Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers

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ABSTRACT

Cellulosic paper and oil insulation in a transformer degrade at higher operating temperatures. Degradation is accelerated in the presence of oxygen and moisture. Power transformers being expensive items need to be carefully monitored throughout its operation. Well established time-based maintenance and conservative replacement planning is not feasible in a current market driven electricity industry. Condition based maintenance and online monitoring are now gaining importance. Currently there are varieties of chemical and electrical diagnostic techniques available for insulation condition monitoring of power transformers. This paper presents a description of commonly used chemical diagnostics techniques along with their interpretation schemes. A number of new chemical techniques are also described in this paper. In recent times a number of electrical diagnostic techniques have gained exceptional importance to the utility professionals. Among these techniques polarisation/depolarisation current measurement, return voltage measurement and frequency domain dielectric spectroscopy at low frequencies are the most widely used. This paper describes analyses and interpretation of these techniques for transformer insulation condition assessment.

Index Terms — **Insulation condition, transformer diagnostics, transformer ageing, dissolved gas analysis, furan analysis, degree of polymerization, oil insulation, cellulose paper, return voltage, polarisation current, depolarisation current, online monitoring, condition based monitoring.**

1 INTRODUCTION

THE insulation system of a power transformer consists mostly of hydrocarbon oil and paper. Many of these power transformers within electric utilities around the world are approaching the end of their design life. Insulation degradation is a major concern for these aged transformers. Insulation materials in transformers degrade at higher operating temperatures in the presence of oxygen and moisture. Practicing engineers currently use a number of modern diagnostic techniques to assess the insulation condition of aged transformers. Among them moisture analysis in transformer oil, dissolved gas analysis (DGA) [1], degree of polymerisation (DP) measurement and furan analysis by high performance liquid chromatography (HPLC) are frequently used [2,3].

Molecular weight studies by single point viscosity measurements are of limited value when dealing with a complex polymer blend such as Kraft paper as used in transformers, particularly in cases where the molecular weight distribution of the paper changes significantly as the degradation proceeds [4]. In these instances, a new technique, gel permeation chromatography is found to be more useful than the viscosity method, because it provides information about the change in molecular weight and molecular weight distribution [4]. A variety of information can be obtained from the X-ray photo-electron spectroscopy (XPS), which includes chemical state information, elemental information, and variation of composition with depth, variation of chemical composition spatially on the surface and thickness of layers. Oxidation changes the colour of the oil and this colour change can be monitored by the change in absorbance of the oil. This can commonly be examined by UV visible spectroscopy. The results from these experiments have been presented in reference [5]. Fourier transform infrared (FTIR) and near-infrared (NIR) spectroscopy have been used to characterise the ageing of cellulosic paper, with the long term aim of developing a technique to assess the condition of paper insulation in electrical transformers [6].

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In recent years, new diagnostic methods have been promoted that are complementary to the classical insulation resistance, power frequency dissipation factor and polarisation index measurements. This is significantly due to the availability of modern computer controlled instrumentation. These new methods are based on either time or frequency domain polarisation measurements. In frequency domain measurement, a sinusoidal voltage is applied and the complex dielectric constant is determined from the amplitude and phase of the current flowing through the sample [7]. On the other hand, time domain measurements are conducted by the application of a step voltage across the insulation object. Time domain measurements based on polarisation/depolarisation current measurement and return voltage measurement have gained significant importance over the last ten years [8]. Particularly, there has been growing interest in the condition assessment of transformer insulation by the return voltage method (RVM) [9].

There are many papers available on these individual diagnostic techniques. However, a review of all these techniques in a single paper is rarely available. Some attempts have been made in the past to review chemical techniques [10]. The author of this paper recently wrote a review paper on time domain polarisation measurement techniques [11]. In this paper a brief introduction of different chemical diagnostic methods will be first outlined. Then different interpretation schemes based on chemical diagnostics will be discussed. This paper will then provide special review of modern diagnostic techniques, in particular, currently available polarisation measurement techniques. Most recent emphasis has been directed to techniques of determining moisture content of insulation indirectly by measuring RV parameters. The major difficulty still lies in the accurate interpretation of return voltage results. This paper will investigate different thoughts regarding the interpretation of RV results for different moisture and ageing conditions. A number of techniques have been correlated with the RV method and hence correlation and comparison will also be briefly discussed in this paper.

2 CHEMICAL TECHNIQUES

2.1 MOISTURE ANALYSIS

Water content in insulation materials increases electric conductivity and dissipation factor and reduces electric strength. It has been a common practice to measure the moisture content in oil by the Karl Fischer titration [12] method and then estimate the moisture in solid insulation by different equilibrium curves [13,14]. There are several direct measurement methods currently reported in the literature. A thin film capacitive humidity sensor was tested for moisture sensing in transformer oil by Oomen [15]. This sensor was found to respond well for oil in transformer in cold and warm weather conditions. Neimanis et al. investigated the near infrared (NIR) spectroscopy for the determination of moisture content in oil impregnated paper [16]. Their results showed that NIR spectroscopy along with their developed multivariate modelling could result accurate estimation of moisture. Gupta [17] reported the effectiveness of NIR spectroscopy technique to detect very small changes in moisture content of paper insulation. A number of polarisation based dielectric diagnostic techniques are also currently in use for indirect moisture analysis of oil-paper insulation system.

2.2 DISSOLVED GAS ANALYSIS (DGA)

Among chemical techniques, dissolved gas analysis (DGA) has gained worldwide acceptance as a diagnostic method for the detection of incipient faults [18]. Fault gases are produced by degradation of the transformer oil and solid insulating materials such as paper, pressboard and transformerboard, which are all made of cellulose. The rate of cellulose and oil degradation is significantly increased in the presence of a fault inside the transformer. The important gases produced from the transformer operation can be listed as follows.

- Hydrocarbon gases and hydrogen: methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), and hydrogen (H_2).
- Carbon oxides: carbon monoxide (CO) and carbon dioxide (CO_2).
- Nonfault gases: nitrogen (N_2) and oxygen (O_2).

According to Emsley et al. [10] a healthy transformer should have less than 0.05 ml of combustible gases (hydrogen and short chain hydrocarbons: methane, ethane, ethylene, acetylene) per 100 ml of oil and insignificant levels of higher hydrocarbon gases. Measurements on free breathing transformers show average $CO + CO_2$ levels of 0.4 ml/100 ml of oil after 15 years. Normally causes of fault gases are classified into three categories:

- Corona or partial discharge
- Thermal heating
- Arcing.

Several authors attempted to classify these gases based on the faults. In the past certain key gases have been correlated with fault type and the rate of gas production correlated with fault severity. IEEE standard [19] with an extensive literature list discusses key gas method in detail with relative proportions of gases for the four general types of fault. It is commonly accepted that hydrogen gas is produced from the corona effect on oil and cellulose. Methane and ethane are produced from low temperature thermal heating of oil and high temperature thermal heating produces ethylene and hydrogen as well as methane and ethane. Acetylene is only produced at very high temperatures that occur in the presence of an arc. Low temperature thermal degradation of cellulose produces CO_2 and

high temperature produces CO. Low energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Electrical arcing produces large amounts of hydrogen and acetylene with minor quantities of methane and ethylene. The most commonly used gas-in-oil diagnostic methods include the following:

(a) IEEE C57.104-1991.

(b) Doernenberg method.

(c) Rogers' method.

(d) IEC 60599.

(e) Duval's triangle.

The IEEE standard [19] also reports two ratio methods based on five ratios. Where

$$Ratio1 = \frac{CH_4}{H_2},\ Ratio2 = \frac{C_2H_2}{C_2H_4},\ Ratio3 = \frac{C_2H_2}{CH_4},$$

$$Ratio4 = \frac{C_2H_6}{C_2H_2},\ Ratio5 = \frac{C_2H_4}{C_2H_6}.$$

The Doernenberg ratio method is based on Ratios 1, 2, 3 and 4. This method is based on special concentrations as shown in Table 1 to determine whether there is any problem and whether there is sufficient generation of each gas for the ratio analysis to be applicable. Then the ratios in the order of Ratio1, Ratio2, Ratio3, and Ratio4 are compared to limiting values, providing a suggested fault diagnosis. The procedure is explained in detail in the IEEE standard [19] and in many other papers. Rogers's ratio method uses only three ratios (Ratio 1, 2 and 5). This method's flow chart along with key gas limits is also given in the IEEE standard [19].

In many situations both the Doernenberg method and the Rogers' method may provide a ratio that does not fit into the diagnostic codes. Other analytical methods such as those based on total dissolved key gas concentration or key gas method should then be used. Duval and De Pablo [20] discussed the interpretation of gas-in-oil analysis using new IEC 60599 publication and IEC TC 10 databases. In IEC publication 60599 five different fault types are discussed [21]. The major gas ratios have been retained for diagnosis with new code limits. Additional gas ratios are also suggested for specific fault cases. More precise definitions of normal and alarm gas concentrations are also highlighted. These faults can be reliably identified by visual inspection of the equipment after the fault has occurred in service [20]. Examples include:

Table 1. Concentration of Dissolve Gas.

Key Gas	Concentrations (ppm)
Hydrogen (H_2)	100
Methane (CH_4)	120
Carbon Monoxide (CO)	350
Acetylene (C_2H_2)	35
Ethylene (C_2H_4)	50
Ethane (C_2H_6)	65

(a) Partial discharge—with possible X-wax formation and of the sparking type inducing small carbonised punctures in paper.

(b) Discharges of low energy—evidenced by larger punctures in paper, tracking or carbon particles in oil.

(c) Discharges of high energy with power follow through—evidenced by extensive carbonisation, metal fusion and possible tripping of the equipment.

(d) Thermal faults below 300°C—evidenced by paper turned brownish and above 300°C when paper carbonises.

(e) Thermal faults above 700°C—evidenced by oil carbonisation, metal coloration or fusion.

In IEC 60599 two additional gas ratios have been introduced for specific diagnosis. The ratio C_2H_2/H_2 is recommended to detect possible contamination from the On Load Tap Changer compartment (when > 3) and the ratio O_2/N_2 to detect abnormal oil heating/oxidation (when < 0.3). Typical values of gas concentrations are also calculated in this publication. Alarm values (maximum acceptable values) and typical rates of gas increase for power transformers are also given in IEC standard. Duval [22] mentioned that a significant number of DGA results in service fall outside the IEEE-IEC codes and could not be diagnosed. Duval proposed his triangle representation for fault diagnosis as shown in Figure 1. According to Duval [22] high rates of paper degradation are indicated when

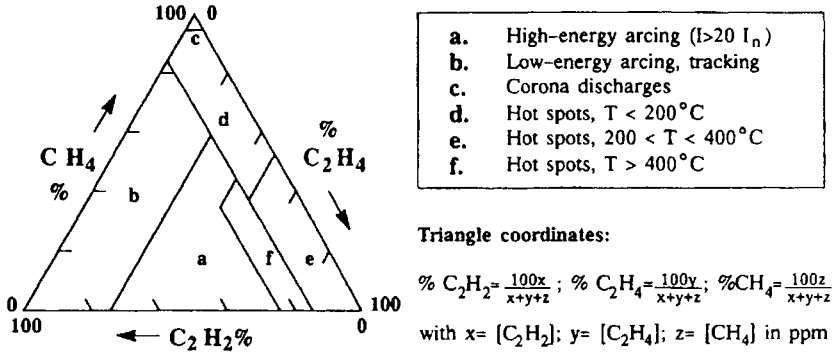

Figure 1. Duval's Triangle [22].

the ethylene concentration increases strongly and the CO_2/CO ratio decreases below a ratio of about 6. At a CO_2/CO ratio less than 2, the probability of failure increases significantly when the combustible gas concentration exceeds about 200 ppm.

Lapworth [23] proposed a new approach using the key gas method of presenting DGA results. The relative proportions of six combustible gases CH_4, C_2H_6, C_2H_4, C_2H_2, H_2 and CO are displayed as a bar chart to illustrate the gas signature. The novel aspect of the approach proposed by the author is that this method is used to investigate and illustrate the clear difference that exists between "normal" and "abnormal" results. A scoring system has been developed which translates a DGA result into a composite DGA score reflecting the perceived seriousness of the signature. Islam et al. described a fuzzy logic approach to develop a computer based intelligent interpretation of transformer faults. They have tested the software using 800 DGA cases and successfully demonstrated detection and verification of 20 transformer faults [24]. A vast number of literatures are available on the DGA method and its interpretation. However, most of these are based on IEEE/IEC methods.

2.3 DEGREE OF POLYMERISATION MEASUREMENTS

The solid insulation (paper, pressboard, transformerboard) used in transformers is a sheet of material made from vegetable cellulose. The main source of cellulose fibre is wood. In a dry condition, wood contains 40 to 50% cellulose, 20 to 30% lignin and 10 to 30% hemicellulose and polysaccharides. Cellulose is a linear polymer composed of individual anhydrous glucose units linked at the first and fourth carbon atoms through a glucosidic bond. The structure of glucose and cellulose is shown in Figure 2. The good mechanical properties of cellulose and its derivatives, on which their utility depends, are due to their polymeric and fibrous nature. The number of monomer units in the polymer is known as degree of polymerisation

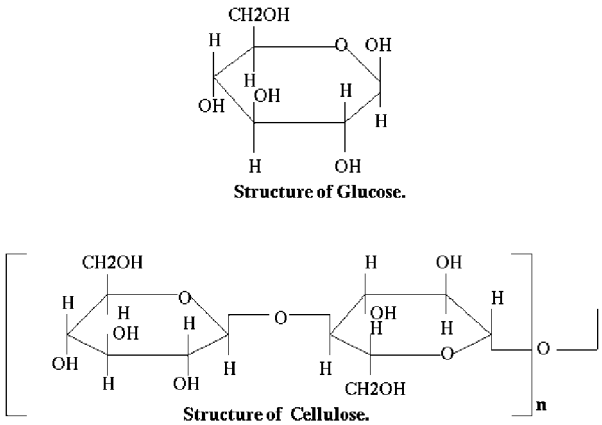

Figure 2. Structure of glucose and cellulose.

(DP). Very often, the quality of the cellulose is measured in terms of its degree of polymerisation by the average viscometric method. The length of the cellulose chain thus measured by the average degree of polymerisation based on viscosity method will be denoted by DP_V.

DP_V measurement has been used as a diagnostic tool to determine the condition of transformers by several workers [13,25–27]. New Kraft paper has an average chain length of 1000 to 1500. After a long period of service at high temperature with high content of water and oxygen, the paper becomes brittle, changes colour to dark brown and DP_V falls to 200 to 250. Sometimes cotton is used as an insulating material. Cotton fibre lengths are greater than those of unbleached soft wood sulphate cellulose, but their diameter is smaller. The average degree of polymerisation for new cotton is higher than Kraft paper. For Kraft paper with a DP_V of 150 to 200 the mechanical strength of paper can be reduced to 20% of its initial strength and this point is regarded as the end of life criterion for transformer insulation [25]. According to reference [25] at DP_V from 900 to 500, the strength of the paper is virtually constant but, in the range 500 to 200, it decreases in direct proportion to DP_V. Comprehensive literature is now available based on accelerated ageing of oil/paper insulation. Most of these papers take the paper end of life criterion as 50% of its original tensile strength or 200–250 as its degree of polymerisation value. Then a thermal endurance curve is plotted to predict the remaining life of paper insulation [28].

Pahlavanpour et al. [29] presents some experimental investigation of the thermal ageing of Kraft paper and suggests that DP_V of paper starts decreasing at 120°C. The decrease of DP_V is faster with increases of temperature, reaching the corresponding end of life DP_V at a temperature of 180°C. McNutt describes the importance of insulation end of life criterion in his paper [30]. He pointed out that different investigators tend to choose different endpoint DP_V levels. Bozzini [31] suggested 100–150, Lampe et al. [32] used 200, Fabre and Pichon [33] proposed 100–200. The author also highlights that many in-service transformers have continued to operate with insulation DP_V levels below 100. McNutt [30] suggested that his own end point DP_V would be 200.

Emsely et al. [34] showed that the reaction rate at any time could be assumed to be proportional to the number of unbroken chain bonds available and their analysis revealed an equation in the form

$$\frac{1}{DP_{vt}} - \frac{1}{DP_{v0}} = kt \qquad (1)$$

where $DP_{vt} = DP_v$ at time t, DP_{v0} = initial DP_V and k = Constant.

They related the slope of the kinetic plot (that is the reaction rate constant k) to temperature by the Arrhenius relationship, plotting $\log(k)$ against reciprocal absolute

temperature. They also showed that the slopes of the plots and hence the activation energy of the reaction remained constant under a wide variety of experimental conditions. Substituting values of initial and final DP_V of 1000 and 200 respectively and combining with equation (2) they have given the equation for transformer remaining life as in equation (3).

$$k = Ae^{-\frac{E}{R(T+273)}} \tag{2}$$

Where T = temperature in Celsius, R = Gas constant = 8.314 J/mole/°K, and E = activation energy, values of A depend on operating conditions.

$$life = \frac{0.004}{A} e^{\frac{13600}{T+273}} hours \tag{3}$$

Emsely et al. [10] provided an excellent review on chemical indicators of degradation of cellulosic materials. They have also highlighted advantages and disadvantages of life prediction from DP_V measurements. DP_V measurements are easy to conduct and can be easily empirically related to insulation condition. On the other hand the mechanisms and kinetics of the process are ill defined. The rate of degradation depends on the type of paper and also on its final chemical treatment. The rate of degradation increases discontinuously with increasing temperature above about 140°C. Heywood et al. [35] discussed in detail the factors affecting the measurement of the average viscometric DP_V. They highlight the errors arising due to preparation of solutions, measurement of viscosity and calculation of DP_V, due to oxidative degradation of the solution, inconsistencies in the measurement temperature and the conversion of intrinsic viscosity of DP_V using the Mark Houwink Sakurada relationship [35].

Moser et al. [36] reported that with an increase of 0.5% water content in an ageing transformer the DP_V value of the paper would be halved. Emsley et al. reported a relationship [37] between the DP_V and tensile strength of the paper and it is shown that to a first approximation tensile strength is directly proportional to reciprocal of DP_V. Hill et al. [38] shows the nonlinear relationship between the tensile strength and the degree of polymerisation DP_w (weight average molecular weight) as measured by GPC measurement. The relationship has been found to be sigmoidal. The tensile strength of the paper decreases slowly with decreasing DP_w until a critical average DP_w of about 500 is reached. It is also reported that the tensile strength depends on the final molecular properties of the cellulose in the paper and is independent of the degradation temperature. Some Australian utilities take paper samples from bushing leads and find a good correlation with DP_V at hot spot positions. Some are introducing dummy samples to be removed for testing at strategic ages [39].

Molecular weight (MW) studies by gel permeation chromatography (GPC) have been found to be more useful

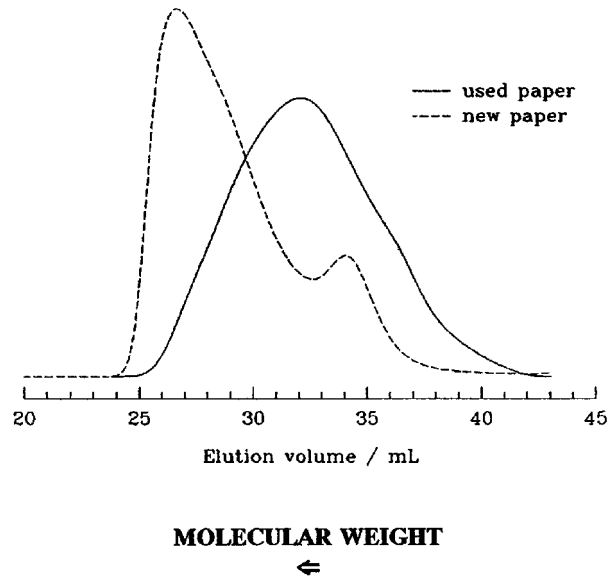

Figure 3. Molecular weight distribution of a new and 25 year old transformer paper [4].

when dealing with Kraft paper, particularly in cases where the molecular weight distribution of the paper changes significantly as the degradation proceeds. GPC provides the most convenient way to obtain a detailed molecular weight distribution for the polymer. As GPC gives the entire distribution for the polymer, any small change in molecular weight during the ageing process of an insulation material is easily observable through the chromatogram. GPC measurement provides information about the change in molecular weight and molecular weight distribution. Prior to molecular weight measurement, the cellulose in the paper samples (which is the major component and that responsible for providing the mechanical strength of the paper) is converted to the cellulose tricarbanilate derivative using the method described previously by Hill et al. [4]. After purification of the cellulose tricarbanilate, it is subjected to molecular weight analysis by gel permeation chromatography at room temperature using tetrahydrofuran as the eluent. A typical GPC chromatogram with molecular weight distributions for a new paper and a 25 years old transformer paper is shown in Figure 3. Figure 3 shows that the higher the elution volume the lower is the molecular weight.

As the paper is 25 years old, the peak molecular weight has been significantly reduced and the shape also changes significantly. The chromatogram of the new cellulose insulation paper shows the presence of two components. One component at lower elution volume or high molecular weight is due to cellulose, while the smaller, lower molecular weight component is due to hemicellulose. In the chromatogram of the cellulose insulation paper taken from an aged transformer, the molecular weight of the cellulose component has decreased significantly. The molecular weight distribution of the cellulose has also broadened

considerably and the peak of hemicellulose has become almost indiscernible, suggesting that the hemicellulose component of the paper may have been largely degraded. GPC measurement has been performed to investigate oxidation and thermal ageing in controlled accelerated ageing conditions and has been found to be very sensitive to ageing [38]. Ali et al. [40] also point out that DP_V gives no more than an approximate estimate of the average chain length of the cellulose and its variation during ageing is a very coarse measure of the change occurring. According to Ali et al. [40] GPC has the potential to give a far more detailed analysis of molecular weight distribution changes during cellulose ageing. GPC could provide the basis of more sophisticated degradation models because more complex situations can be accommodated.

2.4 FURAN ANALYSIS BY HIGH PERFORMANCE LIQUID CHROMATOGRAPHY

Furans are major degradation products of cellulose insulation paper and are found in the insulation oils of operational transformers. Furan analysis offers a more convenient method of analysis than direct measurement on insulation paper [41]. Shroff and Stannett [25] reported on the formation of 2-furfuraldehyde from the degradation of cellulosic insulation papers in accelerated ageing experiments and found that an approximately logarithmic relationship existed between the concentration of 2-furfuraldehyde in the oil and the degree of polymerisation of the cellulose in the paper. Burton et al. [42] made an extensive study and measured the rate of furan formation of several furan products over a wide range of temperatures (120−350°C). They also found an approximately logarithmic relationship between the concentration of 2-furfuraldehyde and the DP_V of the paper. Unsworth and Mitchell [2] used HPLC technique to monitor the formation of furan components during ageing of cellulose insulation paper at 20, 80 and 110°C. They correlated their results for the tensile strength of the paper with the concentration of 2-furfuraldehyde and observed that the decrease in the tensile strength of the paper corresponded to an increase in the concentration of the furans in the oil. Hill et al. [41] developed a kinetic model and found that the concentration of furans in the transformer oil should increase in a parabolic form with degradation time as shown in equation (4)

$$F_t = A(N_c)_0 t + (Akt^2)/2 = bt + ct^2 \qquad (4)$$

where N_c is the number of cellulose chains present per kilogram of paper at time t, A is proportionality constant and k is the rate constant. Also $b = A(N_c)_0$ and $c = (Ak)/2$. The authors [41] determined the values of c/b experimentally and compared those predicted from the model using the values of k and $(N_c)_0$ obtained from a molecular weight study [4]. They also reported that 5-hydroxymethyl-2-furfuraldehyde (HMF) and 2-furfuraldehyde (F) are present in the oil at significantly greater concentrations than any other furan components. Furfuraldehyde is the furan present in greatest amounts. This study also found that the rate of HMF formation is faster with an increase in temperature than the rate of F formation. Emsley et al. reported that production of 2-furfuraldehyde always outweighed that of the other three furans and the main production occurred when the DP_V dropped below about 400 [3]. They also reported that both water and oxygen increase the rate of formation of ageing products, but water is more effective. The most significant rise in furfural level occurs below DP_V 400 as it approached the critical value of 200 where the paper loses all mechanical strength and becomes susceptible to damage [43]. Kraft paper produces more furans than cotton probably due to the presence of hemicellulose in the wood based Kraft paper [43]. They also found logarithmic correlation of the concentration of 2-furfuraldehyde to the DP_V of the paper in the temperature range of 120−160°C.

Pahlavanpour et al. [39] report that furan levels are generally less than 0.1 ppm and these levels may be maintained throughout a transformer's life. However in many older units levels of up to 1 ppm and in some, up to 10 ppm are found [39]. The technique for furan testing is described in IEC [44], but there is no guideline for interpretations. Blue et al. reported a new solid state material which has been specifically designed for furfural detection and has been successful in detecting small concentrations less than 1 ppm of furan within transformer oil [45]. Then Blue et al. [46] reported the construction of a novel electrotechnic sensor for the determination of furan concentrations as low as 0.1 ppm.

Chendong et al. found a linear relationship between the furfural concentration in logarithmic scale and the degree of polymerisation [47]. This was represented by a formula: $\log(F) = 1.51 - 0.0035(DP_V)$. Where F is the furfuraldehyde concentration in mg/L. De Pablo et al. published a comprehensive report on furanic compound analysis [48]. They reported a similar log-linear relationship between the furans and DP_V. They have reported five different relationships based on experiments conducted at different conditions. They have also reported that from more than 5000 European transformers a significant number had furfural concentrations higher than 1 mg/kg of 2-furfuraldehyde in oil.

De Pablo [49] reported a relation between furfural and DP_V as shown in equation (5)

$$DP_V = \frac{7100}{8.88 + FFA} \qquad (5)$$

where FFA is the furan concentration expressed as mg/kg of oil. Pahlavanpour et al. [50] modified the formula based on transformer conditions and an assumption that 20% of winding paper and the inner paper layer degrade twice as

fast as the rest of the paper. The revised formula is given in equation (6)

$$DP_V = \frac{800}{(0.186 \times FFA) + 1} \quad (6)$$

Dakin's [51] chemical reaction rate equation ($K_0 = Ae^{B/T}$) is the most widely used equation for measuring thermal degradation of transformer insulation. Where K_0 is the reaction rate constant and A, B are empirical constants and T is the temperature in degrees Kelvin. McNutt [30] published a list of slope values obtained from different measurements and based on different end of life criterion. McNutt et al. [52] described the thermal life evaluation of a cellulose/oil system, a Nomex/oil system and a hybrid Nomex/cellulose/oil system. Nomex is a meta-aramid paperboard used for higher temperature insulation systems. Life data for an oil/Nomex insulation system operating at 240°C conductor temperature (130°C bulk oil temperature) demonstrated a life in excess of 5000 hours. Actual retained tensile strength of the conductor wrap at 5000 hours was 77% of the initial value.

2.5 NEW CHEMICAL TECHNIQUES

Saha et al. [5,53] reported that during ageing, the surface of the paper which is in direct contact with the transformer oil undergoes a colour change and becomes darker. This is particularly evident in the case of the samples aged in air. In order to identify the nature of the changes which are responsible for the change in colour, the paper samples were subjected to analysis by X-ray Photo-electron Spectroscopy, XPS. An analysis of the oxygen and carbon peaks indicates that there are significant concentrations of doubly bonded carbons and oxygen present in the surface of the air aged samples, which probably arise from oxidation products from the oil being attracted to the polar cellulosic surface of the paper. The presence of the hydrocarbon on the surface of the paper even after extensive washing of the paper with the solvent suggests that the hydrocarbon degradation products from the oil are chemically bound to the surface. If this is so, then they are also unlikely to be removed by treatment with hot kerosene (used in the vapour cleaning technique).

During accelerated ageing in an air environment the oil obviously became oxidised and turned brown in colour. However, during the corresponding studies in a nitrogen environment there was no obvious change in the colour of the oil. To monitor any changes, the absorbance of the oil was examined by UV-visible spectroscopy for the samples aged at 145°C [54]. The absorption spectrum is characterised by a strong absorption peak in the region below 400 nm, with a long absorption tail extending into the visible region which is responsible for the brown colour. The spectrum is typical of that observed for species containing a sequence of conjugated double bonds or aromatic groups. There was no evidence of the formation of significant concentrations of the absorbing species for the samples aged under nitrogen. A sample of oil aged in air in the presence of atmospheric moisture, but in the absence of paper or copper also turned brown, showing that the paper and the copper are not responsible for the formation of the absorbing species and that it arises solely from the oxidation of the oil.

Ali et al. [6] reports Fourier Transform Infrared (FTIR) and Near-Infrared (NIR) spectroscopy to characterise the ageing of cellulose paper. Differences in the spectra of new and aged materials were obtained and this provided the basis of a "fingerprint" method to categorise papers into different families. Palmer et al. studied two kinds of spectral responses by Infrared spectroscopy and UV visible spectrophotometry to monitor the variation of absorbance [55]. Based on the spectral absorption characteristic, a novel methodology for on-line transformer health assessment was developed.

3 ELECTRICAL DIAGNOSTIC METHODS

It is often assumed that when the cellulose insulation ages in a transformer the dielectric properties (dissipation factor at power frequency and breakdown strengths at both power frequency and lightning impulse) do not change drastically. Based on this general assumption, very little systematic research had been undertaken in the area of electrical diagnostic techniques for condition monitoring or for studying the degradation of electrical insulation in power transformers until 1990. Although insulation resistance and polarisation index (ratio of 10 minute insulation resistance to 1 minute insulation resistance) have been used by the electricity utilities for a long time to ascertain the transformer moisture condition. Partial discharge is an electrical phenomenon that occurs inside a transformer and the magnitude of such discharges can cause progressive deterioration and sometime may lead to insulation failure. There are vast numbers of papers available on PD processes, PD patterns and fault mechanisms and are beyond the scope of this paper. A number of researchers have worked on the measurement of dielectric strength of pressboard and paper with different wave shapes (power frequency or lightning impulse or switching impulse or combinations of these). However, in recent years new diagnostic methods have been promoted complementary to the classical insulation resistance, power frequency dissipation factor and polarisation index measurements. These methods will be presented here with applications.

3.1 TIME DOMAIN POLARISATION METHODS [11]

When a dielectric material is charged with an electric field the material becomes polarised. The current density $j(t)$ is the summation of the displacement current and the conduction current. If we expose the insulation to a step

voltage at time $t = 0$ the charging current density is given by equation (7).

$$j_{polarisation} = E(\sigma + \epsilon_o f(t)) \tag{7}$$

where the response function $f(t)$ describes the fundamental memory property of any dielectric system and can provide significant information about the insulation material. If we consider the case where an insulation system with geometric capacitance C_o (the geometric capacitance is simply the capacitance of the transformer containing no insulation, just air or vacuum) is exposed to a step voltage, U_0, the charging current can be given by equation (8)

$$i_{polarisation} = C_o U_0 \left(\frac{\sigma}{\epsilon_o} + f(t) \right) \tag{8}$$

where σ is the dc conductivity and ϵ_o and ϵ_r are respectively the permittivity of vacuum and relative permittivity of the dielectric material. If the step voltage is now disconnected from the insulation, equation (9) gives the discharging or depolarisation current.

$$i_{depolarisation} = -C_o U_0 \{ f(t) - f(t + t_{charging}) \} \tag{9}$$

When a direct voltage is applied to a dielectric for a long period of time and then short circuited for a short period, after opening the short circuit the charge bounded by the polarisation will turn into free charges i.e., a voltage will build up between the electrodes on the dielectric. This phenomenon is called the return voltage. This is shown in Figure 4. We assume that the insulation system was initially discharged and that a constant voltage U_0 is applied. The current density under this open circuit is given by equation (10)

$$j(t) = \sigma E(t) + \frac{dD}{dt} = \sigma E(t) + \frac{d}{dt}(\epsilon_o \epsilon_r E(t) + \Delta P(t))$$

$$j(t) = \sigma E(t) + \epsilon_o \epsilon_r \frac{d}{dt} E(t) + \epsilon_o \frac{d}{dt} \left\{ \int_0^t f(t-\tau) E(\tau) d\tau \right\} \tag{10}$$

During return voltage measurement the circuit being without any supply, $j(t) = 0$ and equation (10) can be solved for return voltage. The return voltage can be calcu-

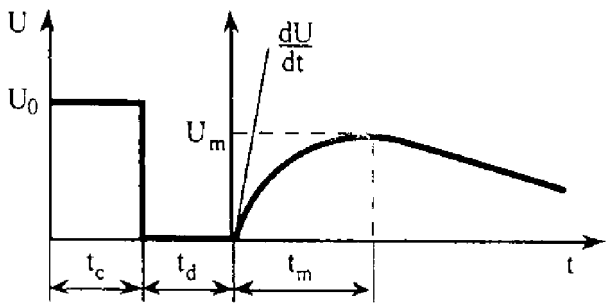

Figure 4. Return voltage phenomena [82].

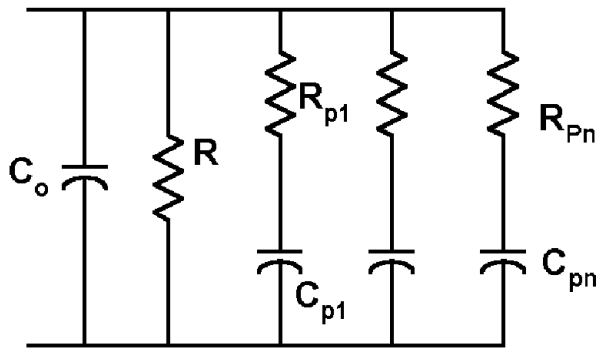

Figure 5. Equivalent circuit of transformer insulation [67].

lated if the response function, permittivity and conductivity are known. A number of thoughts are currently in practice to explain the polarisation results. Many of these are explained with case studies.

Bognar et al. [56,57] reported on the return voltage method and suggested that the insulation structure can be represented by an equivalent circuit as shown in Figure 5, where C_o is the geometric capacitance, R is the insulation resistance and R_{pn}-C_{pn} are substitutes for the individual polarisation processes having time constants of $t_{pn} = R_{pn}C_{pn}$. Figure 5 has been used to represent the extended Debye model, which explains relaxation behaviour of oil/paper insulation. Bognar et al. [56,57] suggest that the initial slope of the return voltage is directly proportional to the polarisation conductivity and the maximum value of the return voltage is proportional to the intensity of polarisation phenomena and the absolute value of the return voltage maximum value is also influenced by the actual value of the insulation resistance. Osvath et al. [58] describe the difference between transformers of widely differing ages and indicate how the return voltage measurement could be used for this. The smaller the central time constant (the time to reach the return voltage peak value); the worse is the condition of the transformer. This is illustrated in Figure 6 [58].

Bognar et al. in the paper [59] compares various methods for the diagnosis of oil/paper insulation. Loss factor

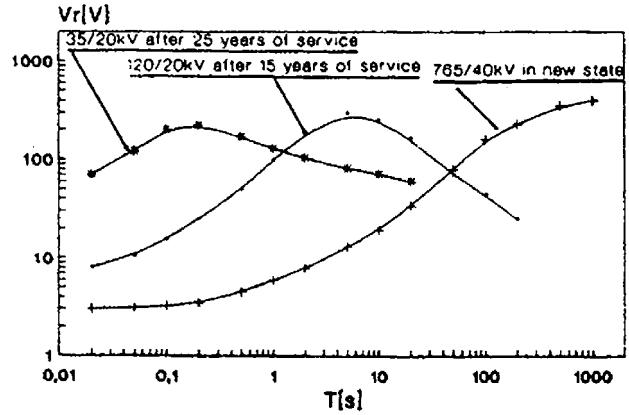

Figure 6. RV spectra for different ages of transformer [58].

is found to always change due to the consequence of polarisation and conductive effects. Their findings suggest that the central time constant (charging time to the peak of the return voltage) is fully independent of the conductivity and of the geometrical capacitance of the transformer insulation, which totally contradicts the suggestion made by Gafvert et al. [7]. Temperature inside the transformer tank is found to be a sensitive parameter for the return voltage measurement. At rising temperatures, the RV curve is found to peak at increasingly shorter times.

Gafvert et al. discuss the polarisation process in detail in reference [8]. Gafvert and Ildstad [60] present modelling of return voltage based on a series combination of oil duct and paper/pressboard dielectric materials. In their modelling work each material is characterised by its conductivity and permittivity along with composite dielectric response function. They verified their model with a simplified structural model of transformer insulation. Their findings suggest that the initial rise of the return voltage (i.e. initial slope) is determined by relaxation of interface charge through the oil gap. They point out that in the case of short charging and discharging times during the return voltage measurement, surface charges completely dominate the magnitude of the return voltage. Ildstad et al. in their reference [61], also present a mathematical simulation tool to describe the fundamental dielectric processes of conduction and polarisation. They also explain the relation between time domain and frequency domain polarisation measurements.

Gafvert et al. in reference [62] describe a comprehensive mathematical tool to describe the moisture and ageing influence on the dielectric properties of transformer insulation. The authors use the geometrical design of a transformer to analyse the polarisation response of the transformers insulation. By knowing the appropriate geometry, the composite dielectric constant of oil/paper insulation is calculated based on oil and paper insulation in series connection. Their findings suggest that the initial current during the polarisation current measurement is proportional to the oil conductivity and the oil conductivity can be calculated from this current [63]. The impact of oil conductivity on polarisation current is demonstrated in Figure 7. The conductivity of the paperboard can be estimated from the stationary dc current of the polarisation current. This stationary current was found to be a good indicator of the moisture content of the paperboard insulation as shown in Figure 8 [63].

In [62] Gafvert et al. recommend polarisation current measurement as the preferred time-domain diagnostic method since the properties of oil and paper can be separately assessed from the experimental results. The authors explain that return voltage measurement results are convoluted by two constituents and it is difficult to separate the oil and paper impacts. Gafvert et al. in reference [7] emphasise that return voltage curves are strongly influenced by the oil conductivity. The authors present different return voltage spectrum for three different oil conductivities [7]. The authors suggest that the oil conductivity (not only the moisture content in paper insulation) strongly affects the central time constant. The authors also show the influence of paper moisture level on return voltage polarisation spectra [7]. The authors here highlight the consistency between polarisation/depolarisation current measurements and recovery voltage measurements [62].

Csepes et al. [64] show that the RV method is insensitive to the effects of local reduction in insulation resistance. A large change in capacitance changes the absolute value of the return voltage while the shape of the curve remained the same. This demonstrates that the characteristic shape of the RV polarisation spectrum is independent of both shunt resistance and shunt capacitance. They recommend that with a little experience in its evaluations, RVM is also useful for evaluating the uniformity of ageing and/or moisture distribution. The RV method is claimed to be insensitive to the choice of test voltage, to external AC fields and to shunt capacity or resistance, as long as the shunt values are not changing during the test.

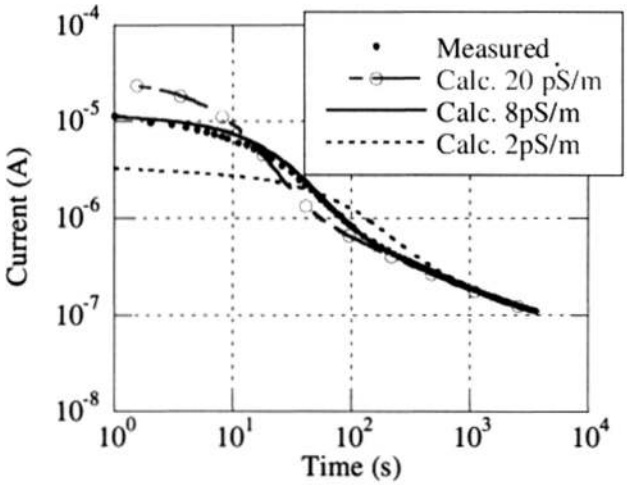

Figure 7. Effect of oil conductivity on polarisation current [63].

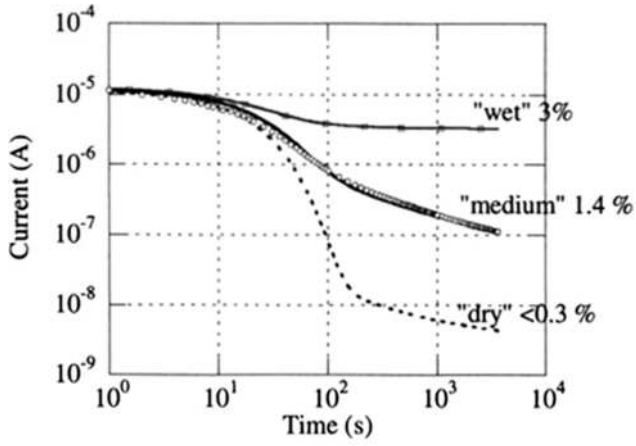

Figure 8. Effect of paper moisture content (paper conductivity) on polarisation current [63].

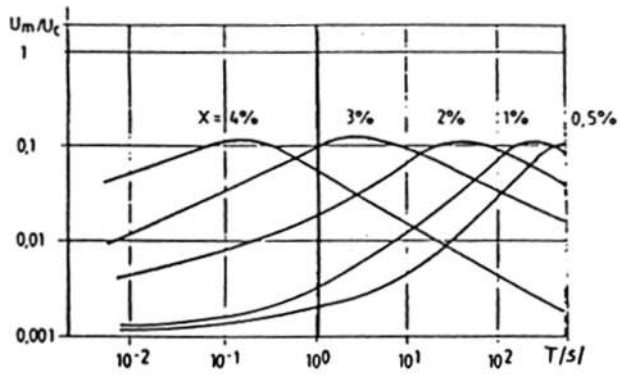

Figure 9. Calibration of RV spectra for different moisture levels [64].

Csepes et al. [64] explain the practical foundation of the RVM method. Based on comprehensive experiments the authors suggest that the return voltage maxima (expressed as relative values normalised to charge voltage) appear at lower charge times with increasing moisture content. Their testing results also confirm that these maxima move toward lower charge times with increasing moisture content as shown in Figure 9. Contrary to Gafvert et al. [7] the authors claim that the dominant time constant or central time constant is not affected by the oil quality, although the presence of multiple polarisation processes can be seen in the slight elevation in the left side of the curve. Dominant time constant is found to decrease with increasing ageing [65], just as it is found with increasing moisture content. The authors define "equivalent moisture content" to explain the effect of both water and ageing products on the RV spectra. The authors model the RV measurement with the circuit shown in Figure 5. They suggest that the RV method is also useful for checking the effectiveness of a drying treatment.

Urbani et al. [66] emphasise the significance of RVM for standard and nonstandard waveshape measurements. When return voltage spectra have unambiguous maxima, a reasonably accurate moisture estimate can be achieved from this measurement. On the other hand, for multiple local peaks, flat curves and curves with discontinuities they recommend that results from other tests and service history can be useful for correct interpretation of results.

Yu et al. [67] present an extended Debye model to describe the return voltage mechanism. They model the transformer with eight relaxation time constants (as an extension to that shown in Figure 5) and show a good fit to explain the return voltage mechanism. Jota et al. [68] propose a mathematical model of the polarisation spectrum. It is shown that from their derived model, some of the hidden RVM peaks could be identified. Using this proposed method the parameters of the equivalent circuit could be determined in tests made in different stages of a transformer's life. The evolution of the parameter values can be correlated with the estimated ones to improve the knowledge about the effect of moisture ingress and ageing on the insulation time constants. The authors validate their models using RVM tests on a 330/11 kV transformer. It is observed that capacitance and insulation resistance change due to thermal ageing and moisture ingress. This method can also help to monitor ageing and moisture ingress, once the models are formed from the measurements.

Der Hohuanesian et al. [69] show that consecutive measurements of the polarisation currents of an oil/paper insulation system can be used to quantify its dielectric response, especially in the low frequency domain. The authors suggest that polarisation spectra as quantified by RV measurements should not be used to quantify the moisture content of the pressboard within a power transformer of unknown construction, as the dielectric response quantities of the board are only a portion of the overall response. Alff et al. [70] find that the relaxation or polarisation/depolarisation currents are directly proportional to fundamental dielectric quantities, i.e. dielectric response function and dc conductivity. A computer program is developed to calculate polarisation index, return voltage spectrum and complex capacitance using the RC circuit as shown in Figure 5. Finally the authors recommend that measurement and evaluation of polarisation current is very simple and efficient to quantify the quality of insulation systems.

Saha et al. [71–74] extensively used the return voltage method for analysing the condition of aged cellulose insulation. Among RV parameters, central time constant is found to be the most sensitive to ageing. In a recent research project, accelerated ageing experiments were performed under air and nitrogen environments over the temperature range 115–145°C. The results are described in the reference [5]. The RV parameters are found to vary at a much slower rate during the ageing of samples in the presence of nitrogen compared to samples aged under air [75].

When paper insulation ages at elevated temperatures, the cellulose chains undergo scission and the chain scission is monitored by the paper molecular weight measurement using gel permeation chromatography [4]. The molecular weight is found to drop significantly due to cleavage of the chain between glucose rings in the polymer. Correlation between molecular weight measurements and RV parameters shows a good correlation for air-aged samples. The findings from nitrogen-aged samples suggest a much lower rate of degradation both from the RV and GPC measurements. A number of power and distribution transformers of different ages were investigated with the return voltage measurement technique. Findings suggest that the polarisation parameters measured by return voltage (RV) vary significantly and consistently with the ageing condition of insulation systems [74]. The authors also find that geometry of the insulation has a strong impact on RV parameters. Overall, the author of

this paper believes that it is very important to consider oil quality and geometry of the insulation structure to accurately interpret the dielectric diagnostic results.

The present author is now working on the separation of aging and moisture by using polarisation/depolarisation currents, decay voltage and RV measurements. Preliminary work has been published in the CIGRE 2002 Paris Session [76]. The authors have investigated a number of accelerated ageing experiments at 115°C with known discrete moisture levels. The aged samples were then analysed by return voltage, polarisation/depolarisation current and molecular weight measurements. Our findings suggest that for the unaged 5% paper moisture sample, the central time constant is located in the smaller time range; on the other hand 2% and 3% paper moisture level unaged sample's central time constants are located in the larger time range. It was very interesting to see that there was little difference in the results for the 2% and 3% paper moisture samples.

The amplitude of long term dc polarisation current is very sensitive to the moisture content in paper insulation. This demonstrates that polarisation current measurement can be used for assessing the paper insulation moisture level. In [76] an attempt has been made to separate the ageing and moisture effects on the polarisation measurements. The polarisation current has been found to be very sensitive to moisture. The oil and paper conductivities have both been found to be sensitive to moisture and ageing. Similarly the central time constant in RV measurement has been found to be sensitive to moisture and ageing as well. When the higher moisture is produced from ageing, it is understood that the moisture and ageing become inseparable. However, the comparison of unaged and aged samples produced some interesting results. From the molecular weight measurements both weight-average and number-average molecular weights show small reductions for 2% moisture aged samples, while there is a significant reduction in molecular weight for the 3% moisture aged samples.

3.2 FREQUENCY DOMAIN POLARISATION MEASUREMENT

In frequency domain polarisation measurement, dissipation factor or $\tan\delta$ is measured as a function of the frequency of the test voltage. In frequency domain the dielectric response function $f(t)$ is the dielectric susceptibility. The susceptibility and response function are related through the Fourier transform given by equation (11) [8,60]. The susceptibility is a complex function of frequency and is related to the relative permittivity given by equation (12).

$$X_s(\omega) = X_s'(\omega) - iX_s''(\omega) = \int_0^\infty f(t)e^{-j\omega t}dt \quad (11)$$

The sinusoidal voltage is applied to the test object and the total current through the test object is measured. It is seen from (12) that the conductivity (σ), the high frequency component of the relative permittivity ϵ_∞ and the electric susceptibility $X(\omega)$ characterise the behaviour of the dielectric material under time harmonic excitation. If the dielectric material is linear, homogeneous and isotropic, the measured information in time or frequency domain is the same. The frequency dependent ratio of imaginary and real parts of the complex permittivity is called the dissipation factor ($\tan\delta$) and this is independent of the geometry. This makes dissipation factor one of the important parameters to study when the geometry of the test object is not known.

$$\epsilon_r(\omega) = \epsilon_r'(\omega) - i\epsilon_r''(\omega) = \epsilon_\infty + X_s'(\omega) - iX_s''(\omega) - i\frac{\sigma}{\epsilon_0\omega}$$

$$\epsilon_r'(\omega) = \epsilon_\infty + X_s'(\omega)$$

$$\epsilon_r''(\omega) = X_s''(\omega) + \frac{\sigma}{\epsilon_0\omega}$$

$$\tan\delta = \frac{\epsilon_r''(\omega)}{\epsilon_r'(\omega)} \quad (12)$$

Gafvert et al. [7] presented dielectric spectroscopy in time and frequency domain for a number of power transformers from a nuclear power station. The authors used low frequency dielectric spectroscopy, polarisation/depolarisation current and return voltage spectra measurements. Significant differences in RV results are detected by change in oil quality and moisture content of solid insulation. The authors while comparing the time-domain versus frequency-domain diagnostic methods suggest that low frequency dielectric spectroscopy (measurement of capacitance and $\tan\delta$ in the frequency range 0.1 mHz to 1 kHz) is the best measurement method for fieldwork. Their findings suggest that the RVM method is useful but more sensitive to systematic errors than the other two methods. RVM is a high impedance input method, and hence leakage current on the bushings can easily corrupt the measurement. Boluis et al. [77] reported that $\tan\delta$ describes the spectrum of energy absorption by the dielectric. An ageing of the cellulose insulation has an influence on its polarisation properties, which can be detected by an examination of $\tan\delta$ versus frequency characteristics. Helgeson et al. [78] reported that in the lower frequency range, low frequency dispersion can sometimes be mistaken for conductivity if not measured at sufficiently low frequencies. They reported that frequency domain measurement is a narrow band measurement and this makes it fairly easy to filter away noise both with analog and digital filters. Kuschel et al. [79] described the coherency between frequency and time domain diagnostics. The authors suggested that for known geometrical information of transformer insulation structure and assuming a linear system good conformity can be achieved between the two techniques. The application of dc stress in time-domain measurement does not produce any partial discharge and

was reported to be not dangerous for oil-paper insulation. On the other hand partial discharge can occur in frequency domain measurements at high voltage level. Ekanayake et al. [80] reported a study of 105 transformers with frequency domain dielectric spectroscopy measurements. Their findings suggest a good agreement between frequency domain dielectric spectroscopy measurements with other chemical and electrical analyses.

CIGRE Task Force 15.01.09 recently published an important report [81] on dielectric response methods for diagnostics of power transformers. They highlight the importance and problems in the interpretation of results from return voltage, polarisation/depolarisation current and frequency domain spectroscopy measurements. They suggest that all the dielectric response methods reflect the same fundamental polarisation phenomena in transformer insulation, the special feature of which is a combination of oil gaps and solid paper/pressboard insulation. They also suggest that the influence of oil gap, i.e. the condition of the oil (in particular oil conductivity) has a significant impact on dielectric response and this must be taken into consideration while attempting to interpret the moisture content of solid insulation. Geometry of the insulation structure also has an influence on the response but not as significant as the effect of oil conductivity.

4 CONCLUSIONS AND DISCUSSIONS

An attempt has been made in this paper to review modern chemical and electrical diagnostic methods. Firstly traditional chemical methods have been discussed with currently available interpretation schemes. Among chemical methods DGA is the most widely used method for investigating incipient faults. A number of interpretation techniques are available to analyse fault types. IEEE and IEC have appropriate Standards for the interpretation schemes. The next widely used method for analysing cellulose ageing is furan measurements by the HPLC technique. Although no standard is available for the interpretation of ageing phenomena, some good literature is available on the technique. DP measurement has been widely used for monitoring cellulose mechanical strength. The cellulose ageing phenomena and its relation to DP are reasonably well understood. Most of the currently used techniques have some drawbacks as well. When transformer oil is replaced or refurbished, the analysis of gases and furans in the refurbished oil may not show any trace of degradation although the cellulose may have degraded significantly. DP estimation is not possible without collecting cellulose samples from the operating transformers. A number of new chemical diagnostic techniques are also presented in this paper and their usefulness is highlighted.

Secondly a critical analysis has also been made on the methods of interpretation of polarisation measurements. A group of papers suggest that RV parameters, in particular central time constant is independent of transformer geometry and is little affected by oil quality. Another group of researchers explained the RV measurements with the help of dielectric theory and polarisation principles. Their findings suggest that RV parameters are strongly influenced by the geometry of transformer insulation and quality of both paper and oil. They have thoroughly investigated the impacts of oil and paper quality separately and put forward a modelling approach to understand this complex behaviour. A number of researchers also proposed polarisation/depolarisation current measurement as the superior tool because this can monitor oil and paper conditions separately. A third group used frequency domain polarisation measurements and their findings suggest that time domain and frequency domain measurements predict the same condition of insulation. We have investigated the impacts of oxidation and thermal ageing phenomena thoroughly by polarisation measurements. Our experience suggests that separation of ageing and moisture impacts on the RV parameters is the most important problem, which is yet to be solved. A number of attempts have been made by the author of this paper to solve this problem and this research is still ongoing.

No single method can be considered as the best diagnostic method. DGA and furan analysis will remain most useful method for practical applications. However, advancement in measurement technologies and data analysis techniques with better computation methods makes the polarisation based electrical diagnostics more attractive. Polarisation methods are now better understood. It is now believed that if polarisation measurements are performed correctly and proper interpretation scheme is used these new methods could be very useful for diagnosis purpose.

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