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Insulation Condition Assessment of Power Transformers Using Accelerated Ageing Tests

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Abstract

Thermal stress due to losses and environment temperature causes degradation to paper/oil insulation systems in transformers, even at operating temperature. Experience indicates that thermal ageing of oil and paper in power transformers leads to the change of some insulation characteristics.

In this paper, insulating papers immersed in oil have been acceleratory aged at 140, 150, and 160 °C under laboratory conditions. Some of the oil properties, such as water content, breakdown voltage, acidity, together with the aged insulating paper properties such as electric strength, dielectric dissipation factor and tensile strength were measured and analyzed. Also, insulation system conditions under thermal stress have been evaluated by electrical/distinctive techniques like recovery voltage, polarization and depolarization currents. Correlations between these parameters have been investigated. Finally, paper tensile strength has been used as a criterion to estimation of insulating paper life time.

Key Words: Transformer, insulation assessment, monitoring, polarization, recovery voltage.

1. Introduction

Transformers are one of the most expensive and strategically important components of any power system, so that their proper and continuous function is important to system reliability. Ageing of the oil/paper insulation system of power transformers is influenced by thermal, electromechanical and chemical stresses. Thermal stress leads to major degradation process for both oil and cellulose paper. Under all these stresses, the paper ultimately becomes brittle and the durability against mechanical stress is strongly reduced. As a result, reduction in expected life of transformer will occur [1–3].

One of the needs in power transformer lifetime management is insulation condition assessment. A variety of electrical, mechanical and chemical techniques are currently available for insulation testing of power trans-

formers. Ageing of oil is monitored by measuring properties of oil such as permittivity, dielectric dissipation factor, breakdown strength, acidity, water content, flash point, interfacial tension, etc. The analysis of gases dissolved in the oil has been used as a diagnostic tool for many years to determine the transformer condition. Criteria are based on experience from failed transformers, transformers with incipient faults, laboratory simulation and statistical studies. The ageing process of paper can be monitored by measuring many properties such as mechanical properties (tensile strength), degree of polymerization (DP), furan content in oil, etc. Degree of polymerization has been related to the paper tensile strength. A new insulating paper has DP value of about 1000–1200, but falls to about 250 when the tensile strength reaches about half its original strength [4]. Therefore determining transformer's insulation condition would be of tremendous important.

Modern electrical testing techniques include frequency domain measurements of dissipation factor, complex capacitance and permittivity of the transformer insulation. In addition, time domain dielectric response measurement technique like return voltage measurement (RVM) and the polarization and depolarization current (PDC) measurements have gained immense popularity as supplements to existing insulation assessment techniques. These dielectric response measurement techniques, in addition to being simple to perform, can provide adequate relevant information about the condition of oil/paper insulation in a transformer [5, 6].

Past investigations have shown transformer life is actually the life of the insulating paper. The authors of [7] carried out long-duration ageing experiments, measuring different parameters such as dissolved gas and furfural content in oil and the degree to which the paper underwent polymerization (DP). They showed that only a few parameters have a good correlation with DP. They also assessed the elapsed life of insulation paper, studying it under accelerated thermal stress. A similar investigation is reported in [8]. In [1, 9], several electrical and chemical properties of paper immersed in oil (such as gel permeation chromatography, dielectric dissipation factor, voltage strength, lightning voltage strength, etc. for aged paper) were studied using short time accelerated thermal ageing experiments from which possible correlations were investigated among measured parameters. In [2], the influences of air and oil type on aging of pressboard have been studied under the influence of a considerable amount of moisture. Also investigated was the DP rate, the development of furanic compounds, as well as gas-in-oil analysis in comparison with the aging of the pure oil under identical conditions. In [10], mathematical models have been presented for formed and dissolved water estimation in oil by using of transmitted water between oil and paper in power transformers. Polarization and depolarization currents on transformers have been measured in [11]. It shows that the peak of recovery voltage changes with charging voltage but does not effect time-to-peak. Also the curve has been extrapolated with the function of polarization and depolarization currents variations.

In [12], a circuit model is described which describes and parameterizes the dielectric behaviour of the transformer's main insulation system. There, the model parameters had been identified from the dielectric measurements before and after treatment. In addition, a correlation has been developed between the physical condition of the insulation and the equivalent model parameters.

In [13], the polarization process has been described with appropriate dielectric response theories; and commonly used polarization methods have been explained with emphasis on return voltage measurements. It showed that increasing in polarization current is related to increase in paper water content. Maximum recovery voltage, in terms of charging time and current slope on power transformers, has been demonstrated in [5].

In this work, we present results of an investigation into the thermal degradation of oil/paper insulation system in copper via a series of accelerated ageing experiments carried out over the temperature range 140–

160 °C. Recovery voltage, polarization and depolarization currents tests are carried out on aged insulation systems at regular periods. Insulating paper properties such as dielectric dissipation factor, voltage strength and tensile strength as well as water content, breakdown voltage and acidity of the insulating oil are measured and the results are discussed and analyzed. Possible relations between observations have been studied.

2. Polarization and Recovery Voltage

Application of DC voltage is to pass a polarized current, which can be used to polarize an insulation system. On short-circuiting the voltage source, the resulting current becomes the *depolarization current*, and the insulation returns to the original, neutral condition. However, a residual polarization may remain when the short circuit is removed and depends on factors such as charging time, short circuit time, charging voltage level, insulation temperature, and design of the test object. The residual polarization results in a voltage, referred to as *recovery voltage* or *return voltage*. Hence the application of a DC charge can be used to characterize the influence of material properties, such as conductivity, on the dielectric response. This method is used to evaluate the moisture content of cellulose in power transformers.

2.1. Polarisation and Depolarization Currents

Assuming a homogeneous electric field $E(t)$ is applied to the dielectric material, the current density through the surface of the material can be written as

$$J(t) = \sigma \cdot E(t) + \frac{d}{dt}D(t). \quad (1)$$

The current density $J(t)$ is the sum of the conduction and displacement currents; σ is the dc conductivity; and $D(t)$ is the electric displacement:

$$D(t) = \varepsilon_r \varepsilon_o E(t) + P(t). \quad (2)$$

Substitution of equation 1 into equation 2 brings

$$J(t) = \sigma \cdot E(t) + \varepsilon_r \varepsilon_o \frac{\partial E(t)}{\partial t} + \frac{\partial P(t)}{\partial t}. \quad (3)$$

In above relations, ε_o is vacuum permittivity and ε_r is the relative permittivity of the insulation at power frequency (typically, $\varepsilon_r = 4.5$ for cellulose paper/pressboard, and $\varepsilon_r = 2.2$ for transformer oil). $P(t)$ is the dielectric polarization and is related to the response function $f(t)$ of the material by the relation

$$P(t) = \varepsilon_o \int_0^\infty f(t - \tau) E(\tau) d\tau. \quad (4)$$

The response function $f(t)$ describes the fundamental memory property of the dielectric system and can provide significant information about the insulating material. The function $f(t)$ can be determined experimentally as the response of the dielectric to a step-function charging field [6].

Now, polarization and depolarization currents are measured for investigation of the polarization process in the time domain. Combining above equations can be rewritten as

$$J(t) = \sigma \cdot E(t) + \varepsilon_r \varepsilon_o \frac{dE(t)}{dt} + \varepsilon_o \cdot \frac{d}{dt} \int_0^t f(t - \tau) E(\tau) d\tau. \quad (5)$$

For a homogeneous material the field strength $E(t)$ can be considered as generated by an external voltage $V(t)$. Thus the current through a test object with geometric capacitance C_o (measured capacitance at or near power frequency, divided by ε_r) can be written as

$$i(t) = C_o \left[\frac{\sigma}{\varepsilon_o} V(t) + \varepsilon_r \frac{dV(t)}{dt} + \frac{d}{dt} \int_0^t f(t - \tau) V(\tau) d\tau \right]. \quad (6)$$

The test object can be materials of a single dielectric or an arrangement of several dielectric materials in series or in parallel. Now, assume that the test object is totally discharged and that a step voltage is applied with the following characteristics:

$$V(t) = \begin{cases} 0 & t < 0 \\ V & 0 \leq t \leq t_c \\ 0 & t > t_c. \end{cases} \quad (7)$$

This will give zero current for times before $t = 0$ and DC-polarized current for times $0 \leq t \leq t_c$. The polarization current is built up in two parts. One part is related to the conductivity of the test object and the other is related to the activation of the different polarization processes within the test object.

As illustrated in Figure 1(a), polarization current has been measured by ammeter when switch S_1 is closed and switches S_2 and S_3 are opened. The polarization current through the object can be expressed as

$$i_p = C_o V_o \left[\frac{\sigma}{\varepsilon_o} + f(t) \right]. \quad (8)$$

For times $t > t_c$, the step voltage is replaced by a short circuit (S_1 and S_3 are opened, S_2 is closed), a depolarization current is built up. The magnitude of the depolarization current is

$$i_{dp} = C_o V_o [f(t) - f(t + t_c)]. \quad (9)$$

References [6, 14] have shown that, for oil/cellulose insulation systems, the general response function can be expressed in parametric form:

$$f(t) = \frac{A}{\left(\frac{t}{t_o}\right)^n + \left(\frac{t}{t_o}\right)^m}, \quad (10)$$

where $t_o > 0$, $A > 0$, $m > n > 0$ and $m > 1$.

In order to estimate the dielectric response function $f(t)$ from a depolarization current measurement it is assumed that the dielectric response function is a continuously decreasing function in time; then if the polarization period is sufficiently long, so that $f(t + t_c) \cong 0$, the dielectric response function $f(t)$ is proportional to the depolarization current. Thus one can rewrite equation (9) as

$$f(t) \cong \frac{i_{dp}(t)}{C_o \cdot V_o}. \quad (11)$$

The parameters of $f(t)$ are obtained from a non-linear least-squares fit of the right-hand side of equation 11.

From the measurements of polarization and depolarization currents, it is possible to estimate the dc conductivity σ of the test object. If the test object is charged for a sufficiently long time so that $f(t + t_c) \cong 0$,

equations (8) and (9) can be combined to express the dc conductivity of the composite dielectric:

$$\sigma \cong \frac{\varepsilon_o}{C_o \cdot V_o} (i_p - i_{dp}). \quad (12)$$

2.2. Recovery Voltage

Following the end of discharge, switches S_1 and S_2 are opened and switch S_3 is closed (see Figure 1(a)). The measured voltage is now called the recovery or return voltage. Now, using Leibniz's integral rule,

$$\begin{aligned} \frac{d}{d\alpha} \int_{\varphi_1(\alpha)}^{\varphi_2(\alpha)} F(x, \alpha) dx &= \int_{\varphi_1(\alpha)}^{\varphi_2(\alpha)} \frac{\partial F(x, \alpha)}{\partial \alpha} dx - F(\varphi_1(\alpha), \alpha) \frac{d\varphi_1(\alpha)}{d\alpha} \\ &+ F(\varphi_2(\alpha), \alpha) \frac{d\varphi_2(\alpha)}{d\alpha}, \end{aligned} \quad (13)$$

equation (6) can be simplified and changed into the form

$$i(t) = C_o \left[\frac{\sigma}{\varepsilon_o} V(t) + \varepsilon_r \frac{dV(t)}{dt} + f(0)V(t) + \int_0^t \frac{df(t-\tau)}{dt} V(\tau) d\tau \right] \quad (14)$$

then

$$i(t) = C_o \left[\frac{\sigma}{\varepsilon_o} V(t) + \varepsilon_r \frac{dV(t)}{dt} + f(0)V(t) + \int_0^{t_d} \frac{df(t-\tau)}{dt} V(\tau) dt + \int_{t_d}^t \frac{df(t-\tau)}{dt} V(\tau) d\tau \right]. \quad (15)$$

On the other hand, we know that

$$\begin{aligned} \int_0^{t_d} \frac{df(t-\tau)}{dt} V(\tau) dt &= \\ \int_0^{t_C} \frac{df(t-\tau)}{dt} V(t) dt &= V_o [f(t-t_C) - f(t)]. \end{aligned} \quad (16)$$

According to 15 and 16, when $t > t_d$, recovery voltage is equal to zero (open circuit); that is

$$\begin{aligned} 0 &= \sigma V_r(t) + \varepsilon_r \varepsilon_o \frac{dV_r(t)}{dt} + \varepsilon_o f(0)V_r(t) + \varepsilon_o V_o [f(t-t_C) - f(t)] \\ &+ \varepsilon_o \int_{t_d}^t \frac{df(t-\tau)}{dt} V_r(\tau) d\tau. \end{aligned} \quad (17)$$

The integral of equation 17 at $t_d < t_i < t_{i+1}$ is

$$\begin{aligned} 0 &= \sigma \int_{t_i}^{t_{i+1}} V_r(t) dt + \varepsilon_r \varepsilon_o \int_{t_i}^{t_{i+1}} \frac{dV_r(t)}{dt} dt + \\ &\varepsilon_o f(0) \int_{t_i}^{t_{i+1}} V_r(t) dt + \varepsilon_o V_o \int_{t_i}^{t_{i+1}} [f(t-t_C) - f(t)] dt + \\ &\varepsilon_o \int_{t_i}^{t_{i+1}} \left\{ \int_{t_d}^t \frac{df(t-\tau)}{dt} V_r(\tau) d\tau \right\} dt. \end{aligned} \quad (18)$$

Solving (18) yields the recovery voltage, $V_r(t)$.

In order to measure recovery voltage, a charge via a dc voltage source is applied to the insulation system. The power supply is shorted at half of charging time and the part of the charge is dissipated. Residual charge

then produces a voltage on the insulation system when the insulation is removed from the circuit after discharge. The maximum of recovery voltage directly depends on polarization ability of insulation and its primitive slope to insulation polarization conduction. Waveform of the mentioned cases is shown in Figure 1(b).

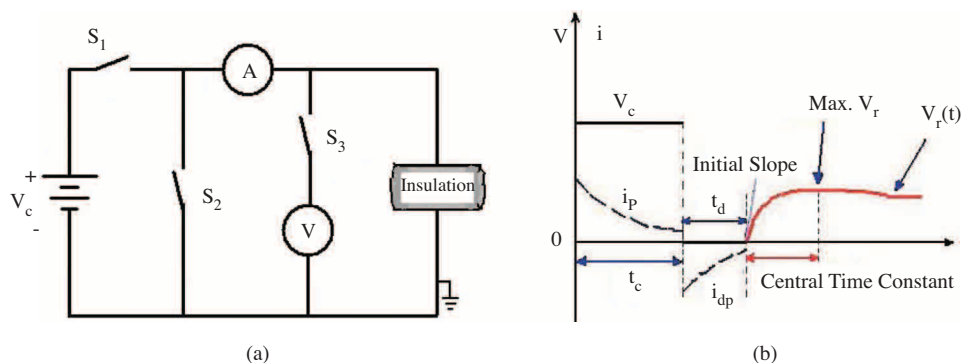


Figure 1. (a) Circuit for polarization current, depolarization current and recovery voltage measurement. (b) Wave form of polarization current, depolarization current and recovery voltage.

3. Accelerated Ageing Tests

To study the influence of thermal stress on oil/cellulose insulation systems in transformers, copper conductors wrapped in paper of 48 μm thicknesses were placed in Pyrex glass dishes in a basket. Insulating paper was stacked between the copper electrodes. Each basket contains two glasses of different length, and a pipe connects the two glasses together. The samples were dried at 1 mbar at 120 $^{\circ}\text{C}$ in oven for 24 hours. Dried and degassed transformer oil (Nynas, class II) was then added to upper glasses placed in every collection so that the conductors in the lower glasses were completely immersed in the oil. In order to extract as much gas and nucleated bubbles from the oil, dry nitrogen was passed through the glasses; following which the glasses were sealed. All baskets containing oil/paper glasses were seated in the oven and were connected to the silica gel container that remained outside the oven. The accelerated ageing experiments were performed at three different temperatures, 140, 150 and 160 $^{\circ}\text{C}$, in oven for various periods of time. Oven temperatures were maintained within ± 2 $^{\circ}\text{C}$ of the desired value. Ageing times are listed in Table 1. After treatment in oven, glass dishes were allowed to cool to room temperature before examination.

4. Results and Discussions

Ageing experiments were conducted on aged oil/paper insulation systems. Length of ageing varied between 72 and 576 hours (3 to 24 days), and by temperature. Temperatures and corresponding ageing times are shown in Table 1.

Table 1. Temperature and length of ageing.

Ageing temperature ($^{\circ}\text{C}$)	Ageing time (hours)
140	192, 384 and 576
150	120, 240 and 360
160	72, 144 and 216

4.1. Measurement of Polarization and Depolarization Currents

PDC measurement tests on aged paper/oil insulation system have been carried out via a two-electrode system. In these tests, polarization and depolarization currents have been measured by dc voltage using charge and discharge times each of 600 s. Figures 2, 3 and 4 shows the variation of polarization and depolarization current as a function of charging time over three different ageing temperatures. It is clear that, between the least and greatest aging times, respectively, there is a definite increase in the difference between polarisation and depolarisation currents which, in turn, is related to total conductivity of the insulation system. With respect to temperature, its increase has caused remarkable difference in polarization and depolarization currents. Figure 4, which shows results for $T = 160^\circ\text{C}$, indicates considerable increase in electrical conduction from lower temperatures, indicating degradation in the insulation resistance. This arises from increasing dissolved water content of the oil. (The water content of oil with ageing time at different temperatures is shown in Figure 7.)

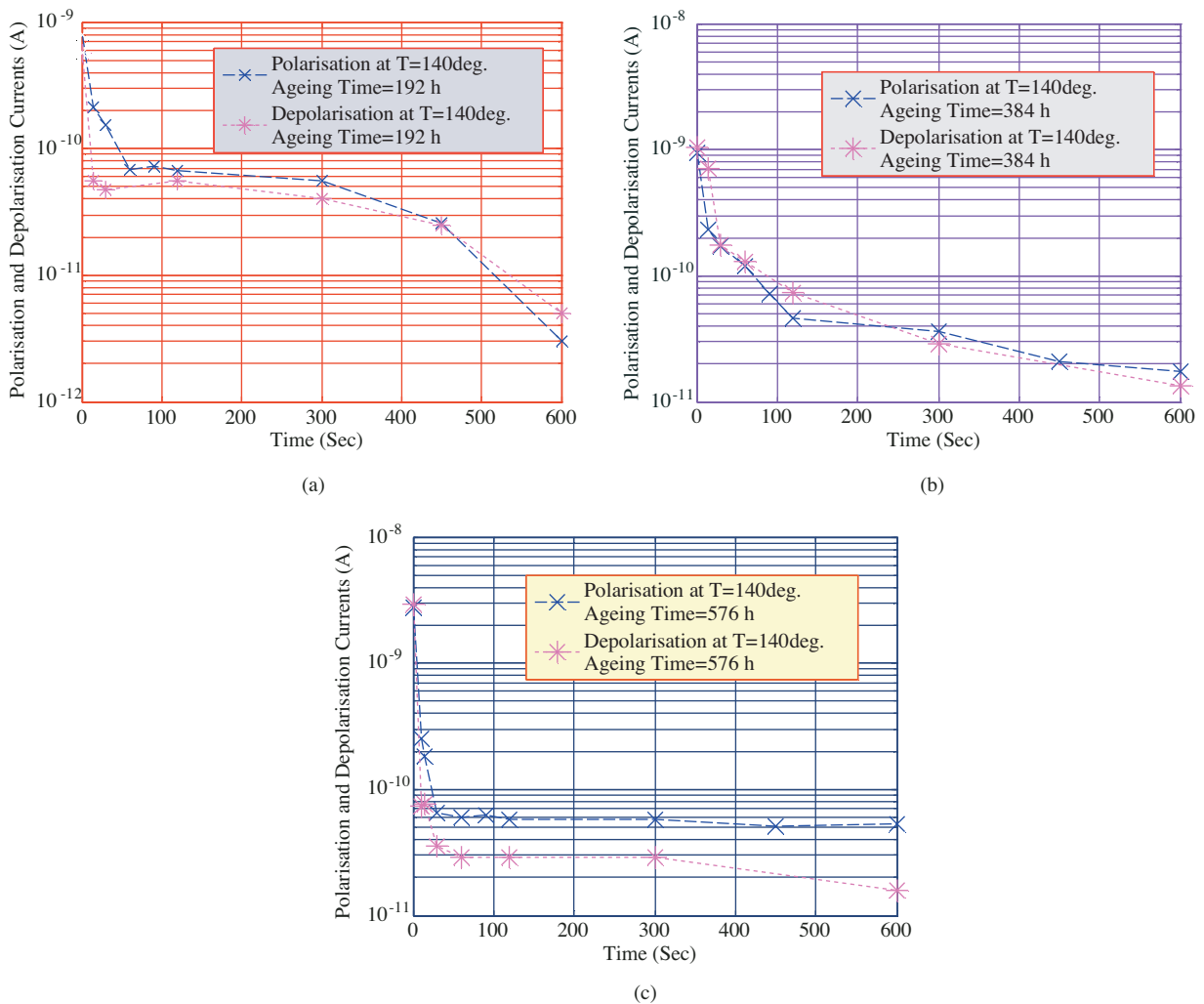


Figure 2. Variation of PDC for aged insulation system vs. time at 140°C (measured at room temperature): (a) After 192 hours; (b) After 384 hours; (c) After 576 hours.

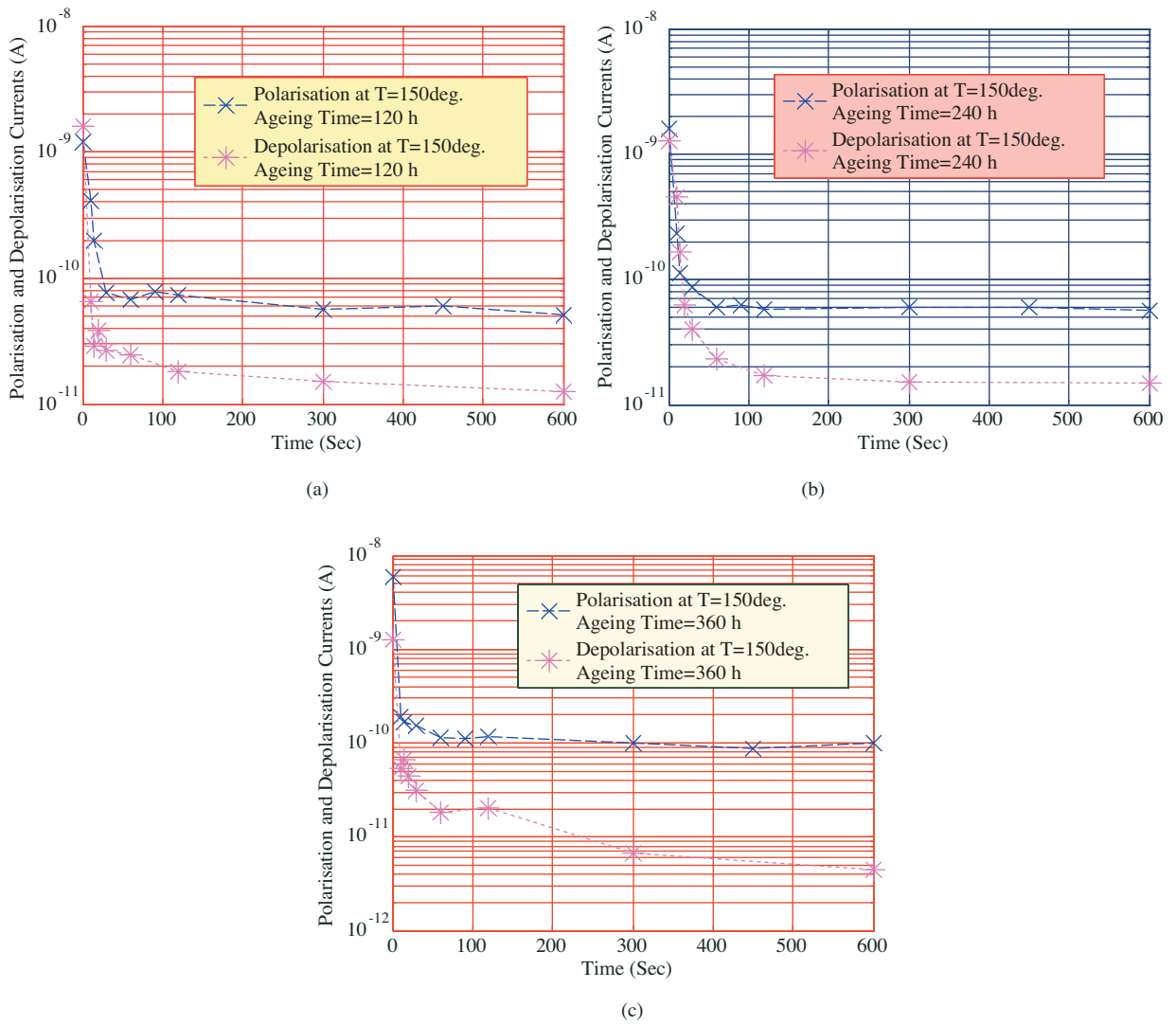


Figure 3. variation of PDC for aged insulation system vs. time at 150 °C (measured at room temperature). (a) After 120 hours; (b) After 240 hours; (c) After 360 hours.

4.2. Recovery Voltage Measurement

In the recovery voltage test, insulation system (paper immersed in oil) has been charged by applying a dc potential for 1200 seconds. It is then discharged at a rate that is half of the charging time, at the end of which the maximum recovery voltage was measured. The ratio of maximum recovery voltage to charging voltage is measured at the three ageing temperatures 140, 150 and 160 °C. Figures 5(a-c) show the variation of Maximum recovery voltage to charging voltage as a function of charging time for charging time over different aged temperatures. Figure 6 shows variation of the ratio of maximum recovery voltage to charging time for different ageing times over three different ageing temperatures. Note the increase in this ratio with ageing time.

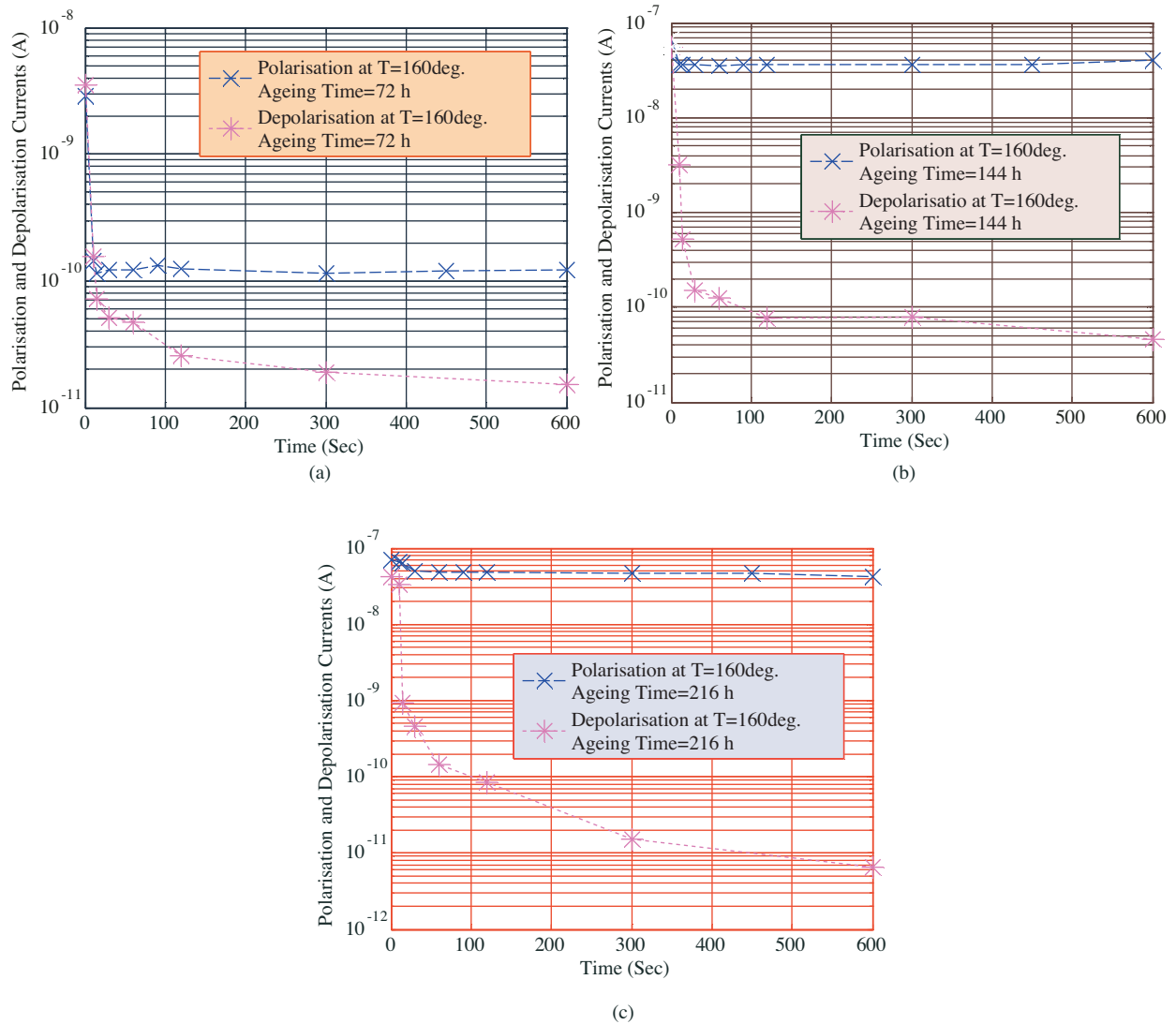


Figure 4. Variation of PDC for aged insulation system vs. time at 160 °C (measured at room temperature). (A) After 72 hours; (B) After 144 hours; (C) After 216 hours.

5. Paper/Oil Insulation Tests

In addition to the above tests, we have also examined the insulation system for water content in oil, oil breakdown voltage, acidity or neutralization number, paper electrical strength, paper dissipation factor, paper tensile strength. Results are detailed in the following sections.

5.1. Water Content in Oil

As the exposure of humidity to oil favours the formation of acids and sludge, water content in oil has been tested via IEC standard 60814. IEC standard limits water content in transformer oil to less 30 ppm. Figure 7

shows the variation of water content as measured in our test systems. In most cases, the water content increased with ageing time. Comparing across the three ageing temperatures, for applicable ageing times, water content was highest in oil aged at 160 °C, and may be due to oil oxidization and rapid thermal degradation of the oil immersed paper system.

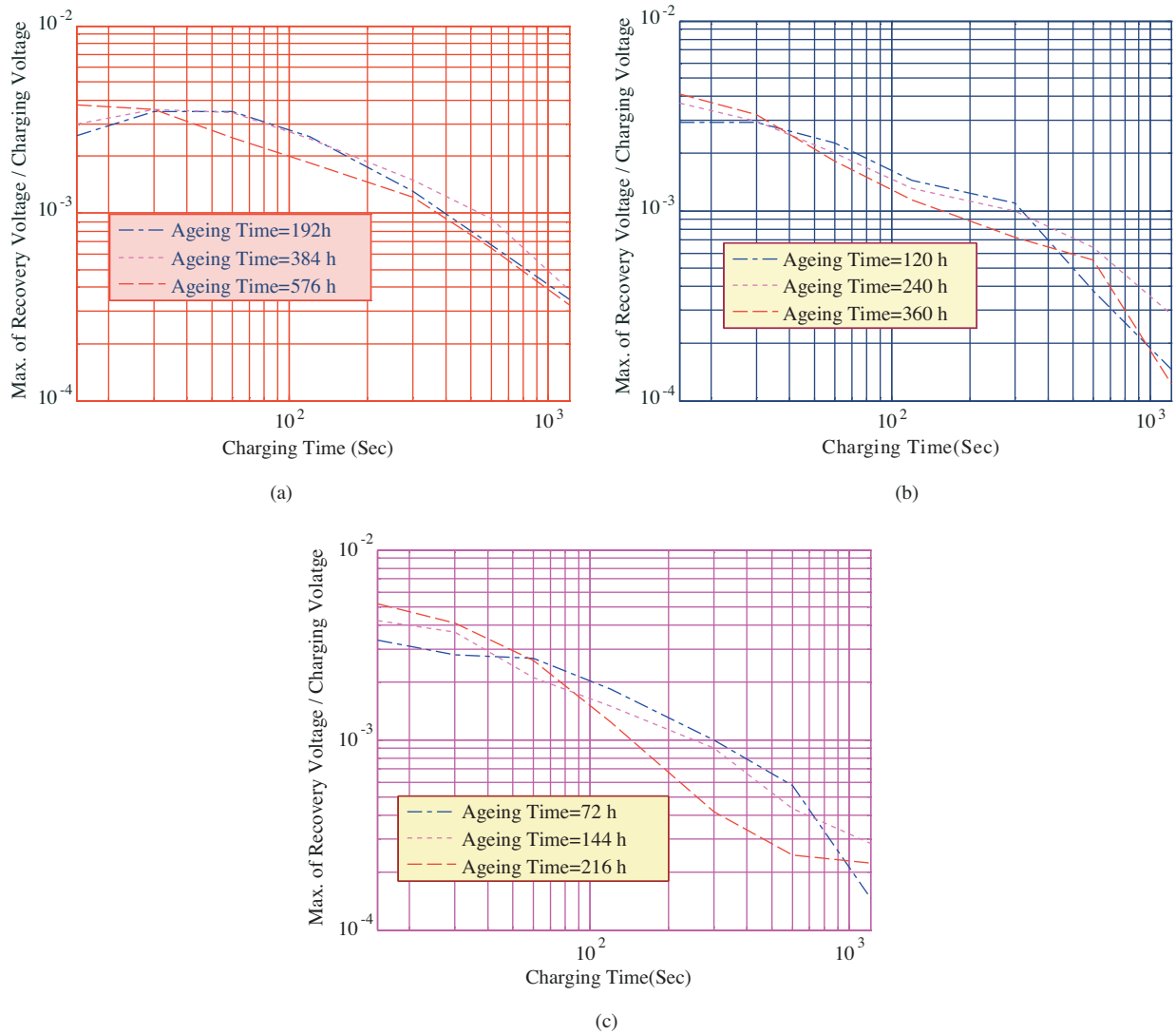


Figure 5. Variation of maximum recovery voltage ratio toward charging voltage vs. charging time: (a) at 140 °C; (b) at 150 °C; and (c) at 160 °C.

5.2. Oil Breakdown Voltage

The breakdown voltage of each aged oil sample has been tested using the IEC60156 standard. Figure 8 shows the variation of oil breakdown voltage for different ageing times over three different temperatures. From this figure it can be seen that the breakdown voltage of aged oil starts with a high value, then decreases with time. Increasing temperature also reduces breakdown voltage. Breakdown voltage drops from 77 kV to 45–30 kV,

varying with ageing time temperature and is due to the oxidation and chemical defects of the oil, as well as increasing suspended fibre particles in oil caused by paper degradation. It is interesting to note that, considering also the relationships shown in Figure 7, one can see increasing water content of oil can affect oil breakdown voltage. That is to say, water, dirt and conducting particles cause the oil to breakdown below acceptable levels.

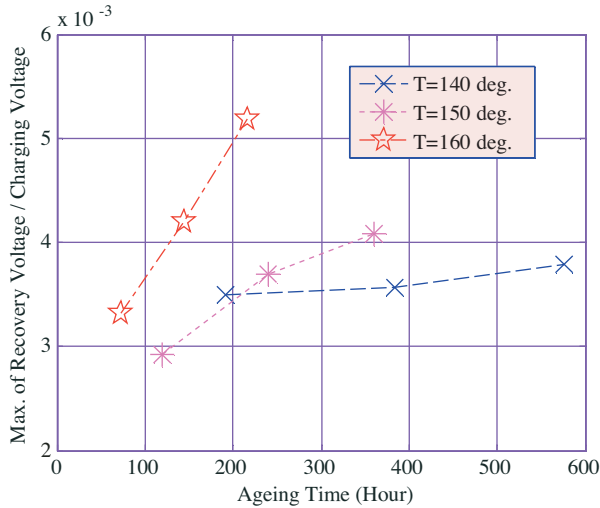


Figure 6. Variation of maximum recovery voltage ratio toward charging voltage vs. time and ageing temperatures.

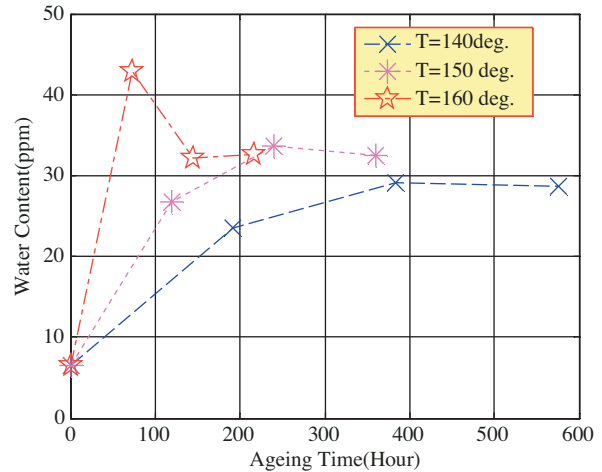


Figure 7. Variation of water content of oil with ageing time at different temperatures.

5.3. Acidity or Neutralization Number

Acidity is examined according to IEC standard 62021-1. In a transformer, acids are formed as oils oxidize over age and service. New oil specification is 0.03 mg KOH/g or less in oil. Figure 9 shows the variation of acidity number for different ageing times over the three different ageing temperatures. The acidity number varies from 0.005 to 0.048. At all temperatures the variation of acidity number increases with ageing time. The acid number

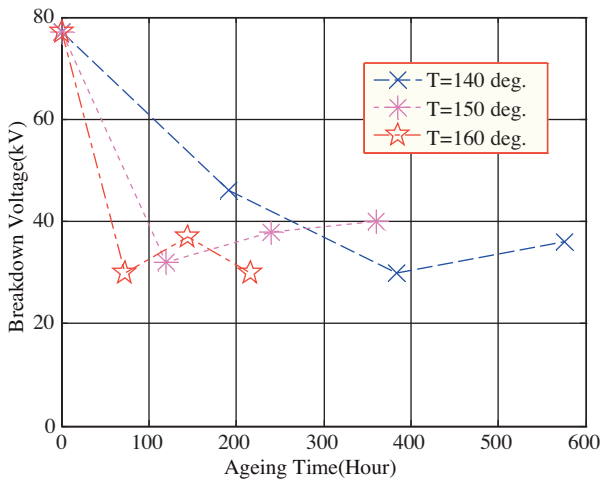


Figure 8. Variation of breakdown voltage of oil with ageing time at different temperatures.

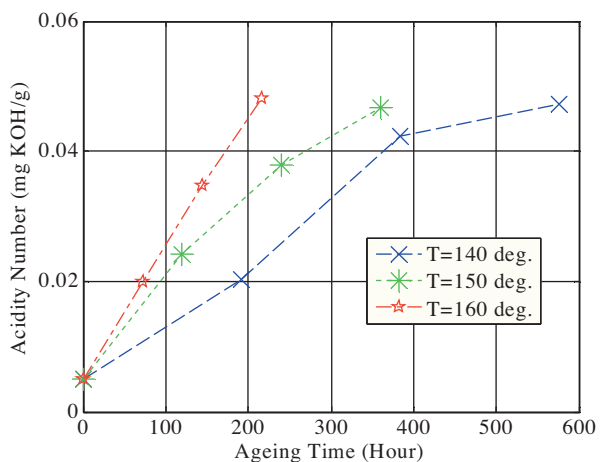


Figure 9. Variation of acidity number of oil with ageing time at different temperatures.

of an oil sample is indicative of age, deterioration and oxidation of the oil and can be used to determine when the oil must be changed.

5.4. Paper Electrical Strength

Electrical strength of aged paper has been measured (via the IEC-60554 standard) at 50 Hz and voltage slew rate of 100 v/s. Figure 10 shows the variation of aged paper electrical strength at 50 Hz for different ageing times over three different temperatures. According to this figure, paper strength voltage has alternated from 10 to 11.8 kV/mm.

5.5. Paper Dissipation Factor

Dissipation factor of each aged paper sample has been tested via the IEC-60554 standard. In this test, the pressure and applied voltage between two electrodes is 2×10^4 Pa and 25 V, respectively. Figure 11 shows the variation of dissipation factor for different ageing times over the three different ageing temperatures. The result shows that thermal stress does not cause increase in paper dielectric dissipation factor.

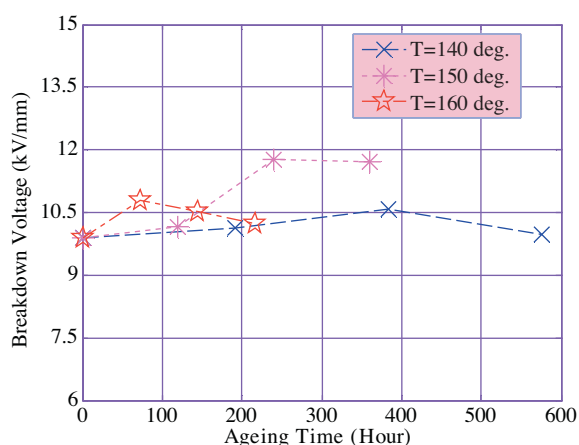


Figure 10. Variation of electrical strength of paper insulation with ageing time at different temperatures.

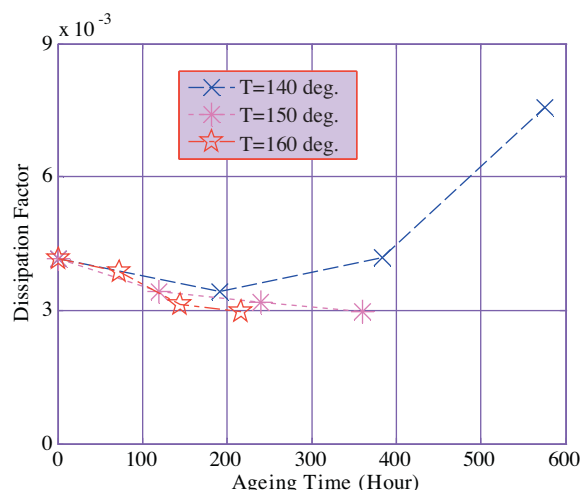


Figure 11. Variation of dielectric dissipation factor of paper insulation with ageing time at different temperatures.

5.6. Paper Tensile Strength

The tensile strength of paper insulation is measured according to the standard IEC-60544. In this test, aged paper is cut in size to dimensions 15×250 mm and tested at deformation rate 60 mm/min. Figure 12 shows that mechanical strength decreases directly with increasing ageing time. Our tests show that decrease in the mechanical strength of the insulation paper causes the increase in the maximum recovery voltage which, in turn, is related to increase in the water content of the oil. The correlations of recovery voltage, water content and acidity number with tensile strength of paper insulation is shown in Figures 13(a–c) and are very significant. These results are consistent with that obtained from aged power transformer samples.

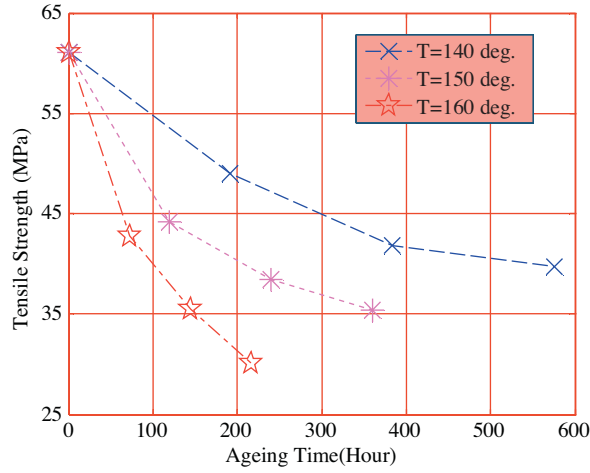


Figure 12. Variation of tensile strength of paper insulation with ageing time at different temperatures.

6. Prediction of Paper Insulation Life Time

Thus the above tests on insulation paper show tensile strength depend not only on ageing time of oil but also on ageing temperatures. With these and those results for tensile strength we now form a model to predict how the insulating paper degrades with time at normal operating temperatures of transformers.

In this paper, tensile strength has been used as the index for degradation of paper. Hence, we index lifetime for the various ageing temperatures to the point at which tensile strength reaches half its initial strength [15].

When temperature is used as the single stress covariate, the Arrhenius model can be an appropriate model. The Arrhenius reaction rate equation is given by

$$r = A \cdot \exp\left(\frac{-E_a}{k_B T}\right). \quad (19)$$

Now assuming that the life of a product is proportional to the inverse of the rate of reaction, the Arrhenius life relation is given by

$$L(T) = B \cdot \exp\left(\frac{E_a}{k_B T}\right) \quad (20)$$

In relations (19) and (20), E_a , k_B , and T are activation energy, Boltzmann's constant and absolute temperature. Also, A and B are constant factors.

The variation in logarithm of lifetime with the reciprocal temperature is shown in Figure 14, from which the activation energy for thermal degradation of the paper calculated from this Arrhenius analysis found to be 1.1096 eV.

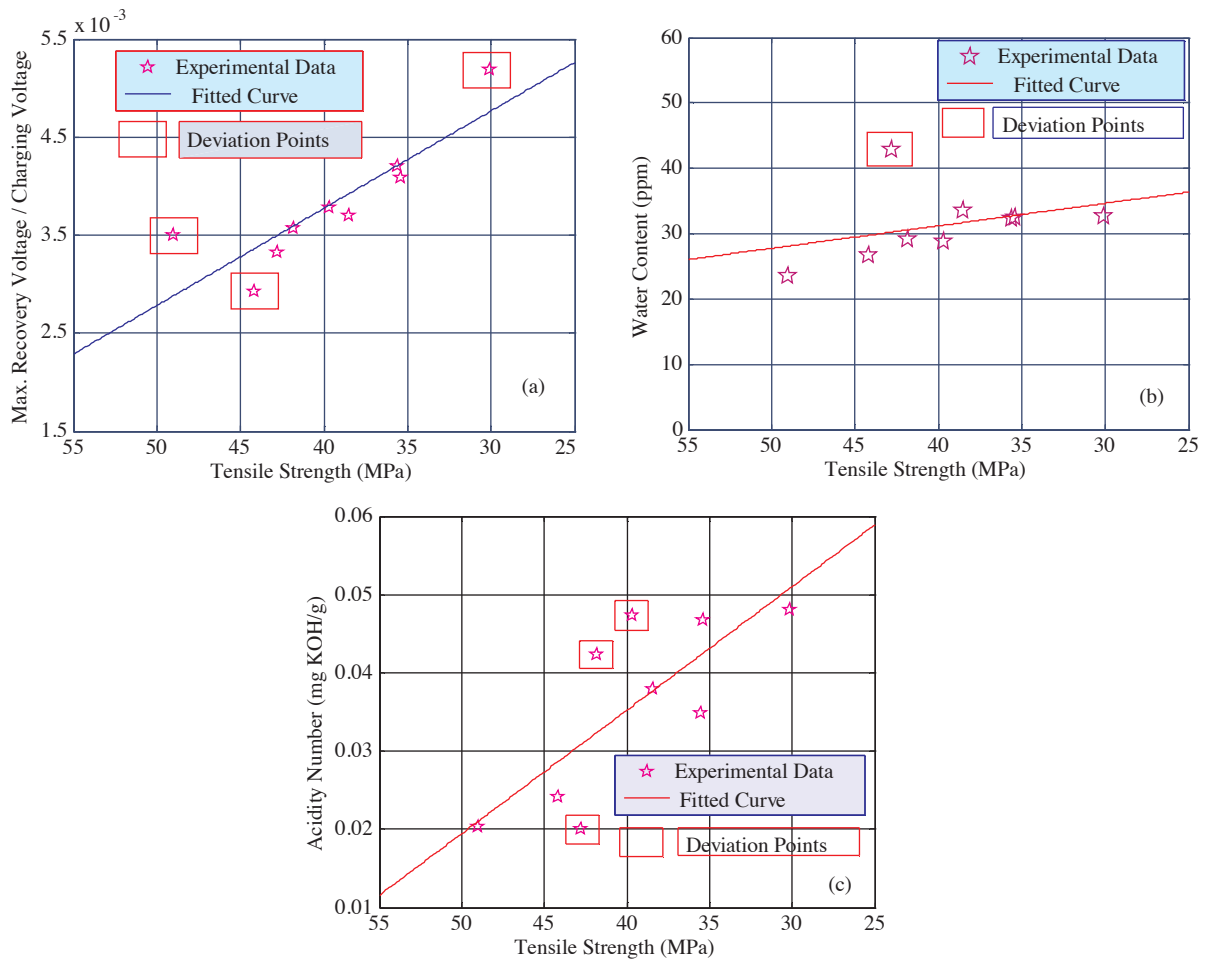


Figure 13. (a) Recovery voltage of insulation system versus tensile strength of paper insulation. (b) Water content of oil versus tensile strength of paper insulation. (c) Acidity number of oil versus tensile strength of paper insulation.

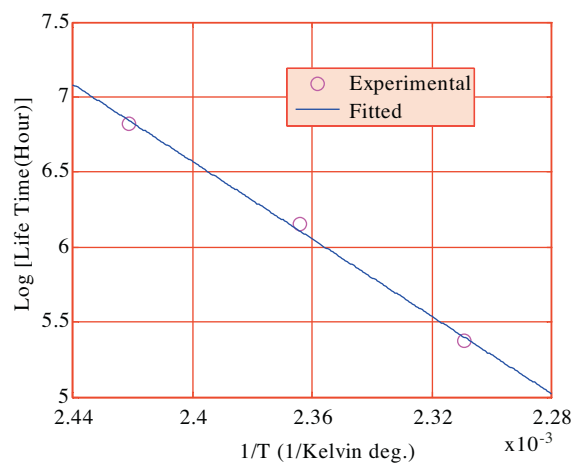


Figure 14. The plot of log of reaction rate versus the reciprocal of temperature.

7. Conclusions

A series of accelerated ageing experiments has been investigated for oil/paper cellulose insulation system used in transformers. Polarization and depolarization currents and recovery voltage of aged cellulose immersed in oil were measured. The aim of tests was condition assessment of insulation system. The main properties of oil and paper were studied. Electrical measurements show that both polarization and depolarization currents are strongly influenced by ageing time and water content of oil and paper. The results have shown that maximum recovery voltage of oil/paper insulation system and tensile strength of paper insulation in power transformers vary significantly and consistently with respect to ageing time and ageing temperatures.

Good correlations have been obtained between the tensile strength of insulating paper with recovery voltage of insulation system, total acid number (TAN), and water content in oil. The tensile strength results have been used to predict how lifetime of insulating paper changes with temperature and time. Therefore lifetime of paper has been estimated by using Arrhenius model. It can predict the life of paper for power transformers at various operational temperatures.

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