

finite range. Hence in Fig. 4-3, 168 h R_p curve and 240 h R_p curve were found to lie within a band of variation.

In OIL, PB and OIP the variation of C_p in 240 hours in Figs. 4-3, 4-5 and 4-7 were 26%, -78% and -22% respectively. Redistribution of water molecules increased the capacitance in oil and decreased the capacitance in OIP and more significantly in PB. In OIL, PB and OIP the variation of ϵ' in Figs. 4-4, 4-6 and 4-8 were 14%, -86% and -14% respectively. It followed the variation of C_p . In OIL, PB and OIP the variation of ϵ'' in Figs. 4-4, 4-6 and 4-8 were -40%, -38% and -17% respectively. It follows the variation of $(1/R_p)$.

Frequency – All the parameters were found to decrease with increase in frequency especially after the equilibrium time of 240 h. With increase in frequency, the energy lost will be more, and R_p decreased. In OIL, PB and OIP the variation of R_p in the measured frequency range in Figs. 4-3, 4-5 and 4-7 were -7%, -4% and -7% respectively. In OIL, PB and OIP the variation of ϵ'' with frequency in Figs. 4-4, 4-6 and 4-8 were -98%, -99.8% and -99.8% respectively and the magnification was due to the dominant role of frequency in ϵ'' in relation to R_p . In OIL, PB and OIP the variation of C_p in the measured frequency range in Figs. 4-3, 4-5 and 4-7 were -75%, -90% and -94% respectively indicating that the polarization was maximum at low frequency and it decreased significantly with increase in frequency. The change was more for PB and OIP. In OIL, PB and OIP the variation of ϵ' with frequency in Figs. 4-4, 4-6 and 4-8 were -73%, -94% and -98% respectively. It followed the variation of C_p . Table 4-1 summarizes the observations. The change in parameter value in the initial period of 0 to 24 h was more and then up to 240 h of equilibrium study, it fluctuated in a definite band. Parameter variation with frequency of operation from 0.01 Hz to 1 Hz is also reported. From the above, it can be concluded that R_p in OIL, PB and OIP increased and all the other parameters decreased in the initial 24 h except for derived parameter τ in PB and OIP. All the parameters had significantly less fluctuation after the equilibrium period. With increase in frequency from 0.01 Hz to 1 Hz, the variation of R_p especially in PB was small and other parameters varied significantly.

Chapter 4 Relaxation Studies in Frequency Domain

Table 4-1: Variation of parameters with equilibrium time, frequency and dielectrics

Time	OIL	PB	OIP
R_p at 0.01 Hz (0 to 24 h)	+51.0%	+41.0%	+19.0%
R_p at 0.01 Hz (24 to 240 h)	$\pm 6.5\%$	$\pm 8.0\%$	$\pm 4.0\%$
R_p at 240 h (0.01 Hz to 1 Hz)	-7.2%	-3.4%	-7.3%
C_p at 0.01 Hz (0 to 24 h)	-6.0%	-76.0%	-31.0%
C_p at 0.01 Hz (24 to 240 h)	$\pm 12.0\%$	$\pm 7.0\%$	$\pm 7.0\%$
C_p at 240 h (0.01 Hz to 1 Hz)	-75.0%	-90.0%	-92.0%
τ at 0.01 Hz (0 to 24 h)	-26.0%	+167.0%	+16.0%
τ at 0.01 Hz (24 to 240 h)	$\pm 15.0\%$	$\pm 3.0\%$	$\pm 14.0\%$
τ at 240 h (0.01 Hz to 1 Hz)	-97.0%	-94.0%	-92.0%
ϵ' at 0.01 Hz (0 to 24 h)	-28.0%	-83.0%	-28.0%
ϵ' at 0.01 Hz (24 to 240 h)	$\pm 12.0\%$	$\pm 15.0\%$	$\pm 6.5\%$
ϵ' at 240 h (0.01 Hz to 1 Hz)	-73.0%	-80.0%	-93.0%
ϵ'' at 0.01 Hz (0 to 24 h)	-33.0%	-28.0%	-16.0%
ϵ'' at 0.01 Hz (24 to 240 h)	$\pm 5.0\%$	$\pm 6.0\%$	$\pm 4.0\%$
ϵ'' at 240 h (0.01 Hz to 1 Hz)	-98.0%	-97.0%	-98.0%

Figs. 4-9 and 4-10 show the parameter variation of 3 dielectrics after equilibrium time. Table 4-2 lists the ratio of these parameters in different dielectrics. PB conducts more using the parameters R_p and ϵ'' , and capacitances of PB and OIP are more than OIL.

Table 4-2: Ratio of R_p , C_p and ϵ'' with dielectric at equilibrium

Figure No.	Ratio in R_p at 0.01Hz	% variation in C_p at 0.01Hz	% variation in ϵ'' at 0.01Hz
4-9 (OIL, PB, OIP)	$R_{p\_PB} / R_{p\_OIL} = 0.08$	$C_{p\_PB} / C_{p\_OIL} = 7.9$	-
4-9 (OIL, PB, OIP)	$R_{p\_OIP} / R_{p\_OIL} = 0.16$	$C_{p\_OIP} / C_{p\_OIL} = 6.0$	-
4-10 (OIL, PB, OIP)	-	-	$\epsilon''_{PB} / \epsilon''_{OIL} = 15$
4-10 (OIL, PB, OIP)	-	-	$\epsilon''_{OIP} / \epsilon''_{OIL} = 12.8$

It is realized that the composite insulation OIP's dielectric response parameters are not simple algebra of OIL and PB component dielectric responses and they vary with frequency also.

4.2.2.4 Comparison of FDS responses at 240 h

For all the samples, measurements were carried for 240 h and by that time, the minimum fluctuation was observed between consecutive readings indicating the insulation may have reached an equilibrium state. A comparison of the general dielectric behavior of OIL, PB and OIP was made after the equilibrium time of 240 h where the variation of the dielectric responses was less with measurement time. Figs. 4-9 and 4-10 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and time of measurement. The dielectric response of the three samples had the same trend with frequency at equilibrium state, but the order of change was different.

- OIP - R_p lies in between pure OIL - R_p and PB - R_p and it follows closely the variation of pure PB - R_p variation.
- OIP - C_p lies in between pure OIL - C_p and PB - C_p and it follows closely the variation of pure PB - C_p variation.
- OIL - τ is the lowest in comparison with pure OIP - τ and PB - τ .

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- OIP - ϵ' lies in between pure OIL - ϵ' and PB - ϵ' and it follows closely the variation of pure PB - ϵ' variation.
- OIP - ϵ'' lies in between pure OIL - ϵ'' and PB - ϵ'' and it follows closely the variation of pure PB - ϵ'' variation.

Fig. 4-9 Variation of R_p , C_p and τ with time and frequency after 240 h in OIL, PB and OIP

Fig. 4-10 Variation of ϵ' and ϵ'' with time and frequency after 240 h in OIL, PB and OIP

4.2.3 Temperature dependence studies by FDS

A research study was taken in the temperature range from 22 °C to 40 °C to evaluate the equilibrium status of OIL, PB and OIP as no reported literature was available. Since the equilibrium studies at each temperature setup took about 10 days, the range of temperature measurement was restricted to understand the different mechanism of relaxation with increase in temperature.

4.2.3.1 OIL alone

Figs. 4-11 and 4-12 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and temperature after equilibrium time.

Fig. 4-11 Variation of R_p , C_p and τ with temperature and frequency in OIL

Fig. 4-12 Variation of ϵ' and ϵ'' with temperature and frequency in OIL

4.2.3.2 PB alone

Figs. 4-13 and 4-14 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and temperature after equilibrium time.

Fig. 4-13 Variation of R_p , C_p and τ with temperature and frequency in PB

Fig. 4-14 Variation of ϵ' and ϵ'' with temperature and frequency in PB

4.2.3.3 OIP in oil

OIP was tested from 22 °C to 40 °C. The equilibrium time decreased marginally around 240 h with increase in temperature. All the measurements had been carried for 240 h. Figs. 4-15 and 4-16 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and temperature after the equilibrium time.

Fig. 4-15 Variation of R_p , C_p and τ with frequency and temperature in OIP

Fig. 4-16 Variation of ϵ' and ϵ'' with frequency and temperature in OIP

Temperature – The conduction is sensitive to temperature changes. Usually, the temperature dependence of the conductivity can be described as an Arrhenius type with an activation energy in the range of 0.5 – 1 eV for the insulating material [28]. All the parameters were found to decrease with increase in temperature especially after the equilibrium time of 240 hours. The change was found to be maximum at low frequency. In OIL, PB and OIP the percentage variation of R_p per deg from 22 °C to 30 °C at low frequency in Figs. 4-11, 4-13 and 4-15 were -4.7%, 7.2% and -6.8% respectively. While from 30 °C to 40 °C, they changed to -4.6%, 2.1% and -2.6% respectively. With increase in temperature, energy loss will be more and R_p decreased in OIL and OIP. This rate of decrease was almost same in OIL, but in OIP, the rate of decrease decreased with increase in temperature. In PB, R_p increased more at low temperature range. The increase may be due to vaporization of water content in PB. Similar type of variation was observed with $(1/\epsilon'')$.

In OIL, PB and OIP the percentage variation of C_p per deg from 22 °C to 30 °C at low frequency in Figs. 4-11, 4-13 and 4-15 were 10.5%, -1.7% and 35.6% respectively. While from 30 °C to 40 °C, they changed to 4.1%, -1.5% and 8.8% respectively. With increase in temperature, more ambient water may have dissolved to increase C_p in

OIL and OIP. PB may have lost the water to decrease its C_p at high temperature range. Similar type of variation was observed with ϵ'

4.2.4 Effect of oxidized impurities on OIP by FDS

It is well known that the aging of OIP will be accelerated [3] due to the presence of impurities, such as water, particle, gases and oxidation byproducts. In this section, the variation of dielectric responses due to the injection of oxidation byproducts in OIP was studied. The oxidation in oil was induced by aging the oil-filled SPT for 1100 h at 100 °C. The exact composition was not analyzed but the oil was dark and thick with floating oxidized materials. Only water content in oil was analyzed and the water content increased from 20 ppm to 52 ppm.

The equilibrium studies were done for 240 h and it was found that the equilibrium reached in about 96 h. Figs. 4-17 and 4-18 show the variation of dielectric responses in terms of R_p , C_p , τ , ϵ' and ϵ'' with frequency and temperature after equilibrium time at 22 °C and 30 °C for OIP immersed in new and oxidized impurity added oils.

R_p of OIP decreases with adding oxidized impurity oil and increase in temperature. With impurity oil, decrease of R_p with frequency is marginal.

C_p of OIP increases with adding oxidized impurity oil and increase in temperature. With impurity oil, decrease of C_p with frequency is more in the low frequency range.

τ of OIP decreases with added oxidized impurity oil and increase in temperature.

ϵ' of OIP like C_p increases with adding oxidized impurity oil and increase in temperature. For impurity oil, decrease of ϵ' is much in the low frequency range.

ϵ'' representing the energy loss or $(1/(\text{frequency} \times R_p))$ increases with adding oxidized impurity oil and decrease in temperature.

Fig. 4-17 Variation of R_p , C_p and τ in OIP with new and added impurity oil, frequency and temperature

Fig. 4-18 Variation of ϵ' and ϵ'' in OIP with new and added impurity oil, frequency and temperature

4.3 Simulation studies in frequency domain

To explain the results of the measurements, mathematical model is a useful method to predict the responses. This mathematical model must be able to predict the relaxation responses with equilibrium time, temperature and oxidized impurities. Extended

Debye model is extensively used to predict the relaxation behavior of oil-filled power apparatus. Geometrical model is used to predict the relaxation behavior of oil-filled laboratory transformer in terms of pure oil and pressboard. The method appears to be based on varying dimension to relate with oil-filled transformer FDS response. No empirical relationship is reported. In this study, using a simple capacitor sample the responses were measured and a novel model was developed. Since ϵ' and ϵ'' varied with frequency in 3 samples and the classical Debye model used one RC in series to represent the relaxation response, the developed model is continued on the same concept.

4.3.1 Developed relaxation model - FDRC model - of OIL, PB and OIP

Reported earlier measurements were shown in C_p and R_p configuration to evaluate the variation of polarization and dielectric loss due to equilibrium, temperature and added oxidized impurity. Since series model can be better used to represent the dielectric response time, the analysis in building the model is focused on series C_s and R_s variation with respect to frequency. A typical variation in OIL shown in Fig. 4-3 is redrawn as C_s and R_s variation with frequency in Fig. 4-19 using (4-3). All the responses followed the same trend. The experimental observation shown in Figs 4-3, 4-5 and 4-7 in terms of series model suggests the possible variation of C_s and R_s with reference to frequency. R_s varies exponentially with frequency in log-linear scale and C_s varies linearly in log-log scale.

The mathematical functions (4-10) and (4-11) are used to fit the experimental observations. In that “a”, “b”, “c” and “d” are constants which can be evaluated by fitting.

$$C_s(f) = af^b \quad (4-10)$$

$$R_s(f) = ce^{df} \quad (4-11)$$

If one plots (4-10) in log-log scale, “a” stands for the intercept in y axis and “b” stands for the rate of decrease of $\log(C_s)$ with $\log(f)$. “c” stands for R_s at zero frequency and “d” stands for the rate of logarithmic variation of R_s with linear frequency.

Fig. 4-19 Variation of R_s and C_s with time and frequency in OIL (Fig. 4-3 is redrawn)

The new developed relaxation model - Frequency dependent RC model (FDRC) - for OIL, PB and OIP is shown in Fig. 4-20(a). A typical fitted plot is shown below in Fig. 4-20(b). The maximum error is found to be within $\pm 5\%$.

Fig. 4-20(a) Developed relaxation model - FDRC model - for OIL, PB and OIP

Fig. 4-20(b) Typical FDRC model fitting with the measured data on OIL at 240 h in Fig. 4-3 and Fig. 4-19

4.3.2 Variation of “a”, “b”, “c”, “d” with reference to equilibrium time, temperature and addition of oxidized impurities

Using the above FDRC model, a close fitting of all the measured responses are made. The variation of “a”, “b”, “c” and “d” with equilibrium time, temperature and added oxidized impurities are evaluated.

4.3.2.1 Equilibrium time

Fig. 4-21 shows the variation of fitted “a”, “b”, “c” and “d” values during equilibrium process. With equilibrium time, the change is the minimum. The parameter “a” which stands for C_s at low frequency is the maximum for PB and minimum for OIL, and it appears to reach equilibrium in about 100 h. The parameter “b” stands for the rate of decrease of $\log(C_s)$ with $\log(f)$. PB is found to decrease more during the initial period of equilibrium. For OIL, it is a slow rise. In OIP, a marginal fluctuation is observed. The parameter “c” stands for R_s at zero frequency. For OIL, it is the maximum and for PB, this is the minimum. After 100 h of equilibrium time, a marginal variation is

observed. The parameter “d” stands for the rate of logarithmic variation of R_s with linear frequency. For PB and OIP, the variation is not significant. For OIL, this is decreasing at various rates with equilibrium time.

Fig. 4-21 Variation of “a”, “b”, “c” and “d” with equilibrium time on PB, OIL & OIP

4.3.2.2 Temperature

The role of temperature after the equilibrium time was evaluated by separate experiments. With temperature, the change is minimum with “a” and “b”. The parameter “a” which stands for C_s at low frequency is maximum for PB and minimum for OIL. For OIP, at high temperature range, it matches with PB. The parameter “b” stands for the rate of decrease of $\log(C_s)$ with $\log(f)$. The variation in PB is the minimum. For OIL, it is a slow rise. In OIP, a steady rise is observed with temperature. The parameter “c” stands for R_s at zero frequency. For PB, the variation is the minimum. For OIL, it decreases at an increasing rate with increase in temperature. For OIP, it decreases up to 30 °C and then the change with temperature is the minimum. The parameter “d” stands for the rate of logarithmic variation of R_s with linear frequency. For PB, it decreases steadily with increase in temperature. For OIL, it rises marginally. For OIP, it increases more at low temperature range and at high temperature range; it increases at a lesser rate. The sample OIL used for

temperature dependence is different from OIL used in equilibrium studies. Hence, discontinuity in OIL responses at 22°C is noticed.

Fig. 4-22 Variation of “a”, “b”, “c” and “d” with temperature on PB, OIL & OIP

4.3.2.3 Added oxidized impurities

The role of oxidized impurities in OIP after the equilibrium time and with rise in temperature was evaluated by separate experiments. The results are tabulated in Table 4-1. The parameter “a” which stands for C_s at low frequency increases with oil containing impurities and increase in temperature. The parameter “b” stands for the rate of decrease of $\log(C_s)$ with $\log(f)$. The rate of decrease is less with oil containing impurities. The parameter “c” stands for R_s at zero frequency. It is less for the oil containing impurities. The parameter “d” stands for the rate of logarithmic variation of R_s with linear frequency. It is less for oil containing impurities.

Table 4-3 “a”, “b”, “c”, and “d” of added oxidized impurities OIL in OIP

	a	b	c	d
20 °C (Imp.)	3.41e-8	-1.33	4.68e7	-0.08
30 °C (Imp.)	9.37e-8	-1.26	2.20e7	-0.01
20 °C (New)	4.80e-9	-1.46	11.6e7	-0.20
30 °C (New)	9.87e-9	-1.41	7.18e7	-0.13

4.3.3 Predicted OIP model in terms of OIL and PB models

The equilibrium data on OIL, PB and OIP are taken and the relationship of OIP model in terms of PB and OIL models is evaluated to understand the individual role of PB and OIL on OIP. The variation of C_s and R_s in PB, OIL and OIP with frequency is plotted in Fig. 4-23. The characteristics of OIP lie in between OIL and PB for both C_s and R_s . This suggests that OIP characteristics may be a parallel combination of OIL and PB individual characteristics. When we fitted the responses to match OIP, the match is not good. Various network combinations are explored. The value of R_s of OIP is less than R_s of OIL and more than R_s of PB. Hence, in the parallel combination, OIL circuit is taken as the starting network. To match with OIP, another parallel element is to be introduced to reduce R_s and increase C_s . A best match could be made by taking a series combination of modified OIL and PB network as shown in Fig.4-24. In Fig. 4-24, $R_{so}(f)$, $R_{sp}(f)$, and $R_{sop}(f)$ stand for the series resistance of OIL, PB and OIP insulation respectively. While $C_{so}(f)$, $C_{sp}(f)$, and $C_{sop}(f)$ stand for the series capacitance of OIL, PB and OIP insulation respectively. $\alpha = 0.021$ and $\beta = 3.06$ are the matched coefficients for OIL and PB respectively. Using the developed parallel-series RC model, the dielectric response of OIP can be predicted if one knows the dielectric responses of PB and OIL individually. Fig. 4-25 shows the predicted OIP response in equilibrium time at 22 °C.

Fig. 4-23 Variation of R_s and C_s with frequency after 240 h in PB, OIL & OIP

Fig. 4-24 The developed parallel-series RC model for OIP

In this model the values of α and β under temperature and impurities need to be solved. It is convenient to use impedance of the three samples to build the new model. When using series models of the OIL, PB and OIP, the impedances of them with frequency are:

$$Z_o(\omega) = R_{so}(\omega) + \frac{1}{j\omega C_{so}} \tag{4-12}$$

$$Z_p(\omega) = R_{sp}(\omega) + \frac{1}{j\omega C_{sp}} \quad (4-13)$$

$$Z_{op}(\omega) = R_{sop}(\omega) + \frac{1}{j\omega C_{sop}} \quad (4-14)$$

In Fig. 4-24,

$$\frac{1}{Z_o(\omega)} + \frac{1}{\alpha Z_o(\omega) + \beta Z_p(\omega)} = \frac{1}{Z_{op}(\omega)} \quad (4-15)$$

After simplification

$$\frac{1}{\alpha Z_o(\omega) + \beta Z_p(\omega)} = \frac{1}{Z_{op}(\omega)} - \frac{1}{Z_o(\omega)} \quad (4-16)$$

$$Z_e(\omega) = \frac{1}{\frac{1}{Z_{op}(\omega)} - \frac{1}{Z_o(\omega)}} = \text{Re}(Z_e) + j\text{Im}(Z_e) \quad (4-17)$$

$$\alpha Z_o(\omega) + \beta Z_p(\omega) = Z_e(\omega) \quad (4-18)$$

$$\alpha \text{Re}(Z_o) + j\alpha \text{Im}(Z_o) + \beta \text{Re}(Z_p) + j\beta \text{Im}(Z_p) = \text{Re}(Z_e) + j\text{Im}(Z_e) \quad (4-19)$$

$$\alpha[\text{Re}(Z_o) + j\text{Im}(Z_o)] + \beta[\text{Re}(Z_p) + j\text{Im}(Z_p)] = \text{Re}(Z_e) + j\text{Im}(Z_e) \quad (4-20)$$

This is a non-standard non-negative linear curve fitting problem. It can be easily solved by Matlab® [66].

4.3.3.1 Variation of matching coefficients α and β

The validity of the developed model with equilibrium time, temperature and added oxidized impurities is explored in this section. The responses of OIL and PB shown in Sections 4.2.2, 4.2.3 and 4.2.4 are used to match OIP characteristics. Fig. 4-26 shows the variation of matched coefficients with equilibrium time and temperature. The coefficient for OIL, α in the series element is always less than 0.02 indicating the minority role of OIL in contributing to the series resistance and the dominant role of OIL in contributing to the series capacitance. With equilibrium time, it decreases sharply and stabilizes to a constant value. With increase in temperature, α decreases,

Fig. 4-25 The predicted OIP response in equilibrium time at 22 °C

Fig. 4-26 Variation of α and β with equilibrium time and temperature

indicating the increased role of OIL capacitance in OIP responses. The coefficient for PB, β in the series element varies from 0.4 to 3.5. With equilibrium time, it decreases and a small fluctuation is observed in longer hours. With increase in temperature, β decreases to indicate the increased role of PB capacitance in OIP responses. The rate of decrease of α and β with increase in temperature varies.

4.3.3.2 Discussion on the FDRC model

The developed model may be useful to relate the dielectric response of individual dielectric in a composite dielectric environment. The analysis is developed in terms of serial model given by Debye which used frequency independent single RC connected in series. The dielectric response is measured mainly by the response time. Here we discuss the usefulness of the model to explain the relaxation phenomena with equilibrium time and temperature in OIL, PB and OIP.

In all the cases of study, τ , C_s and R_s of OIP is not a simple function of the corresponding parameters of OIL and PB. The developed model is able to relate OIP relaxation behavior by a parallel combination of OIL response and serially connected OIL and PB responses.

Fig. 4-27 presents the variation of τ with frequency for OIL, PB, OIP and the series branch of FDRC model at 0 h and 240 h of equilibrium time and at two temperatures of 22 °C and 40 °C. First let us discuss the relaxation behavior with respect to the equilibrium time at 22 °C. The τ at 0 h is shown as line without symbols while at 240 h, the corresponding line has marker. For OIL, τ decreases from 1350 s to 680 s. While for PB, τ increases from 550 s to 1550 s and for OIP, τ decreases marginally from 780 s to 740 s. This may be due to internal redistribution of different states of water and other polarizing impurities in OIL, PB and OIP kept in the sealed stainless steel tank in the corresponding test period of 240 h. The fitted model from the experiments suggests that α and β decrease with equilibrium time. It means that R_s decreases and C_s increases in the serially connected OIL and PB branch. The combined R_s decreases and C_s increases. τ of serially connected branch increases from 600 s to 1400 s in Fig. 4-27 (a) indicating the sensitivity of this interface of OIL and PB. This is not reflected significantly in the measured OIP characteristics which change from 780 s to 740 s. The model clearly suggests that the measured response of OIP at 22 °C after equilibrium time is dictated by OIL relaxation behavior. At the starting of equilibrium time at 22 °C, the behavior of OIP is dictated by PB relaxation behavior.

(a) at 22 °C

(b) at 40 °C

Fig. 4-27 Variation of τ with frequency at 0 h and 240 h on OIL, PB, OIP and serial element of developed FDRC model

As a second part of discussion, let us look at the relaxation behavior with respect to the equilibrium time at 40 °C. For OIL, τ decreases marginally with equilibrium time from 850 s to 700 s. While for PB, τ decreases from 1600 s to 1050 s and for OIP, τ decreases from 480 s to 320 s. Serially connected branch of FDRC model changes from 1500 s to 1050 s. At high temperature, τ changes significantly for PB and OIP with equilibrium time. Redistribution takes some time in PB and OIP.

The fitted model from the experiments suggests that α and β decrease with equilibrium time. It means that R_s and C_s of PB decrease in the serially connected OIL and PB branch. τ of serially connected branch decreases from 1500 s to 1050 s indicating the sensitivity of this interface of OIL and PB. This is also reflected significantly in the measured OIP characteristics which change from 480 s to 320 s. The model clearly suggests that the measured response of OIP at 40 °C after equilibrium time is dictated by both OIL and serially connected OIL and PB interface relaxation behavior. At the starting of equilibrium time at 40 °C, the behavior of OIP is dictated by OIL relaxation behavior. As the temperature rises in OIP, the movement of water in the interfaces of OIL and PB may result in reduced τ in the serially connected OIL and PB. In turn, it reduces the τ of OIP at 40 °C.

The model suggests that the serially connected branch representing the dielectric interface is more sensitive to equilibrium, temperature and polar impurities and a refined research is to be carried out to identify this observation.

4.4 Discussion on relaxation studies in frequency domain

Measurement at the lowest frequency indicated the maximum change in parameters suggesting that the maximum polarization and dielectric loss phenomena connected with relaxation occurs at the lowest measured frequency. All the measured parameters were compared with reference to that measured lowest frequency.

Equilibrium time – Using FDS, the relaxation behavior of OIL, PB and OIP kept in sealed container were studied. Literatures [21] [22] report that the time to establish equilibrium for OIP structure is around 1600 h. Fig. 4-3 shows that equilibrium in OIL may be reached in 120 h at 22 °C. R_p , C_p , and ϵ' increase with longer period of measurement time. ϵ' increases with the measurement time indicating the increase in polarization or the existence of more water content in OIL as per Fig. 2-6 (a). ϵ'' representing the energy loss or $(1/(\text{frequency} \times R_p))$ decreases with increase in measurement time indicating the decreased conductance in OIL. As per Fig. 2-6 (b), this means less water content. Loss factor in OIL decreases with measurement time indicating the decrease of water content as per Fig. 2-7 (a). τ decreases with

measurement time indicating the disappearance of slow polarization elements. The above observations suggest that during equilibrium time, water content in some form across the electrodes may have decreased and the space may have reached equilibrium status with more fast polarizing time constant elements.

Fig. 4-5 shows the characteristics in PB. The equilibrium time is around 120 h. R_p and τ increase and C_p , ϵ' and ϵ'' decrease with the measurement time. Loss factor increases with the measurement time. The above observations suggest that water from PB may have distributed to sealed tank in reaching some equilibrium status.

Fig. 4-7 shows the characteristics in OIP. The equilibrium time is around 24 h. Similar observation is reported [58]. R_p increases and τ , C_p , ϵ' and ϵ'' at low frequency decrease with the measurement time. Loss factor decreases marginally with the measurement time. The above observations suggest that water content in OIP may have decreased as per Fig. 2.7(a).

Most of the reported relaxation measurements and theories are related to OIP. In this thesis, for the first time an attempt was made to compare relaxation process of the individual and composite dielectrics. Fig. 4-9 compares the individual dielectric performance with OIP after the equilibrium time. It suggests that OIP characteristics lie in between PB and OIL. With R_p , C_p , ϵ' and ϵ'' OIP characteristics follow closely PB. While with τ , OIP characteristics follow closely OIL. This suggests that the relaxation behavior in OIP is not a simple function of individual dielectrics as proposed in the literature shown in Section 2.1.7.

Temperature – After the equilibrium study, the effect of temperature of operation in the range of 20 °C to 40 °C was investigated. Rise in temperature of OIL reduces R_p and increases C_p , τ , ϵ' and ϵ'' in Figs. 4-11 and 4-12. Loss factor is the maximum at 40 °C. The increase in conductance and capacitance suggests that more polarizing and conducting materials like water in different forms move in between the electrodes. The rise in relaxation time constants with temperature indicates that there may be slow polarizing elements.

Rise in temperature of PB increases R_p and decreases C_p , τ , ϵ' and ϵ'' in Figs. 4-13 and 4-14. Loss factor is the minimum at 40 °C. This is different from the behavior in OIL. The decrease in conductance and capacitance suggests that more polarizing and conducting materials like water in different forms move out from PB kept in between

the electrodes. The decrease in relaxation time constants with temperature indicates that there may be only fast polarizing elements at high temperature.

Rise in temperature of OIP decreases R_p and τ , and increases C_p , ϵ' and ϵ'' in Figs. 4-15 and 4-16. This follows the behavior of OIL except for τ . Loss factor does not vary much with temperature while Fig. 2-7(b) reports that loss factor increases with temperature. The decrease in conductance and capacitance suggests that more polarizing and conducting materials like water in different forms move out from OIP kept in between the electrodes. The decrease in relaxation time constants with temperature indicates that there may be only fast polarizing elements at high temperature. At 22 °C, τ of OIP lies between that of OIL and PB. At 40 °C, OIP's τ is the lowest.

Oxidized impurities - The influence of oxidation products on dielectric responses was not reported in the literature. Effect of injected oxidized impurities in OIP and temperature of operation in the range of 20 °C to 30 °C was investigated. The characteristics before adding the impurity was slightly different from Figs. 4-7 and 4-15 due to new OIL sample. Polarizing impurity reduces R_p and τ , and increases C_p , ϵ' and ϵ'' in Figs. 4-17 and 4-18. Loss factor increases with impurity. The increase in conductance and capacitance suggests that more polarizing and conducting oxidized impurities like water in different forms move into OIP kept between the electrodes. The decrease in relaxation time constants with impurity indicates that there may be only fast polarizing elements. With rise in temperature, the change is more. In general, loss factor increases and relaxation time reduces with temperature and impurities.

FDRC Model - A new FDRC model shown in Fig. 4-20 based on FDS experimental results is proposed with a view to identify some model parameters with relaxation behavior. Variation of R_s is equated to exponential function of frequency while the variation of C_s is equated to power law function of frequency with "a", "b", "c" and "d" parameters defined by (4-5) and (4-6). Determining the parameters of EDM and geometrical models is not simple and may not give unique values.

Equilibrium time - Fig. 4-21 shows the variation of fitted "a", "b", "c" and "d" values during equilibrium process in OIL, PB and OIP. After equilibrium time, the change is the minimum. The parameter "a" is the maximum for PB and minimum for

OIL. The parameter “b” stands for the rate of decrease of $\log(C_s)$ with $\log(f)$. PB and OIP are found to have maximum similar changes compared to OIL after the equilibrium time. The parameter “c” stands for R_s at zero frequency. For OIL, it is the maximum and for PB, this is the minimum. After, 100 h of equilibrium time, a marginal variation is observed. The parameter “d” stands for the rate of logarithmic variation of R_s with linear frequency. For PB and OIP, the variation is not significant. For OIL, this is the maximum after equilibrium time.

Temperature - Fig. 4-22 shows the variation of fitted “a”, “b”, “c” and “d” values with temperature in OIL, PB and OIP. The parameter “a” is maximum for PB and minimum for OIL. Variation of “a” with temperature is more with OIP and then with OIL. Variation of “b” with temperature is more with OIP and then OIL. Variation of “c” with temperature is more with OIL and then with OIP. The variation of “d” with temperature is significant with OIP and then with OIL.

Oxidized impurities – Table 4-1 lists the computed “a”, “b”, “c” and “d” values with impurities and temperature. As new OIL was used, the fitted range was different. Significant changes in “a”, “b”, “c” and “d” were observed due to aging at 22 °C and these changes are significantly more with a, c and d.

Predicted OIP model in terms of OIL and PB models

This new FDRC model helps to predict parallel-series RC model for OIP shown in Fig. 4-24 in terms of pure OIL and PB models in the entire frequency range which was quite different from other models described in Sections 2.1.7 and 2.5.3. This linking model connecting individual dielectric to composite dielectric was able to explain the variation of relaxation property with temperature and equilibrium. It is possible to predict the role of individual dielectric in composite dielectric under various conditions.

Chapter 5

Relaxation Studies in Time Domain

This chapter presents the experimental results of OIL, PB and OIP relaxation behavior in time domain and their analysis. In time domain measurement, RVM polarization spectrum was measured with equilibrium time and temperature. The analysis in the form of extended Debye model (EDM) and Frequency Dependent RC model (FDRC) to identify the parameters of relaxation is presented.

5.1 Introduction

RVM method described in Section 2.4.2 is a good relaxation practical technique in time domain to monitor the condition of oil and paper insulation system of power apparatus, especially to evaluate the moisture content of the paper [12]. The water content in the paper is temperature dependent and takes a long time to stabilize [65]. Chemical methods to measure the water content in oil are used [63] [68]. The commercial RVM instrument reports that the remaining life of power apparatus can be evaluated from the computed polarization spectrum [12] [70]. In simple terms, the spectrum is sensitive to aged products especially to water content as per the literature [48]. Also, the spectrum is very sensitive to temperature. With that point of view, some fundamental studies were taken up to understand the RVM relaxation processes in time domain with OIL, PB and OIP. Chapter 4 identified by Dielectrometry measurements on each insulation material that the relaxation phenomenon stabilizes after equilibrium time and changes with temperature. Also, it was found that the frequency dependent relaxation processes of individual insulation have a definite relationship of their role in the composite insulation. To verify such observations in time domain, this study was undertaken. Reported RVM studies [40] [43] are done in fabricated or commercial oil-filled apparatus with composite insulation. Not many RVM studies have been published with single insulation and its relationship with the composite insulation. Therefore, the first part of this chapter reports the measured RVM results on OIL, PB and OIP with equilibrium time and temperature change and

the second part of this chapter reports the fitted analytical models and determined parameters to understand the various relaxation processes in time domain.

5.1.1 Procedures for relaxation program 2 – in time domain

The Program 2 measurements were RVM polarization spectrum measurement on OIL, PB and OIP.

(a) The moisture equilibrium experiments at 22 °C

As done in earlier chapter, the followed steps are listed.

Step 1: The relaxation behavior of PB was evaluated by keeping it in an air-tight sealed stainless steel tank without oil at the tank ambient air-conditioned laboratory temperature of 22 °C. RVM polarization spectrum measurement was done regularly once in 24 h until there was minimum fluctuation in the consecutive dielectric spectrums.

Step 2: Step 1 was repeated by replacing PB with OIL.

Step 3: Step 2 was repeated by keeping the tank with OIP immersed in OIL.

(b) Temperature dependent measurements at 30 and 40 °C

Step 4: The sealed stainless steel tank either with PB, OIL and OIP was kept into the environmental chamber. The temperature in the environmental chamber was set to 30 °C with humidity level of 60%. Measurements described in Steps 1 to 3 were repeated.

Step 5: Step 4 was repeated at 40 °C.

The typical setting of RVM measurement in this research program was:

Charging time $t_c(s)$: 1, 10, 100, and 500;

Discharging time $t_d(s) = t_c(s)/2$: 0.5, 5, 50, 250;

Sampling time $t_s(s)$: 0.2, 0.2, 0.2, and 0.5;

Measuring time $t_m(s)$: 40, 40, 40, and 100;

Neutral grounding time $t_n(s)$: 3600;

Charging voltage $U_0(V_{DC})$: 50;

5.2 Experimental results

The RVM polarization spectrum measurements were conducted with equilibrium time and by changing temperature on OIL, PB and OIP as carried out in frequency domain presented in Section 4.2.2. The equilibrium time for RVM polarization spectrum was defined as the time at which minimum variation in RVM was observed.

5.2.1 Moisture equilibrium studies using RVM technique

The samples were kept in sealed tank at 22 °C and periodic RVM polarization spectrum measurements were done to identify the changes with measurement time and to understand the equilibrium characteristics of three samples for any change in environment.

5.2.1.1 OIL

For all the charging times (t_c), single peak double exponential pulse responses were obtained in Fig. 5-1. It rose initially very fast and then decayed slowly. For small t_c , RVM peaks in the order of 1 V were obtained and for large t_c , RVM peaks lied in the range of 0.5 V. More changes were observed in the first 120 h and then it reached the equilibrium state with a limited band of variation. The variation was noticeable in the decay portion of the response indicating the dominant influence of slow polarization process in OIL. RVM peak responses were extracted with respect t_c and the plotted RV polarization spectrum in Fig. 5-2 showed the equilibrium trend clearly. The fast polarization process gave rise to peaks around 1 V. Initially the rate of decrease of maximum RV with t_c was high. With equilibrium time, the rate of decrease in the charging interval of 10 s decreased and then decreased very steeply up to 100 s. Polarization with time constants up to 100 s may have played greater role in equilibrium.

Fig. 5-1 Variation of RV with t_m , t_c and equilibrium time in OIL

Fig. 5-2 Variation of RVM polarization spectrum with t_c and equilibrium time in OIL

5.2.1.2 PB

The next series of RVM polarization spectrum measurements was done on PB. The shape of response pattern was the same as OIL. Compared to OIL, decreased peaks were observed in Fig. 5-3. For short t_c , the peak value was more than that for long t_c .

Peak value of RV changed from 0.4 V to 0.85 V. Extracted RVM polarization spectrums shown in Fig. 5-4 showed the trend of equilibrium after 144 h. The trend at equilibrium was different from Fig. 5-2. The rate of change of peak with t_c in Fig. 5-4 was more in t_c interval of 1 s to 10 s. Then it decreased. Different rates with t_c indicated the presence of different fast and slow polarization processes. With equilibrium time, the RVM polarization spectrum stabilized at higher recovery voltage levels in t_c range of 1 s to 10 s.

Fig. 5-3 Variation of RV with t_m , t_c and equilibrium time in PB

Fig. 5-4 Variation of RVM polarization spectrum with t_c and equilibrium time in PB

5.2.1.3 OIP

The next series of RVM polarization spectrum measurements was done on OIP. The response pattern in Fig. 5-5 showed that peak RV rose for the increase of t_c in the interval up to 10 s and then it decreased slowly for the increase in t_c . Compared to OIL and PB, increased peaks were observed in Fig. 5-5. Peak value of RV changed from 0.8 V to 2 V. Extracted RVM polarization spectrums shown in Fig. 5-6 showed the trend of equilibrium after 168 h. The trend was different from Figs. 5-2 and 5-4 at the beginning. After equilibrium, the rate of change of peak with t_c in Fig. 5-6 was smaller with OIP in the t_c range of 10 s and then it decreased at a fast rate. It indicated the presence of more slow polarization processes with time constants greater than 10 s.

Fig. 5-5 Variation of RV with t_m , t_c and equilibrium time in OIP

Fig. 5-6 Variation of RVM polarization spectrum with t_c and equilibrium time in OIP

Figs. 5-1 to 5-6 indicate that the measured responses stabilize after the equilibrium time of 144 h. The equilibrium time depends on the environmental internal conditions of sealed tank and the history of test samples. The experiment suggests that the polarizing impurities in OIL, PB and OIP distribute and stabilize to give RV responses with less scatter after equilibrium time.

Using (5-6) given in page 110, one can clearly estimate the range of τ_i . If one set t_c to about $3\tau_i$ and above in RVM, 60% of the respective charging voltage will be retained. Based on that principle, range of τ_i was estimated.

Effect of equilibrium time on OIL, PB and OIP

OIL – Variation of RV with t_m and equilibrium for the selected t_c s is shown in Fig. 5-1. It clearly indicated that it dominantly contained polarizing impurities with τ in the range of 0.3 to 3 s since maximum RV was obtained with t_c of 1 and 10 s. The dominant polarizing impurity causing peak variation during equilibrium may have τ of 3 s. The leakage resistance was very sensitive to equilibrium time and it caused the variation in the tail. Its discharge time constant may vary with t_c in the range of 160 s to 5000 s. Fig. 5-2 shows the variation RV peak with t_c . Rate of fall or rise was minimum in the t_c interval of 1 to 10 s. Spectrum indicated that the polarization was

caused mainly by the relaxation impurities with a time constant in the range of 0.3 s to 3 s. With equilibrium, the peak moved up indicating the formation of polarization materials with high time constants.

PB - Variation of RV with t_m and equilibrium time for the selected t_c s is shown in Fig. 5-3. It clearly indicated that it dominantly contained polarizing impurities with τ in the range of 0.3 s which gave a maximum RV with $t_c=1$ s. The dominant polarizing impurity causing peak variation during equilibrium may have τ of 0.3 s as the maximum peak variation with equilibrium time was observed at $t_c=1$ s. Here also the leakage resistance was very sensitive to equilibrium time and it caused the variation in the tail. Its time constant may vary with t_c in the range of 160 s to 5000 s. Fig. 5-4 shows the variation of RV peak with t_c . Rate of fall was minimum in the t_c interval of 1 to 10 s. Spectrum indicated that the polarization was caused mainly by the relaxation impurities with a time constant in the range of 0.3 s to 3 s. With equilibrium, the peak moved up indicating the formation of polarization materials with high time constants.

OIP - Variation of RV with t_m and equilibrium time for the selected t_c s is shown in Fig. 5-5. It clearly indicated that it dominantly contained polarizing impurities with τ in the range of 3 s as maximum RV was observed with t_c of 10 s. The leakage resistance was very sensitive to equilibrium time and it caused the variation in the tail. Its time constants may vary with t_c in the range of 80 s to 10000 s as a wide variation was observed at $t_c=1$ s and 100 s. Fig. 5-6 shows the variation of RV peak with t_c . Rate of fall or rise was minimum in the t_c interval of 1 to 100 s. Spectrum indicated that the polarization was caused mainly by the relaxation impurities with a time constant in the range of 0.3 s to 30 s. With equilibrium, the peak moved down. Rate of spectrum variation with t_c decreased indicating the formation of uniform polarization materials with time constants in the range from 0.3 s to 30 s.

5.2.2 Comparison of RVM responses after equilibrium time

Fig. 5-7 presents RV variation with t_m for OIP, PB and OIP together at equilibrium time and 22 °C. OIP and OIL were found to have peak responses with t_c of 10 s indicating the presence of dominant polarizing impurity with τ in the range of 3 s. For

PB, the peak RV occurred with t_c of 1 s. In all t_c s, peak voltage was more with OIP indicating the increased capacitance of polarizing impurity in OIP. It was minimum with PB. Fig. 5-8 shows the RV spectrum with t_c indicating the presence of dominant polarizing time constants up to 33 s in OIL, PB and OIP. Equilibrium time altered the distribution of different polarizing impurities so the peak RV varied. With equilibrium time, change in the RV peak with t_c reduced in t_c range of 1 to 100 s in OIL, PB and OIP insulation. It affected the leakage characteristics of complete insulation to alter the discharge rate in the tail region on selected t_c s.

Fig. 5-7 Comparison of RVM responses of OIL, PB and OIP with 50 V

Fig. 5-8 Variation of RVM polarization spectrum with t_c in OIL, PB and OIP after equilibrium time

5.2.3 Temperature dependence study

An experimental study was carried in the temperature range from 22 °C to 40 °C to evaluate the equilibrium status of OIL, PB and OIP. Since the equilibrium studies took about 10 days, the range of temperature measurement was restricted to understand the different mechanism of relaxation with increase in temperature.

5.2.3.1 OIL alone

Fig. 5-9 shows the variation of RV with t_c and t_m . As the temperature increased, RV decreased. The difference increased for increased t_c . The initial rise with t_m was seen at lower t_c . RVM polarization spectrum shown in Fig. 5-10 showed that the maximum peak of 1.75 V was obtained at 22 °C around t_c of 30 s. As the temperature was increased to 40 °C, the maximum peak reduced to 1.15 V occurring at 9 s.

Fig. 5-9 Variation of RVM responses of OIL with temperature

Fig. 5-10 Variation of RVM polarization spectrums in OIL with temperature

5.2.3.2 PB alone

Fig. 5-11 shows the variation of RV with t_c and t_m . As the temperature increased, RV increased in contrast with OIL response. The difference was almost the same for $t_c > 1s$. The initial rise with t_m was seen in all the responses. RVM polarization spectrum

shown in Fig. 5-11 showed that the maximum peak of 0.93 V was obtained at 30 °C around t_c of 10 s. From $t_c = 10$ s to $t_c = 100$ s, it decreased quickly. At 22 °C, the observed peak of 0.8 V occurred around t_c of 1 s.

Fig. 5-11 Variation of RVM responses of PB with temperature

Fig. 5-12 Variation of RVM polarization spectrums in PB with temperature

5.2.3.3 OIP in oil

The temperature dependence RVM studies on OIP were carried out from 22 °C to 40 °C. The samples were kept in sealed container to eliminate the influence of outside

laboratory condition. Fig. 5-13 showed the variation of RV with t_c and t_m . As the temperature increased, RV increased like PB response. But the increase was more at low t_c . The initial rise with t_m was seen in all the responses. RVM polarization spectrum shown in Fig. 5-14 showed that the maximum peak of 3.2 V was obtained at 40 °C around t_c of 10 s. From $t_c=10$ s to $t_c=100$ s, it decreased quickly. At 22 °C, the observed peak of 1.6 V occurred around t_c of 10 s.

Fig. 5-13 Variation of RV responses of OIP with temperature

Fig. 5-14 Variation of RVM polarization spectrums in OIP with temperature

To summarize the RVM experimental observations with temperature change, it can be seen that:

Effect of temperature on OIL, PB and OIP

OIL – Variation of RV with t_m and aging temperature for the selected t_c s was shown in Fig. 5-9. Maximum peak voltage was obtained at 22 °C with t_c of 100 s. By raising temperature, peak voltages at 30 °C and 40 °C occurred with t_c of 10 s. It clearly indicated that dominant polarizing impurities with τ in the range of 33 s at 22 °C got changed to 3 s by raising temperature up to 40 °C. The leakage resistance was very sensitive to temperature with t_c above 100 s. More variation was noticed at 22 °C. The discharge time constant can vary with t_c in the range of 300 s to 2000 s. Fig. 5-10 shows the variation RV peak with t_c . The peak voltage decreased with increase in temperature. The initial rate of rise was maximum at 22 °C indicating the presence of dominant polarizing impurities with τ in the range up to 33 s. This decreased with increase in temperature indicating the change in τ in the range of 3 s. The higher the temperature, the peak occurred with low t_c agreeing with others [56].

PB – Variation of RV with t_m and aging temperature for the selected t_c s is shown in Fig. 5-11. The maximum peak voltage was obtained at 30 °C with t_c of 10 s. At 22 °C the peak voltage occurred with t_c of 1 s. With increase in temperature, dominant polarizing impurities moved to high time constant. The leakage resistance was very sensitive to temperature and it caused the variation in the tail with t_c above 1 s. Its time constant will vary with t_c and may lie in the range of 200 s to 2000 s. Fig. 5-12 shows the variation of RV peak with t_c and temperature. Rate of fall or rise was minimum in the t_c interval of 1 to 10 s. Spectrum indicated that the polarization was caused mainly by the relaxation impurities with time constants in the range of 0.3 s to 30 s. The peak voltage increased with increase in temperature.

OIP – Variation of RV with t_m and aging temperature for the selected t_c s was shown in Fig. 5-13. The maximum peak voltage was obtained at 22 °C, 30 °C and 40 °C with t_c of 10 s indicating the presence of polarization time constant in the range of 3 s. The leakage resistance was very sensitive to temperature and it caused the variation in the tail. Its time constant may be in the range of 200 s to 20000 s. Fig. 5-14 shows the variation of RV peak with t_c and temperature. Rate of fall or rise was minimum in the t_c interval of 1 to 100 s. Spectrum indicated that the polarization was caused mainly

by the relaxation impurities with a time constant in the range of 0.3 s to 30 s. The peak voltage increased with increase in temperature.

Temperature affected the insulation's localized polarizing impurities so the peak RV varied. By increasing the temperature, in OIL the peak RV decreased and moved towards to low t_c ; while in PB and OIP the peak RV increased. It affected the leakage characteristics of complete insulation to alter the discharge rate in the tail region on selected t_c s.

5.3 Simulation studies in time domain

To explain the results of the measurements, two mathematical models are used. Extended Debye model (EDM) is extensively used to predict the relaxation behavior of oil-filled power apparatus. The developed FDRC model in Section 4.3 is also investigated with RVM data.

5.3.1 EDM

EDM shown in Fig. 2-15 with multi RC relaxation elements is used to explain the relaxation behavior of OIP in time domain using RVM measurements [1] [12] [61]. Here the model is used to explain the temperature dependence of RV measurement in OIL, PB and OIP.

Following the reference [12] [61], the recovery voltage $U_r(t_m)$ at recovery time t_m for any t_c can be predicted by (5-1) to (5-6). The discharging time t_d is kept as half of t_c .

$$U_r(t_m) = U_0 \hat{A}_1(t_m)(1 - e^{-\frac{t_c}{\tau_1}})e^{-\frac{t_c}{2\tau_1}} + \dots + U_0 \hat{A}_n(t_m)(1 - e^{-\frac{t_c}{\tau_n}})e^{-\frac{t_c}{2\tau_n}} \quad (5-1)$$

where

$$\hat{A}_i(t_m) = \sum_{j=1}^n A_{i,j} e^{t_m p_j} \quad (5-2)$$

$$A_{i,j} = \frac{k_i \prod_l (p_j - z_{i,l})}{p_j \prod_{k \neq j} (p_j - p_k)}$$

$$j, k = 1, \dots, n+1$$

$$i, l = 1, \dots, n$$

$$k_j = \frac{\tau_g}{\tau_g \tau_l} \quad (5-3)$$

$$\tau_g = R_g C_g, \tau_i = R_{pi} C_{pi}, \tau_{gi} = R_g C_{pi} \quad (5-4)$$

p_j is the pole of the denominator of the RV in Laplace form, $U_r(s)$.

$$U_r(s) = \frac{\sum_{i=1}^n [U_{ci} s \tau_{gi} \prod_{\substack{j=1 \\ j \neq i}}^n (s \tau_j + 1)]}{(s \tau_g + 1) \prod_{i=1}^n (s \tau_i + 1) + \sum_{i=1}^n [s \tau_{gi} \prod_{\substack{j=1 \\ j \neq i}}^n (s \tau_j + 1)]} \quad (5-5)$$

and U_{ci} in (5-5) is the residual voltage after t_d ,

$$U_{ci}(t_c) = U_0 (1 - e^{-\frac{t_c}{\tau_i}}) e^{-\frac{t_c}{2\tau_i}} \quad (5-6)$$

U_0 = the charging voltage

τ_g = the geometric time constant of the EDM

τ_i = the different polarization time constants of the EDM

τ_{gi} = the cross polarization time constants between the geometric resistance and polarization capacitances.

The difficulty in EDM is to identify the parameter value and fix the number of polarizing elements. In reference [12] the author used the dielectric dissipation factor test to get the geometric capacitance and a pole-zero modeling together with the spectrum are used to identify the polarization time constants. This method will be complicated when more polarization elements are needed.

5.3.1.1 Developed method to determine the parameters of EDM

(a) Determination of R_g and C_g

Since the tested sample is a laboratory model, the geometrical parameters C_g and R_g can be determined for EDM using high and low frequency measurements in FDS.

(b) Determination of R_{pi} and C_{pi}

In all the measured RV responses, a single peak is observed and this response behavior is used to determine the parameters of polarization elements by introducing the following constraints (5-7) in optimized fitting.

If the peak value of the a recovery voltage appears at t_p for a cycle of measurement,

$$\begin{cases} \frac{dU_r(t_m)}{dt} \big|_{t_p} = 0 \\ U_r(t_p) = U_{rp} \end{cases} \quad (5-7)$$

The numerical optimization method [6] is used to determine the unknown $2n$ elements. For this project, the guessing of the initial value of unknowns is important since the values of R_{pi} and C_{pi} differ in a wide range. A new method is developed to get meaningful results and for quick converging. This developed optimization method is carried out with time constants defined by (5-4).

After optimizing, R_{pi} and C_{pi} can be determined using (5-8).

$$\begin{cases} C_{pi} = \frac{\tau_{gi}}{R_g} \\ R_{pi} = \frac{\tau_i}{C_{pi}} \end{cases} \quad (5-8)$$

The used optimization method is Levenberg-Marquardt method [66]. Using digital sampling, N pairs of measured recover voltages with measuring time can be obtained as (t_1, u_1) , (t_2, u_2) , (t_N, u_N) . Taking $g(t_i, \tau_i)$ as the predicted value using (5-1) for a set t_i and τ_i as indicated by (5-9) and comparing with the measured value u_i , the difference is minimized by (5-10) to find τ_i .

$$g(t_i, \tau_i) = U_{ri}(t_i) \quad (5-9)$$

$$\min_{\tau} \sum_{i=1}^N \|u_i - g(t_i, \tau_i)\|^2 \quad (5-10)$$

Levenberg-Marquardt method is used for optimization.

The next requirement is in fixing the number of polarizing elements. The fitting will be good with more number of elements [12]. For more elements, mathematical processing time will be more. The reference [12] suggests that the suitable fitting can be made with more than 2 polarizing elements on power apparatus. In this project, 5 RC elements are found to make a fitting with an error less than 5%.

(c) Determination of the initial value of the R_{pi} , C_{pi} by FDS results

The initial values of R_{pi} and C_{pi} are estimated by FDS measured results. Using FDS, $R_p(f)$ and $C_p(f)$ are measured with frequency. They in general decrease monotonically with increase in frequency. The measured FDS lies in a frequency range from 0.01 Hz to 1 kHz indicating the polarization time constants may lie in 0.001 s to 100 s. At high

frequency, the contribution appears to be due to one fast polarization element. Since it is limited to 5 sets of polarization elements, the initial guess may be made from high frequency data to represent one element. The mathematical procedure can be followed from (5-13) to (5-15).

Fig. 5-15 Equivalent circuit of EDM in time and frequency domains

The equivalent of the admittance $Y_{eq}(f)$ of the EDM at a specified frequency ω is

$$Y_{eq}(f) = \frac{1}{R_g} + \sum_{i=1}^n \frac{\omega^2 R_{pi} C_{pi}^2}{1 + \omega^2 R_{pi}^2 C_{pi}^2} + j\omega C_g + \sum_{i=1}^n \frac{C_{pi}}{1 + \omega^2 R_{pi}^2 C_{pi}^2} \quad (5-11)$$

The equivalent parallel resistance $R_p(f)$ and capacitance $C_p(f)$ are

$$\frac{1}{R_p(f)} = \frac{1}{R_g} + \sum_{i=1}^n \frac{\omega^2 R_{pi} C_{pi}^2}{1 + \omega^2 R_{pi}^2 C_{pi}^2} \quad (5-12)$$

$$C_p(f) = C_g + \sum_{i=1}^n \frac{C_{pi}}{1 + \omega^2 R_{pi}^2 C_{pi}^2} \quad (5-13)$$

R_{p1} and C_{p1} can be determined by taking the FDS data at $f = 1$ kHz and taking $n=1$ in (5-12) and (5-13). By taking another set of FDS data at a frequency less than 1 kHz, the R_{p2} and C_{p2} can be estimated by taking $n=2$ in (5-12) and (5-13). By taking the FDS data up to 0.01 Hz, the five RC polarizing elements can be estimated approximately.

FDS can be measured from 0.0001 Hz to 1 kHz. The equivalent time constant of the polarization elements of EDM can range from 0.001 s to 10000 s for that set of measurements. Using the above technique, initial determination of R_{pi} and C_{pi} can be made.

A Matlab program is developed to determine the parameters using (5-8) to (5-10) using the measured RV data and the above initial values. The typical fitting in OIP at

temperature 22 °C is shown in Fig. 5-16 and the maximum computed summed error is less than 5%.

Fig. 5-16 Measured and fitted RV of OIP at 22 °C

5.3.2 Determined EDM parameters for OIL, PB and OIP

Using the developed algorithm, a satisfactory fitting was made with 5 polarization elements for OIL, PB and OIP under different temperatures from 22 °C to 40 °C. The experimental results are shown in Fig. 5-9 for OIL, Fig. 5-11 for PB and Fig. 5-13 for OIP.

5.3.2.1 Temperature dependent variation of EDM parameters in OIL

Three measured RV responses with temperature were fitted to EDM and the variation of the fitted parameters for Fig. 5-9 data on OIL is shown in Fig. 5-17.

Fig. 5-17 (a) Variation of OIL parameters with temperature - resistances

Fig. 5-17 (b) Variation of OIL parameters with temperature - capacitances

Fitted R_g of OIL decreased with temperature from 210 MΩ to 170 MΩ and geometrical capacitance C_g increased with temperature from 0.1 μF to 0.6 μF. For the polarization elements, fitted R_p varied from 1000 MΩ to 5000 MΩ. Three resistive elements decreased with increase in temperature and one remained constant. One of

the elements was found to increase with temperature rise. While the fitted value of C_p varied from 0.02 μF to 15 μF . The dominant C_{p5} was found to decrease with increase in temperature as FDS measurement shown in Fig. 4-11 and the next dominant C_{p1} was found to increase with increase in temperature. No simple relation can be found about the variation of parameters of OIL with temperature.

5.3.2.2 Temperature dependent variation of EDM parameters in PB

The variation of the fitted parameters for Fig. 5-11 data on PB is shown in Fig. 5-18. Fitted R_g of PB increased with temperature from 20 $\text{M}\Omega$ to 30 $\text{M}\Omega$ and geometrical capacitance C_g decreased with temperature from 0.35 nF to 0.345 nF. For the polarization elements, fitted R_p varied from 76 $\text{M}\Omega$ to 2000 $\text{M}\Omega$. All the resistive elements increased with increase in temperature as FDS measurement shown in Fig. 4-13. While the fitted value of C_p varied from 0.01 μF to 10000 μF . C_p decreased with increase in temperature as FDS measurement.

Fig. 5-18 (a) Variation of PB parameters with temperature - resistances

Fig. 5-18 (b) Variation of PB parameters with temperature - capacitances

5.3.2.3 Temperature dependent variation of EDM parameters in OIP

The variation of the fitted parameters for Fig. 5-13 data on OIP is shown in Fig. 5-19. Fitted R_g of OIP decreased with temperature from 55 $\text{M}\Omega$ to 22 $\text{M}\Omega$ and geometrical capacitance C_g increased with temperature from 5 μF to 19 μF . For the polarization elements, fitted R_p varied from 6 $\text{M}\Omega$ to 400 $\text{M}\Omega$. All the resistive elements decreased with increase in temperature as FDS measurement shown in Fig. 4-15. While the fitted value of C_p varied from 0.1 μF to 5 μF . C_p in general increased with increase in temperature as FDS measurement.

Fig. 5-19 (a) Variation of OIP parameters with temperature - resistances

Fig. 5-19 (b) Variation of OIP parameters with temperature - capacitances

5.3.3 Comparison of time constants of OIL, PB and OIP using EDM

Using (5-4), the various time constants can be determined for OIL, PB and OIP. The variation of these time constants with temperature is shown in Fig. 5-20. For OIL, τ_g

varied from 40 s to 100 s and increased with increase in temperature. τ_1 varied from 1.9 s to 2.5 s and it decreased with increase in temperature. τ_2 varied from 5 s to 13 s and it also decreased with increase in temperature. τ_3 varied from 40 s to 75 s and it also decreased with increase in temperature. τ_4 varied from 310 s to 350 s while τ_5 varied from 5000 s to 20000 s. For PB, τ_g varied from 0.006 s to 0.01 s and increased with increase in temperature. τ_1 varied from 70 s to 75 s and it decreased with increase in temperature. τ_2 varied from 19 s to 23 s and it also decreased with increase in temperature. τ_3 varied from 800 s to 1900 s and it also decreased with increase in temperature. τ_4 varied from 38000 s to 60000 s and it increased with increase in temperature. τ_5 also varied from 25000 s to 30000 s and that also increased with increase in temperature. For OIP, τ_g varied from 300 s to 450 s and increased with increase in temperature. τ_1 varied from 0.5 s to 2.5 s. τ_2 varied from 15 s to 40 s. τ_3 varied from 340 s to 400 s. τ_4 varied from 180000 s to 210000 s. τ_5 also varied from 190000 s to 230000 s. They increased up to 30 °C and then it decreased in the range from 30 °C to 40 °C.

τ_g for OIP was maximum indicating that the geometrical capacitance at high frequency and leakage resistance at low frequency were maximum. Also the analysis indicated that the time constant of the polarization elements also varied from 0.5 s to 230,000 s. Our measurement was done with the maximum time interval of only 1000 s. Hence, the fitting of polarization elements with higher time constants may not have played much role. Taking the first three polarization elements, it appeared that OIL time constants were the lowest and OIP time constants were the highest. PB time constants lied in between the above characteristics. It was contracting with FDS measurements shown in Fig. 4-9. This had to be studied more carefully taking into the effect of geometrical parameters of EDM.

Fig. 5-20 Variation of τ in OIL, PB and OIP with temperature

5.4 Predicted behavior of EDM results in frequency domain

Since extensive study is done using FDS, an attempt is made to compare and use RV results to predict the relaxation behavior in frequency domain. The reason is that the relaxation measurements in field can be carried out easily with RVM. It needs an extensive analysis to relate with the polarization parameters. The used indicators like RV spectrum, initial slope and central time constant are not related with the polarization behavior of insulating materials. But the complex natures of polarization time constants are identified by FDS experiments. To bridge this, mathematical procedures are developed. In this, the bridging link is EDM network. Due to much experimental variation on samples, a good match is not made. Since the matching can be analyzed in terms of resistive and capacitive components, the following sections present the experimentally measured FDS data reported in Chapter 4 and the predicted values using EDM predicted network using RVM.

5.4.1 Variation of C_p and R_p in OIL

For the measured frequency range, equivalent C_p and R_p of EDM at a frequency was determined and the calculated results are plotted in Fig. 5-21. For comparison Fig. 4-11 data of FDS is also presented. In both time domain and frequency domain measurements, R_p decreased with increase in frequency and temperature. C_p increased with increase in temperature and decreased with increase in frequency. The percentage change of R_p at 10 mHz with temperature change from 22 °C to 30 °C in FDS and EDM were -39% and -14% respectively. While the corresponding percentage change in C_p with FDS and EDM were 80% and 150%. The tendency was same but the order of predicted values was different.

Fig. 5-21 Variation of R_p and C_p in OIL with temperature and frequency

5.4.2 Variation of C_p and R_p in PB

Similar prediction and comparison is made with PB and the results are presented in Fig. 5-22. For comparison Fig. 4-13 data of FDS is also presented. In both time domain and frequency domain measurements, R_p decreased with increase in frequency and decrease in temperature. While C_p increased marginally with increase in temperature and decreased with increase in frequency. The percentage change of R_p

at 10 mHz with temperature change from 22 °C to 30 °C in FDS and EDM were 56% and 51% respectively. While the corresponding percentage change in C_p with FDS and EDM were -14% and -10%. The tendency was same but the order of predicted values was different.

Fig. 5-22 Variation of R_p and C_p in PB with temperature and frequency

5.4.3 Variation of C_p and R_p in OIP

Similar prediction and comparison is made with OIP and the results are presented in Fig. 5-23. For comparison Fig. 4-15 data of FDS is also presented. In both time domain and frequency domain measurements, R_p decreased with increase in frequency and temperature. While C_p increased with increase in temperature and decreased with increase in frequency. The percentage change of R_p at 10 mHz with temperature change from 22 °C to 30 °C in FDS and EDM were -54% and -44% respectively. While the corresponding percentage change in C_p with FDS and EDM were 150% and 78%. The tendency was same but the order of predicted values was different.

Fig. 5-23 Variation of R_p and C_p in OIP with temperature and frequency

5.4.4 Discussion on EDM model

An attempt was made to fit the results to FDRC model. A satisfactory fitting can be made indicating that the model still can be used for any measurements. The evaluated factors “a”, “b”, “c” and “d” differed considerably for OIL, PB and OIP. The slope parameters “b” and “d” followed the trend of Fig. 4-21 with OIP characteristics lying in between PB and OIL characteristics. But the y-axis intercept parameters “a” and “c” variation differed with EDM results.

The reasons for the variation in R_p and C_p in Figs. 5-20 to 5-22 can be many and it had to be explored. Possible reasons are : (1) tank effect cannot be eliminated in RVM, (2) usage of different brand of transformer oil in RVM, (3) measurement accuracy/errors in RVM in short and long duration due to limited sampling and (4) fitting errors in parameter calculation.

To summarize, time domain measurement RVM is also sensitive to equilibrium time and temperature variation in OIL, PB and OIP. It was found that even 5 mm thick sample with 50 mm x 100 mm electrodes kept in 4 L sized sealed tank took about 120

h to give results with a limited band of variation. It may be due to the movement of moisture remaining in different status within the sample and tank.

Fig. 5-10 shows the effect of temperature in OIL. With rise in temperature, maximum RV magnitude decreased and its occurrence moved to lower charging time in RV spectrum. The shape of RV spectrum was like a bell. Fig. 5-12 shows the effect of temperature in PB. With rise in temperature, maximum RV magnitude increased and the voltage fall with increase in charging time. Fig. 5-14 shows the effect of temperature in OIP. With rise in temperature, maximum RV magnitude increased and it occurred at the same charging time. The shape of RV spectrum was like an inverted triangle.

To fit the RVM results with EDM, a new fitting method was proposed with time constants defined by (5-4). Five RC elements were found to fit all the responses. Using the fitted parameters, frequency dependent relaxation responses can be predicted. By comparing with FDS measurements and FDRC model, the predicted parameters followed the same trend. But the magnitude differed due to sample variation. EDM studies suggested that the polarization time constants ranged from 0.006 s to 230,000 s. While in Chapter 4, the time constants ($R_s \times C_s$) range was from 5 s to 1500 s. Analyzing the results, it is thought that this may be due to error in mathematical fitting which cannot converge, and the data that does not take the role of geometrical parameters used in EDM. This has to be explored further.

5.5 Discussion on relaxation studies in time domain

Measurement in time domain was an industrial way of evaluating the relaxation behavior. The relaxation was measured in terms of relaxed charge built up at the open-circuited terminals of power apparatus. The leakage impedance and capacitance at the terminals play a greater role. Hence, this measurement was very sensitive to ambient conditions but the required instrumentation was not that sophisticated as FDS. RVM was also sensitive to equilibrium time and temperature variation in OIL, PB and OIP.

Equilibrium time – The movement of moisture remaining in different status within the sample and sealed tank affects RVM also. Fig. 5-1 shows the variation of RV in

OIL with the period of measurement up to 240 h. The slope of the tail remained the same but the initial front slope and its peak magnitude varied with equilibrium time of measurement. The RVM spectrum in Fig. 5-2 showing maximum RV at each t_c can identify the distribution of the responses. In about 120 h, it reached the equilibrium range with limited scatter in responses beyond that time. Maximum RVM was obtained in the first $t_c=1$ to 10 s. The shifting of peak from $t_c=1$ to 10 s suggested that lesser water content from the starting time to equilibrium time with reference to Fig. 2-10. The polarizing time constants may be in the range of 10 s.

Fig. 5-3 shows the variation RV in PB with the period of measurement up to 240 h. The slope of the tail remained the same but the initial front slope and its peak magnitude varied with equilibrium time of measurement. The RVM spectrum in Fig. 5-4 showing the equilibrium time may be in the range of 120 h. Maximum RVM was obtained in the first $t_c=1$ s to 10 s. The above observations suggested that water from PB may have distributed to sealed tank in reaching some equilibrium status. The shifting of peak from $t_c=1$ s to 10 s suggested that lesser water content from the starting time to equilibrium time with reference to Fig. 2-10. The polarizing time constants may be in the range of 10 s.

Figs. 5-5 and 5-6 show the characteristics in OIP. The equilibrium time was around 144 h. Maximum RV was obtained with OIP. The response spectrum was different from OIL and PB. It rose from 1 to 10 s and then fell steeply up to 100 s. After 100s, it fell slowly. It suggested that the polarizing impurities in OIP may have time constants in the range from 1 to 100 s. The reduction of peak from the starting time to equilibrium time suggested that water content in OIP may have decreased.

Fig. 5-8 compared the individual RV spectrum with OIP after the equilibrium time. It was suggested that the OIP characteristics may be a sum of factorized PB and OIL characteristics. This method of relaxation measurement was based on stored charge and FDS may be the rate of relaxation change which has to be explored more.

Temperature - Effect of temperature of operation in OIL in the range of 22 °C to 40 °C is investigated. Rise in temperature of OIL reduced maximum RV and moved the occurrence to low t_c in Fig. 5-10. It followed Fig. 2-9 and a reduction in peak magnitude with increase in temperature was noticed in these studies. The reduction

was significant above $t_c > 10$ s. Increased conductance at high temperature may have reduced the peak response.

Rise in temperature of PB increased the maximum RV and moved the occurrence to high t_c in Fig. 5-12 in contrast to Fig. 2-9. Lesser capacitance and reduced conductance at high temperature may have increased the maximum RV.

Rise in temperature of OIP increased the maximum RV and moved the occurrence to high t_c in Fig. 5-14 in contrast to Fig. 2-9. Lesser capacitance and increased conductance at high temperature may have increased the maximum RV significantly.

Relaxation measurement in terms of recovered voltage appeared to be good technique but the terminal parallel capacitance and resistance may control the response in the long period of measurement.

EDM – The parameters of the EDM were determined by fitting the experimentally measured individual responses by trial and error by references [12] [61]. There is no unique way to determine the parameters of EDM which can fit the experimental results. Since the selected R and C values can vary widely, a new optimization method using time constants defined by (5-4) was developed to fit the measured results within 5% error. EDM model studies in OIP suggested that the polarization time constants ranged from 0.5 s to 230,000 s. While in Fig. 4-15, the time constants ($R_s \times C_s$) range was only from 20 s to 730 s. Analyzing the results, it was thought that this may be error due to mathematical fitting which cannot converge to that range. The fitting method was to be improved more by inserting some constraints. A simple attempt was made to fit the results of EDM parameters to FDRC model. A satisfactory fitting can be made indicating that the FDRC model still can be used for any RV measurements.

Chapter 6

Relaxation Studies on Thermally Aged SPT

Any insulation can be aged faster by a combination of electrical, thermal, chemical and mechanical stresses [10]. It is identified in Section 2.3.1 that the principal factor influencing aging and life expectancy of oil and paper insulation is thermal stress. Not many reported research is available about the relaxation studies before, during and after aging. This chapter reports about the FDS and RVM results which were obtained on a single-phase oil-filled transformer (SPT) before, during and after accelerated thermal aging (ATA) in laboratory, and the associated analysis.

6.1 Introduction

Relaxation behavior of oil filled insulation depends on water and other polar impurities present in the composite insulation. By aging, the quantity of these impurities can be increased [10] [29]. The quantitative measurement of the impurities by different techniques requires extensive calibration procedures and various test facilities. Hence, a simple research was undertaken to study the relaxation behavior of oil-filled insulation by periodic FDS and RVM during and after ATA in comparison with the behavior before aging. The aged byproducts have been described in Section 2.3.2. Their effects on relaxation are studied by frequency and time domain measurements in oil-filled SPT.

The objectives of this study are: (1) to study the relaxation responses during the thermally aged process of the oil and paper insulation of SPT by relaxation measurements, (2) to get some relaxation parameters of the EDM model relating aging and temperature of operation so that the changing of the SPT relaxation condition can be evaluated.

6.1.1 Procedures for relaxation program 3 – thermally aged SPT

The program 3 studied the temperature dependence, ATA effects and equilibrium status of SPT relaxation characteristics. Fig. 6-1 shows the profile of temperature set

for aging single-phase transformer (SPT) in open environment with the corresponding time duration. The experiment was conducted for a continuous period of 2500 hours. SPT was aged for 1100 hours at 100°C. Before and after aging, FDS and RVM measurements were also carried out at temperatures of 22 °C, 30 °C, 40°C, and 50°C to understand the role of temperature.

(a) Temperature dependent measurements from 22 °C to 50 °C before ATA

The following experimental steps were followed.

Step 1: The SPT was put into a metal tank without top lid and the tank was filled with fresh transformer oil. It was left for about one month to get impregnated. Then the complete arrangement was kept in the environmental chamber and necessary ambient temperature was set. Using the insulated terminal leads, FDS and RVM measurements were conducted regularly once in 24 h until there was little change in the consecutive dielectric spectrums. The studied temperature settings were 22 °C (room temperature), 30 °C, 40 °C and 50 °C. For each temperature setting, the relaxation responses were recorded continuously for 10 days.

Fig. 6-1 Temperature profile on SPT during the test period

(b) RVM studies during ATA

Step 2: The SPT in the oil-filled metal tank without lid was aged at 100 °C for 1100 h. The ambient oxygen and water vapor interacted with oil and SPT insulation. Small amounts of copper, steel and aluminum were added as catalysts to accelerate the aging process. The water content in oil was measured before and after aging tests. FDS measurement was not done during aging as the measured current was beyond the

range of the instrument. But RVM was done periodically in an interval of 72 h to understand the relaxation processes at high temperature of 100 °C and during aging.

(c) Temperature dependent measurements from 50 °C to 22 °C after ATA

Step 3: After 1100 h, the environmental chamber temperature was reduced to 50 °C. FDS and RVM measurements were done regularly once in 24 h until there was little change in the consecutive dielectric spectrums. The studied temperature settings were 50 °C, 40 °C, 30 °C and 22 °C. For each temperature setting, the measured period was 10 days.

The setup of a RVM measurement cycle in Program 3 with SPT was changed as follows:

Charging time $t_c(s)$: 1, 3, 6, 9, 20, 40, 80, 200, 400, and 1000;

Discharging time $t_d(s)=t_c(s)/2$: 0.5, 1.5, 3, 4.5, 10, 20, 40, 100, and 500;

Sampling time $t_s(s)$: 0.2, 0.2, 0.2, 0.2, 0.2, 0.5, 0.5, 1.0, 1.0, and 2.0;

Measuring time $t_m(s)$: 200, 200, 200, 200, 200, 500, 500, 1000, 1000, and 2000;

Neutral grounding time $t_n(s)$: 3600;

Charging voltage $U_0(V_{DC})$: 100;

6.2 Relaxation measurement results of SPT

SPT was tested for temperature dependent FDS and RVM studies before and after aging to evaluate the change in relaxation behavior due to operating temperature and aging. FDS measurement was not carried out during aging at high temperature as the measuring current exceeded the limit. The temperature dependence measurement period for each temperature setting was about ten days because of the reason to get the equilibrium state for the SPT.

6.2.1 FDS results

The reported FDS results in Figs. 6-2 and 6-3 are taken after equilibrium time. Hence the effect of equilibrium change was minimized. It presents the relaxation parameter variation with frequency, temperature change from 22 °C to 50 °C, before and after

aging of SPT for 1100 h at 100 °C. Following Section 4.2.3, variation of R_p , C_p , τ , ϵ' and ϵ'' with frequency are presented.

R_p , C_p , τ , ϵ' and ϵ'' decreased with increase in frequency before and after aging. It decreased exponentially with increase in frequency. After aging, R_p decreased and C_p increased. ϵ' and ϵ'' increased with rise in temperature and after aging. The loss factor increased after aging.

6.2.1.1 Before ATA

At 22 °C, by changing frequency from 10 mHz to 1 Hz, the change in R_p and C_p were -85% and -57% respectively with reference at 10 mHz. At 50 °C, the corresponding values were -90% and -55% respectively. The corresponding change in ϵ' and ϵ'' due to frequency were -57% and -21% respectively with reference at 10 mHz. At 50 °C, the corresponding values were -33% and -84% respectively.

The change in R_p and C_p with respect to frequency was same irrespective of temperature rise. But ϵ' and ϵ'' changed significantly with frequency for a rise in temperature.

The change in R_p at 10 mHz and 22 °C to R_p at 10 mHz and 50 °C was -13% with reference to 22 °C. The change in C_p at 10 mHz and 22 °C to C_p at 10 mHz and 50 °C was -57% with reference to 22 °C. The corresponding change in ϵ' and ϵ'' at 10 mHz due to temperature were 200% and 400% respectively.

The water content in the oil was measured as 20 ppm by Karl Fischer titration before ATA.

6.2.1.2 After ATA

At 22 °C, by changing frequency from 10 mHz to 1 Hz, the change in R_p and C_p were -78% and -85% respectively with reference at 10 mHz. At 50 °C, the corresponding values were -60% and -66% respectively. The corresponding change in ϵ' and ϵ'' due to frequency were -12% and -80% respectively with reference at 10 mHz. At 50 °C, the corresponding values were -77% and -93% respectively.

Rate of change in R_p and C_p with respect to frequency changed after aging. Also, ϵ' and ϵ'' changed significantly with frequency for a rise in temperature.

The change in R_p at 10 mHz and 22 °C to R_p at 10 mHz and 50 °C was -77 % with reference to 22 °C. The change in C_p at 10 mHz and 22 °C to C_p at 10 mHz and 50 °C was -15% with reference to 22 °C. The corresponding change in ϵ' and ϵ'' at 10 mHz due to temperature were 150% and 100% respectively.

The water content in the oil was measured as 54 ppm by Karl Fischer titration after ATA. No other chemical analysis was done.

6.2.1.3 Effects of ATA

Dominant changes were observed at low frequency range of 10 mHz and the results were compared at that frequency due to aging. The change in R_p after and before ATA at 10 mHz and 22 °C was -73%. At 50 °C, the change increased to -91%. Similar calculation on C_p after and before ATA at 10 mHz and 22 °C was 328%. At 50 °C, the change reduced to 173%. With ϵ' , the change at 22 °C and 50 °C were 80% and 131% respectively. With ϵ'' , the change at 22 °C and 50 °C were 150 % and 75% respectively. All the parameters changed with aging. Change in C_p and ϵ'' at 22 °C was maximum and at 50 °C, change in C_p and ϵ' was maximum. τ at 22 °C did not change much but at 50 °C, τ reduced after aging to 13 s from 72 s.

Fig. 6-2 Variation of R_p , C_p and τ with frequency and aging of SPT

Fig. 6-3 Variation of ϵ' and ϵ'' with frequency and aging of SPT

6.2.1.4 The explanation of the results

The temperature effects of FDS on OIP have been explained in Chapter 4, its effects on SPT before and after aging are similar. After ATA, the oil was dark and thick with floating oxidized materials. The water content was less than 20 ppm before ATA, after ATA it was more than 50 ppm. Therefore, only the aging on FDS is explained. From the response in frequency domain, it can be explained that the aging of oil and paper produced more water content and impurities, the conductivity of the oil increased and the R_p of the oil and paper composite insulation decreased. At the same time, C_p increased because of increase in water content of oil. The ϵ' was similar as C_p and it increased after aging. ϵ'' was proportional to conductivity and loss factor, and it increased with decrease in R_p .

6.2.2 RVM results

The reported RVM results in Figs. 6-4 and 6-5 are taken after equilibrium time. Hence the effect of equilibrium was minimized. It presents the measured RV variation with t_e .

and change in operating temperature in 3 tested conditions. They were tested before aging at 22 °C and 50 °C, during aging at 100 °C and after aging at 22 °C and 50 °C. In all t_c settings, single peak response was obtained.

6.2.2.1 Before ATA

Fig. 6-4 shows the variation RV with t_m and t_c . For 100 V_{DC} charging, a maximum of about 10 V was obtained at 22 °C for $t_c > 9$ s. The increase in rise was due to different sample and the DC voltage level used for charging. At 50 °C, the maximum voltage increased to 12 V at $t_c = 40$ s. The effect of temperature change from 22 °C to 50 °C varied the responses shown in Fig. 6-4. Up to $t_c < 200$ s, the recovered voltage at 50 °C was more than the value at 22 °C. It showed that the fast polarization process with time constants up to 100 s was active at 50 °C. The slow polarization process with time constants > 100 s dominated 22 °C response in comparison with 50 °C response. The RVM polarization spectrum was extracted and plotted in LHS of Fig. 6-5 at 22 °C and 50 °C. It was found to have a more flat characteristic with a maximum value around 10 V before aging. The maximum peak response of 12.7 V was obtained at 50 °C with $t_c = 40$ s. It suggested the existence of more polarizing impurities at high temperature resulting maximum relaxed peak voltage. The occurrence of this maximum at $t_c = 40$ s suggested the dominance of fast polarization process with time constant of 40 s at 50 °C. At 20 °C, it was controlled by slow polarization elements making the response almost flat insensitive to t_c .

A plot showing the time of peak RV occurrence with respect to t_c is drawn in RHS of Fig. 6-5. It clearly indicated that at 50 °C, the peak occurred quickly and it may be due to higher conductance for polar impurities.

Hence, initial slope in RV response at low t_c setting may indicate the conduction mechanism. Fast polarizing carriers responded in such a short duration. As the charging time was increased, slow polarizing carriers were also activated to increase the polarization capacitance. At high t_c , a reduced peak magnitude with a slow rise and decay response may be due to increased capacitive polarization at 50 °C.

Maximum RV was observed around t_c of 10 s to 80 s indicating the dominant polarization time constant range.

Fig. 6-4 Variation of RV with t_m , t_c and temperature in SPT before aging

Fig. 6-5 (a) Variation of RVM polarization spectrum and temperature in SPT
(b) Variation of time of maximum RV with t_c and temperature in SPT before aging - 100 V

6.2.2.2 During ATA

Periodic RV measurement at the aging temperature was done during the aging period. Fig. 6-6 shows the variation of RV with t_m and t_c at 100 °C of aging around 96 h and

1050 h of aging. With aging time, RV increased at all charging times. The peak RV with 100 V_{DC} charging increased rapidly in the initial aging period to 15 V at 96 h of aging and it stabilized around 19 V after 1050 h of aging at $t_c=10$ s as shown in Fig. 6-7(a). The RV was more after long hours of aging indicating the creation of more polarizing impurities and easy mobility of polarizing impurities at 100 °C. There was not much change due to aging time with fast responding polarizing impurities at $t_c=1$ s in Fig. 6-6. The reason may be that the maximum charge was contributed by the polarizing impurities with $\tau > 6$ s. The initial slope in Fig. 6-6 also increased considerably with aging time.

Fig. 6-6 Variation of RV with t_m , t_c and temperature in SPT during aging

LHS of Fig. 6-7 showed the RVM polarization spectrum due to aging at 100 °C. A single increasing peak response with aging time was observed. The initial slope increased and the rate of change in the falling portion decreased with aging time. The peak shifted to higher t_c . RHS of Fig. 6-7 showed the plot of time at RV peak occurred with reference t_c . The peak occurrence time for each t_c increased with aging time. This indicated that the relaxation period may be more after aging due to increased number of polarization charges and increased relaxation time constant.

Fig. 6-7 (a) RVM polarization spectrum and aging time in SPT
(b) Variation of time of maximum RV with t_c and aging time in SPT

6.2.2.3 After ATA

Fig. 6-8 shows the variation RV after aging period of 1100 h with t_m and t_c . For 100 V_{DC} charging, a maximum of about 13 V was obtained at 22 °C. At 50 °C, the maximum voltage increased to 20 V at $t_c=40$ s. The effect of temperature change from 22 °C to 50 °C varied the responses shown in Fig. 6-8. for all t_c , RV at 50 °C was more than the value at 22 °C. It seemed that both the fast and slow polarization processes were active at 50 °C. The polarization process from $t_c=200$ s to 400 s resulted in the same type of rise in RV.

The RVM polarization spectrum was extracted and plotted in Fig. 6-9 at 22 °C and 50 °C. The RV spectrum peak increased to 12 V at 22 °C and 20 V at 50 °C. The t_c for maximum RV shifted to 100 s at 22 °C and to 40 s at 50 °C. It suggested the existence of more polarizing impurities after aging and it resulted in maximum relaxed peak RV. The occurrence of this maximum at $t_c=40$ s suggested the dominance of fast polarization process with τ of 40 s at 50 °C. It seemed that at 20 °C, it was controlled by slow polarization elements with $\tau>100$ s.

A plot showing the time of peak RV occurrence with respect to t_c is drawn in RHS of Fig. 6-9. It clearly indicated that at 50 °C, the peak occurred slowly after aging and it may be due to more number of polar impurities.

The shifting of maximum RV spectrum for increased temperature to lower t_c was observed in Figs. 6-4 and 6-8 before and after aging. Similar observation was observed by others [6]. The only difference was that the maximum RV increased when it moved to lower t_c .

Fig. 6-8 Variation of RV with t_m , t_c and temperature in SPT after aging

Fig. 6-9 (a) RVM polarization spectrum and aging time in SPT
(b) Variation of time of maximum RV with t_c and aging time in SPT

An analysis of the variation of parameters due to aging is presented in Table 6-1. The second column shows the variation of parameters with frequency before aging at 22 °C and 50 °C. The third column shows the same after aging at two temperatures. The

fourth column shows the ratio due to aging while the fifth column shows the ratio due to temperature of operation.

Table 6-1: Variation of dielectric parameters due to aging of SPT

	Frequency range 0.01 Hz to 1 Hz Before Aging		Frequency range 0.01 Hz to 1 Hz After Aging		Ratios at 0.01Hz After/Before aging		Ratios at 0.01Hz 22 °C/50 °C	
	22 °C	50 °C	22 °C	50 °C	22 °C	50 °C	Before	After
R_p	-85%	-90%	-78%	-60%	-73%	-91%	-13%	-77%
C_p	-57%	-55%	-85%	-66%	328%	173%	-57%	-15%
τ	-99%	-99%	-99%	-100%	-98%	-99%	-82%	-45%
ϵ'	-57%	-33%	-12%	77%	80%	131%	200%	150%
ϵ''	-21%	-84%	-80%	93%	150%	75%	400%	100%

Before aging (2nd Column) – At 22 °C, R_p , C_p and ϵ' decreased significantly with increase in frequency while at 50 °C, R_p , C_p and ϵ'' decreased significantly with increase in frequency. At 22 °C, the dielectric loss was minimum while at 50 °C, the relative permittivity decreased.

After aging (3rd Column) – At 22 °C, R_p , C_p and ϵ'' decreased significantly with increase in frequency while at 50 °C, R_p , C_p , ϵ' and ϵ'' decreased significantly with increase in frequency. At 22 °C, the dielectric loss was maximum due to aging while at 50 °C, the relative permittivity and losses increased due to the formation of aged polar products.

Aging effect (4th Column) – All the parameters showed a significant variation due to the formation of aged polar products. Water content increased from 20 ppm to 50 ppm.

Temperature effect (5th Column) – Before aging, the effect of temperature was significant on ϵ' and ϵ'' affecting polarization and dielectric losses.

6.3 The analysis of ATA results

The best way for interpretation is to come up with the model. Analyzing the ATA results for relaxation is done by EDM in terms of various RC elements. Classically,

dielectric relaxation is analyzed in terms of ϵ' and ϵ'' in frequency domain. In Section 4.3.1, FDRC model is proposed. In ATA measurements, the variation of these relaxation parameters with change in operating temperature and aging period was studied to understand the physical mechanism.

6.3.1 Analysis by EDM

EDM is an extension of Debye model in which the relaxation is represented by RC elements and geometry of the object is represented by a parallel combination of many series connected RC elements. Using RVM results before and after aging shown in Figs. 6-5 and 6-9, the analysis is made. The procedure to determine the parameters was described in Section 5.3.1.

6.3.1.1 EDM parameters

The fitted R_g , C_g , R_{pi} and C_{pi} parameters before and after aging at the two tested temperatures 22 °C and 50 °C are plotted in Fig. 6-10. In general, the fitted resistance parameter was found to decrease with increase in temperature. After aging, the resistance parameter increased considerably at both temperatures. Before aging, R_{pi} at 22 °C varied from 2 M Ω to 1200 M Ω and it decreased at 50 °C in the range of 0.1 M Ω to 100 M Ω . After aging, R_{pi} at 22 °C increased and the variation was in the range from 200 M Ω to 2200 M Ω and it decreased marginally at 50 °C in the range of 100 M Ω to 1000 M Ω . Before aging, R_g varied at 22 °C and 50 °C as 8500 M Ω and 900 M Ω . After aging, it increased to 50000 M Ω and 20000 M Ω respectively.

While, the fitted C_{pi} was found to increase with temperature significantly before aging. After aging, C_{pi} decreased. Before aging, C_{pi} at 22 °C varied in the range of 0.1 μ F to 100 μ F and it increased at 50 °C in the range of 1 μ F to 1800 μ F. After aging, C_{pi} at 22 °C decreased and the variation was in the range of 0.02 μ F to 40 μ F and it increased marginally at 50 °C in the range of 0.2 μ F to 80 μ F. Before aging, C_g varied at 22 °C and 50 °C as 500 pF and 1000 pF. After aging, it increased to 50 nF and 100 nF respectively.

Fig. 6-10 (a) Variation of R_{pi} with temperature before and after aging

Fig. 6-10 (b) Variation of C_{pi} with temperature before and after aging

Fig. 6-11 Variation of τ_i with temperature before and after aging

Time constants as per (5-4) were determined and the variation of these τ_i with temperature and aging is plotted in Fig. 6-11. Before aging, τ_i at 22 °C varied in the range of 0.15 s to 20000 s and it changed at 50 °C in the range of 0.3 s to 15000 s. After aging, τ_i at 22 °C changed in the range of 10 s to 80000 s and at 50 °C it changed to 12 s to 90000 s. From FDS measurements, it was found that τ_i lied in the range of 1 s to 1000 s. Hence neglecting τ_4 and τ_5 which lied in the range of 100000 s, further analysis was done. They may be very slow responding polarizing carriers. Before aging, τ_1 and τ_2 increased with increase in temperature and τ_3 decreased. After aging τ_1 , τ_2 and τ_3 increased with increase in temperature. In general, after aging the value of τ increased.

6.3.1.2 Interpretation

Transformer oil and pressboard are very dissimilar materials, in that the former is hydrophobic and the latter is hydrophilic. Typical value [29] for the water content of pressboard is 0.5 to 5 % by weight, while in oil at room temperature the moisture content is about 20 ppm. The dielectric constant of water is around 80 while that of oil and paper is around 2.2 to 4.3 respectively. The migrated water may remain in oil in

three forms. It may be in dissolved state or as free water or as oxidized form. As a consequence, almost all of the moisture present in the system resides in the pressboard at 22 °C. As the temperature changes to 50 °C, moisture will move out of the pressboard by diffusion. As the temperature rises, R_{pi} decreased due to increased conductivity in oil. The migration of water particles from pressboard to oil also reduced R_{pi} and increased C_{pi} at high temperature. This tendency was same before and after aging. After aging, R_{pi} and τ_i increased and C_{pi} decreased as per the model fitting. It was a bit contradictory and the mistake may be that the fitting technique was not perfect without proper constraints.

6.3.2 Analysis by FDRC model

Using FDS results shown in Fig. 6-2 before and after aging, the analysis was made. The procedure to determine the parameters defined in (4-5) and (4-6) was described in Section 4.3.1. The results were converted to C_s and R_s and a satisfactory fitting was made. The determined parameters “a”, “b”, “c” and “d” with temperature and aging were shown in Fig. 6-12.

Fig. 6-12 Variation of FDRC model parameters with temperature and aging

The parameter “a” which stands for C_s at low frequency increased with temperature and aging. This may be due to increased migration of moisture from pressboard to oil at high temperature and the formation of polarizing impurities after oxidation.

The parameter “b” stands for the rate of decrease of $\log(C_s)$ with $\log(f)$. It decreased with increase in temperature. Polarization was more active at high temperature reflected with more C_s at low frequency. Then it decreased fast at high frequency. The rate of change of “b” with temperature was more after aging. After aging also, more polarizing impurities sensitive to lowest frequency got formed and it decreased fast at high frequency.

The parameter “c” stands for R_s at zero frequency. It decreased with increase in temperature and aging. The conductivity of oil increased with increase in temperature making R_s lower. After aging, more conducting impurities may have formed to reduce R_s .

The parameter “d” stands for the rate of logarithmic variation of R_s with linear frequency. It decreased with increase in temperature and aging. The conductivity of oil increased with increase in temperature making R_s lower at high temperature. After aging, more conducting impurities may have formed to reduce R_s . At high frequency, fast polarizing ionic impurities play a dominant role with reduced polarization phenomena to reduce R_s .

6.4 Summary

The relaxation studies done on SPT indicated that the relaxation parameters were significantly different before and after ATA. This was verified by both FDS and RVM. During aging at 100 °C, only RVM was done due to limitation on FDS instrument. The maximum RV was recorded during the end of aging period.

In FDS shown in Fig. 6-2, R_p , C_p , ϵ' and ϵ'' decreased with increase in frequency before and after aging. It decreased exponentially with increase in frequency. After aging, R_p decreased and C_p increased. ϵ' and ϵ'' increased with rise in temperature and after aging. Loss factor increased after aging.

In RVM shown in Figs. 6-5 and 6-9, peak voltage increased with aging and increase in temperature. A single increasing peak response with falling tail response was

observed. After aging, t_c at which peak occurred moved to lower t_c values. At 20 °C, the ratio of peak occurrence time at the selected t_c with t_c was less after aging. But at 50 °C, the ratio of peak occurrence time at the selected t_c with t_c was more after aging. During aging, the initial slope increased and the rate of change in the falling portion decreased with aging time. The peak shifted to higher t_c . The peak occurrence time for each t_c increased with aging time. This indicated that the relaxation period may be more after aging due to increased number of polarization charges and increased relaxation time constant. The shifting of maximum RV spectrum for increased temperature to lower t_c was observed both before and after aging.

For interpretation of relaxation phenomenon, an attempt was made with the traditional EDM parameters derived from RVM data and with the developed FDRC model developed with FDS data. The limitation of mathematical fitting of RVM response with EDM parameters was identified in terms of relaxation time constants range and the predicted response with temperature and aging. Developed FDRC model was able to explain the relaxation behavior in terms of 4 parameters.

6.5 Discussion on relaxation studies under thermally aged condition

Having identified the sensitivity of FDS and RVM techniques to identify the relaxation processes, an attempt was made with an oil-filled SPT to identify the relaxation processes before, during and after aging at 100 °C for 1100 h. After oxidation, the oil was dark after and thick with floating oxidized materials. The water content was less than 20 ppm before oxidation, and after oxidation it was more than 50 ppm. The reported literature was very limited with aging studies using FDS and RVM. It was found by RVM in Fig. 2-8 and other references [4] [9] [60] that the maximum RV peak shifts to lower t_c . Other work on aging was reported in references [13] [25] [26] [27] [28] [31] [52].

BEFORE AND AFTER AGING

Effect of ATA – FDS

Dominant changes were observed at the lowest frequency of measurement, 10 mHz in Figs. 6-1 and 6-2 and all the results were compared at that frequency due to aging. R_p and τ decreased with aging and C_p , ϵ' and ϵ'' increased with aging. Comparing with

the results in Fig. 2-6, it was suggested that more water content appeared after aging. By raising the temperature from 22 °C to 50 °C, R_p and τ decreased more with aging and C_p , ϵ' and ϵ'' increased more with aging. It agreed with the observation made in Fig. 2-7.

Effect of ATA – RVM

RV spectrum in Fig. 6-4 shows a maximum of 10 V in flat response with t_c before aging. After aging, it increased to 13.5 V with the peak occurrence time shifted to higher t_c at 22 °C in Fig. 6-8 (a). It contradicted with Fig. 2-8 in which with the aging peak occurrence time moves to lower t_c . At 50 °C, increase in RV maximum with aging was more than 22 °C and the peak occurrence moved to lower t_c agreeing with the observation of time of peak occurrence shift in Fig. 2-8. The plot in Fig. 6-4(b) showing t_c and the corresponding time of maximum RV before aging at 22 °C indicated that the gradient was more in comparison with the gradient after aging shown in Fig. 6-8(b). This characteristic changed the other way at 50 °C. Increase in maximum RV after aging will be due to the formation of more polarized impurities and the increase in RV with temperature may be due to the induction of polarization impurities of lower time constant. This is indicated by the reduced time of maximum RV occurrence in Fig. 6-8(b).

EDM – Using RVM data

Using the developed fitting method, R_{pi} , C_{pi} and other parameters were determined. The fitted R_{pi} increased after aging at all the temperatures as shown in Fig. 6-9(a). While C_{pi} was found to decrease after aging in most of the cases as shown in Fig. 6-9(b). The computed τ_i also increased after aging as per the model. While FDS results shown in Fig. 6-1 suggested the effective R_p will decrease after aging, effective C_p will increase after aging and τ will decrease after aging. Hence the program to determine the parameters is to be improved by introducing some constraints.

DURING AGING

Aging was done at 100 °C for 1100 h and the measured current exceeded the limit of FDS and only RVM was done as shown in Fig. 6-5. With aging time, RV increased at all t_c . The peak RV from 15 V at 96 h increased to 19 V at 1050 h of aging. This clearly indicated the formation of more polarizing impurities with time of aging. The

change in Fig. 6-6(a) was more in the initial period. The peak shifted to high t_c with aging in contraction to Fig. 2-8. The increase in RV with period of aging may be due to the induction of more polarization impurities of lower time constant. This was indicated by the reduced time of maximum RV occurrence in Fig. 6-6(b).

Chapter 7

Conclusions and Recommendations

This chapter summarizes the findings of this project and presents new recommendations for future research work.

7.1 Conclusions

In this limited period of research work, the laboratory relaxation studies on OIL, PB, OIP and oil impregnated SPT as described in Table 3-1 were carried out in sealed tank using FDS and RVM techniques. Carefully planned three relaxation programs – measurements in frequency domain, time domain and on thermally aged SPT - were carried out with mathematical analysis. The study focused on the change in relaxation characteristics with time of equilibrium, temperature of operation, injected polarizing impurities and accelerated thermal aging. Detailed analysis in the form of newly developed frequency dependent RC (FDRC) model and existing Extended Debye Model to quantify and compare the different observations were made. The main conclusions are summarized in the following according to the above-mentioned three relaxation programs:

(a) Relaxation studies in frequency domain

Studies in frequency domain were done with OIL, PB and OIP by insulation diagnosis analyzer - IDA 200. The results were presented by the variation of dielectric properties with frequency. Effects of the equilibrium time, temperature and oxidized impurities effects were studied. The measurement results showed that the time needed to reach equilibrium state was different for OIL, PB and OIP kept in completely sealed tank at room temperature. For PB, it was about 120 h and for OIL, it was slightly more than 120 h. For OIP, it was around 24 h. With rise in temperature, this equilibrium time reduced. In general the relaxation parameters - R_p , C_p , τ , ϵ' , and ϵ'' decreased with increase in frequency. Significant changes were observed at the lowest

measured frequency of 0.01 Hz. In OIL, R_p , C_p and ϵ' increased with longer period of measurement/equilibrium time. τ and ϵ'' decreased with the measurement time. In PB, R_p and τ increased with the measurement time and C_p , ϵ' and ϵ'' decreased with the measurement time. In OIP, R_p increased and C_p , τ , ϵ' and ϵ'' decreased with the measurement time. In general, after equilibrium time, it was found that the OIP characteristics lied in between PB and OIL. With R_p , C_p , ϵ' and ϵ'' , the OIP characteristics followed closely PB. While with τ , the OIP characteristics followed closely OIL.

Rise in operating temperature of OIL decreased R_p and increased C_p , τ , ϵ' and ϵ'' . While in PB, rise in temperature increased R_p and decreased C_p , τ , ϵ' and ϵ'' . In OIP, rise in temperature decreased R_p and τ , and increased C_p , ϵ' and ϵ'' . The OIP characteristics followed that of OIL except on τ . At 22 °C, τ of OIP lied between that of OIL and PB. At 40 °C, OIP's τ was the lowest.

Injection of polarizing oxidized impurities in OIP reduced R_p and τ , and increased C_p , ϵ' and ϵ'' . With rise in temperature, the change was more.

New simulation FDRC model based on FDS results in terms of 4 parameters was able to explain the relaxation behavior with equilibrium measurement time, temperature of operation and injection of polarized impurities. Variation of R_s was equated to exponential function of frequency while the variation of C_s was equated to power law function of frequency.

(b) Relaxation studies in time domain

RVM polarization spectrums in time domain were used to study the relaxation properties of OIL, PB and OIP with respect to the effects of equilibrium time and temperature. A single peak response was obtained in all the studied dielectrics and the shapes of RV were different with OIL, PB and OIP. The equilibrium time in OIL was around 120 h and after that period, the RV responses varied in a limited range. The RVM polarization spectrum of OIP was a sum of factorized individual PB and OIL RVM spectrums as per Fig. 5-8.

Rise in temperature of OIL reduced the maximum RV and moved the RV peak occurrence to low t_c . While in PB, the rise in temperature increased the maximum RV and moved the occurrence to high t_c . Rise in temperature of OIP increased the maximum RV and moved the occurrence to high t_c .

To determine the parameters of EDM, a new optimization method using time constants was developed and tested as the range of R and C to be fitted was very wide. The fitted parameters using RVM results suggested that the relaxation time constants in OIP can vary from 0.5 s to 230,000 s. The measured time constants using FDS varied between 20 s to 730 s in these types of samples. It was realized that the fitting method had to be improved by inserting the constraints to get unique solution.

(c) Relaxation studies on oil-filled SPT under thermally aged condition

Laboratory oil-filled 1 kVA rated SPT was aged at 100 °C for 1100 h. FDS and RVM measurements in frequency and time domains showed significant changes in relaxation property before and after the aging process.

With FDS, determined R_p and τ decreased, and C_p , ϵ' and ϵ'' increased with aging. By raising temperature from 22 °C to 50 °C, R_p and τ decreased more and C_p , ϵ' and ϵ'' increased more with aging.

With RVM polarization spectrum the peak occurrence time shifted to higher t_c and the peak RV increased after aging.

The above observations suggested that more polarizing impurities were formed due to aging. Using Karl Fischer Coloumetric Titrator, it was found that water content in OIL increased from 20 ppm to more than 50 ppm after aging.

Fitted EDM parameters R_{pi} increased and C_{pi} decreased after aging in most of the cases. It was contradicting with FDS measurements. It was realized that EDM parameter determination method had to be improved. Developed FDRC model was able to fit these observations.

From these changes in the relaxation properties in frequency and time domains, it may be possible to evaluate the moisture content and the insulation condition of oil-filled transformer if sufficient data are available.

With reference to the initial objectives stated on page 5, I like to present below the achieved results:

- (1) Exact matching of the relaxation parameters with FDS and RVM measurements could not be achieved due to many factors like the conditions of samples, preparation of them for experimentation, measuring techniques and resolution of the measurement, non-guarded measurements and ambient conditions. But the trend of variation with two methods was found to be same with equilibrium time, temperature variation and aging.
  - (2) The relationship of relaxation property of individual dielectrics like OIL and PB with composite dielectric OIP was established. Fig. 4-24 shows the relationship clearly. By using series configuration, it was found $OIP - R_{sop}(f)$ and $C_{sop}(f)$ can be equated to a parallel combination of $OIL - R_{so}(f)$ and $C_{so}(f)$, and series connected $OIL - \alpha R_{so}(f)$ and $C_{so}(f)/\alpha$ and $PB - \beta R_{sp}(f)$ and $C_{sp}(f)/\beta$ in the entire frequency range. Matched α and β varied with temperature. α varied as 0.01, 0.005, 0.001 at 22 °C, 30 °C and 40 °C respectively, while β varied as 2.8, 0.55, 0.35 for the above temperature settings. In general, OIL relaxation properties were found to be dominant in comparison with PB in controlling the relaxation behavior of OIP.
  - (3) Both RVM and FDS techniques resulted significant relaxation changes in OIP with equilibrium time, operating temperature and injection of polarized impurities in oil. Significant changes were observed in PB and OIL also with equilibrium time and operating temperature. FDS technique was found to be more sensitive to the above changes and it could give relaxation parameters in a precise way especially in the lowest frequency range.
  - (4) Significant relaxation changes were observed with aging time. The measurement was done only with RVM. Mathematical fitting to get unique parameters restricted to come up with relationship on changes in parameter with aging.
  - (5) A new frequency dependent FDRC model was found to indicate the relaxation changes with only 4 parameters.
- It is felt that more research is to be done with systematic and controlled measurements.

7.2 Recommendations

As clearly reported, the relaxation measurement in oil-paper based insulation is an interesting area of electrical research to predict the aging rate and remaining life of the operating apparatus. The study requires the careful preparation and conditioning of the samples, and evaluation of them in a sealed environment. The study requires long hours of testing with electrical and chemical instrumentation. Also, mathematical models are to be developed to relate and predict the observations. The following research areas could be explored further.

(1) The large amount of data base is to be established with details on geometry, chemical and electrical data for statistical analysis of relaxation measurements. Different sized single and composite dielectric samples in guarded electrode configuration have to be evaluated with reference to water content, temperature, aging and externally added known polar impurities. In Dielectrometry studies, the frequency sweep could be from 1 μ Hz to 100 MHz. Recovery Voltage and Polarization and Depolarization current measurements may be supplemented to identify the method for practical use. Apart from chemical water content analysis, other tests like acidity, oxidation level, and furan test, degree of polymerization (DP), breakdown strength and tensile strength could be incorporated to corroborate the polarization measurements.

(2) In practical site, oil-filled transformers always operate at higher temperature above 40 °C. Hot spot temperatures in the insulation system may vary from 70 °C to 120°C and therefore, the relaxation responses at higher temperature need to be investigated.

(3) One of the main purposes to conduct the relaxation measurement on oil-paper insulation is to predict the remaining life and evaluate the aging rate by mathematical model and analysis. Development of remaining life models based on relaxation parameters need to be carried out. This study should be carried out by fabricated transformers of different winding and insulation structures with different geometries and they could be aged electrically and thermally. It should be extended to field transformers of different ratings, aging levels and loading conditions.

(4) One of the major limitations in this investigation was the limitation of research time and laboratory facilities. With proper instrumentation, water content in OIL, PB and OIP, and the corresponding level of the oxidized impurities should be accurately measured. Vacuum treated chamber, sealing conditions, guarded electrode system, temperature controller and stirring arrangement in sealed chamber could help to reduce the interference from ambient uncertainties. As the role of polarizing impurity - water in oil and pressboard is a very critical factor in the entire study, this has to be dynamically evaluated by FDS, RVM and PDC measurements.

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Appendix A

Physical and Chemical Properties of Transformer Oil Shell Diala “B”

Colour:	<0.5, pale light yellow
Odour:	Odorless / light petroleum
Melting point/pour point:	-57°C
Initial boiling point:	>250°C
Density at 20°C:	888 kg/m ³
Flash point, PM:	146°C
Auto ignition temp.:	>270°C
Solubility in water:	Non soluble.
Solubility in organic solvents:	Soluble
Decomposition temp.:	>280°C
Vapor pressure at 100°C:	160 Pascal
Viscosity at 40 °C:	9.0 cSt
DMSO extractible compounds according to IP 346:	< 3%
Relative dielectric constant:	2.3
Resistivity:	10 ¹² -10 ¹³ Ωcm

Appendix B

Physical and Chemical Properties of Pressboard PUCARO®

Nominal thickness:	5.0 mm
Density:	0.8 g/cm ³
Tensile strength (MD):	52 N/mm ²
Moisture content:	5.5%
Breakdown voltage:	29 kV/mm
Conductivity:	6.0mS/m
Shrinkage:	0.5%

Appendix C

LabVIEW Interface for RVM Measurements

Curriculum Vita

Education:

- Ph. D** (27/08/2001-26/08/2004), Research student of Ph.D,
School of EEE, Nanyang Technological University, Singapore
- M. Eng.** (07/07/1989-06/07/1992) in High Voltage Engineering
Xi'an Jiaotong University, Xi'an, China
- B. Sc.** (01/09/1985-06/07/1989) in High Voltage Engineering
Xi'an Jiaotong University, Xi'an, China

Work Experience:

07/1992-07/1994	I worked in the National Testing Laboratory of Metal Oxide Arrester (MOA) in Electrical Power Research Institute of China (CEPRI) in Beijing. I developed PMOA with polymer coating, and made research on on-line monitoring of high voltage MOA.
07/1994-07/1999	I worked in a subsidiary company of CEPRI - Voltamp Electrical Co.. As a main developer, I developed Auto-tuning Arc-Suppression Coil System used in the neutral of distribution system in 1995. The system is being used in some 20 utilities all over China. In 1999, I attended the training of ISO9001 certification. I was promoted to Senior Engineer in the Ministry of Electrical Power of China by the end of 1999.
05/1999-08/2001	I was responsible for producing ZBX Auto Tuning Arc-suppression Coil System. During 2000-2001, I took part in the commissioning of $\pm 500\text{kV}$ HVDC and HVAC transmission system which is the longest HVDC transmission line transmitting the power from Tianshengqiao in Guangxi province to Guangzhou in Guangdong province. I was responsible for the measurement and monitoring of the over voltage phenomena in AC and DC. Until August 2001,

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Curriculum Vita

I was the product manager of the Voltamp Electric Company of CEPRI. I am also a registered senior engineer in power system of China.

09/2004-present   I am working in PowerGrid of Singapore Power in cable and transformer condition monitoring section.

Skills:

- Familiar with the hardware of PC and IPC (industry PC) such as PC104, microprocessor such as MCS 80196, analog and digital circuits design, power relay protection, power electronics and EMC.
- Skillful in using computer languages such as, LabVIEW, Matlab, AutoCAD and Turbo C and Assembly language.

All my measurement system in NTU was using the LabVIEW real-time software to control the instruments, and data acquisition board, the data processing and communication with other computers by internet.

- Familiar with the high voltage techniques, high voltage testing and measuring instruments, the lightning protection of the substation and transmission line, over voltage protection and insulation coordination. In addition I know the use of simulation softwares such as ATP, EMTDC and PSpice.

Honors, Awards

- 2000 Excellent engineer of CEPRI
- 1999 First Class Award of Science and Technology Progressing of CEPRI
- 1994 First Class Award of Science and Technology Progressing of CEPRI

Publications related with this research work:

1. Cao Hongyan and S. Birlasekaran, "Temperature dependent relaxation studies on oil-filled transformer", Conference Record of the 2002 IEEE International Symposium on Electrical Insulation, Boston, MA, USA, pp. 174-178, 7-10 April 2002.
2. Cao Hongyan, S. Birlasekaran, and S. S. Choi, "Accelerated aging study on oil-filled paper transformer insulation using relaxation studies", Proceedings of the 6th International Power Engineering Conference, Singapore, Paper No: P2171, 22-24 May 2003.

Other publications:

1. Cao Hongyan, "The study of induced overvoltage on transmission lines", Thesis of Master Degree, Supervisor: Professor Wang Bingjun, Xi'an Jiaotong University, 1992.
2. Wang Bingjun and Cao Hongyan, "The study of induced overvoltage caused by lightning strokes on tower top", 21st International Conference on Lightning Protection, Berlin, Germany, pp. 519-523, 21-25 Sep. 1992.
3. Cao Hongyan, "The analysis of the MOA's protection effect on 10kV distribution substations", (Chinese Journal), Agriculture Electrification, pp. 15-16, No. 12, 1994.
4. Cao Hongyan and Fan Li, "Studies of the non-linear resistor residual voltages and their overshoots under steep current impulses", (Chinese Journal), Insulators and Surge Arresters, pp. 35-39, No. 4, 1996.
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