

Article

Effectiveness Analysis and Temperature Effect Mechanism on Chemical and Electrical-Based Transformer Insulation Diagnostic Parameters Obtained from PDC Data

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Abstract: The dielectric monitoring/diagnostic tool, such as Polarization and Depolarization Current (PDC) measurement, is now being widely applied to obtain the status of deteriorated transformers around the world. Nowadays, several works have reported that the chemical and electrical-based transformer insulation diagnostic parameters (absorption ratio, polarization index, paper conductivity, oil conductivity, insulation resistance, etc.) can be easily calculated from the PDC data. It is a fact that before using these parameters to obtain the status of deteriorated transformers, the power engineers should prudently investigate the effectiveness of these parameters. However, there are few papers that investigate the important issue. In addition, the understanding of temperature effect mechanism on these parameters should also be prudently studied. In the present work, we firstly prepare several oil-impregnated pressboard specimens with various insulation statuses by using a sequence of thermal ageing and moisture absorption experiments launched in the laboratory, and then the PDC measurement is performed to obtain the chemical and electrical-based transformer insulation diagnostic parameters. Finally, we systematically interpret the effectiveness and temperature effect mechanism on these chemical and electrical-based transformer insulation diagnostic parameters.

Keywords: dielectric monitoring/diagnostic tool; polarization and depolarization current (PDC); transformer; chemical and electrical-based transformer insulation diagnostic parameters; effectiveness; temperature effect mechanism

1. Introduction

Power transformers, generally speaking, can be regarded as a ‘heart’ in electric power transmission and transformation area around the world [1]. It is believed that many of installed transformers are close to the end-stage of their design life [2]. In current economic condition, replacing them with new transformers (only attributed to their ageing/degradation) are unreasonable due to some of these may be still in a healthy status [3–5]. In addition, the unexpected power outage due to the ageing/degradation of transformer insulation can lead to huge financial loss to the utility all over the world, such as hospital, transportation, and factory, etc. [6]. Therefore, in order to extend the

service life of transformers to the maximum extent, it would be interesting for power utilities to know the insulation condition in oil-filled transformers. Presently, many early papers have widely reported that the life of the cellulosic insulation materials can determine the remaining life of a transformer [7,8]. Hence, it is of great significance for power utilities, by virtue of suitable diagnostic techniques, to reliably and timely obtain the status of transformer cellulose insulation. Historically, the dissolved gas analysis (DGA) [9] and the chemical and electrical-based transformer insulation diagnostic parameters such as oil conductivity (OC), paper conductivity (PC), insulation resistance (IR), polarization index (*P.I.*), and absorption ratio (AR) have been generally utilised for status diagnosis of transformer insulation [2,10,11]. Unfortunately, obtaining these condition monitoring/diagnosis parameters, in practice, may cost lots of manpower and time consumption, and therefore it is becoming a hot research issue about how to effectively solve this technological problem. Over last several decades, the increasing requirements to nondestructively and reliably acquire the insulation status in transformers using advanced tools have immensely promoted the development of dielectric response diagnostic techniques, such as Return Voltage Measurement (RVM) [12,13], Polarization and Depolarization Current (PDC) [14–16], and Frequency Domain Spectroscopy (FDS) [17–19]. Among these dielectric response diagnosis tools, the PDC technique is gaining exceptional significance to the utility professionals due to that it can provide sufficient insulation information about the ageing degree and water content level on transformer insulation system.

So far, several works have reported that the chemical and electrical-based transformer insulation diagnostic parameters (absorption ratio, polarization index, paper conductivity, oil conductivity, insulation resistance, etc.) can be obtained from the PDC data [5,11,16,20,21]. This is a great contribution for reducing the manpower and time cost. However, it is a fact that before using these parameters to obtain the status of deteriorated transformers, the power engineers should prudently investigate the effectiveness of these parameters. Unfortunately, there are few works that investigated this issue. In addition, the temperature is an important factor, which should be taken into consideration due to the fact that PDC data are severely temperature dependent [5,14]. It is believed that the mean annual temperature could be as high as 40 °C (even higher in some countries) with only few winter weeks in hot countries. While, in the cold countries, the mean annual temperature could be as low as 0 °C (even lower in some countries) [5]. These extreme temperatures can result in a mass process of migration, distribution, and equilibrium of moisture/conductive pollutant between dielectric oil and cellulose paper/pressboard [5,15], and these behaviors, therefore, can affect these parameters. Furthermore, the temperature effect mechanism is rather complicated. Thus, it is necessary to systematically study the temperature effect mechanism on chemical and electrical-based transformer insulation diagnostic parameters.

This paper reports the understanding and interpretation of the effectiveness and temperature effect mechanism on chemical and electrical-based transformer insulation diagnostic parameters that were obtained from PDC data. In the present work, we firstly prepare several oil-impregnated pressboards with various insulation statuses using a series of thermal ageing and moisture absorption experiments launched in laboratory conditions, and then perform the PDC measurement to obtain the chemical and electrical transformer insulation diagnostic parameters. Finally, the effectiveness and temperature effect mechanism on chemical and electrical-based transformer insulation diagnostic parameters are systematically studied.

2. Experimental Specimens and PDC Measurement Platform [4,11]

The cellulose pressboard disc specimens, which are shown in Figure 1, are provided by Chongqing Aea Group Transformer Co., Ltd. (Chongqing, China). The thickness and diameter of these pressboard disc specimens are 2 mm and 160 mm, respectively.



Figure 1. Cellulose pressboard disc specimens used in our experiments.

The transformer oil used in our experiments is the Karamay No. 25 naphthenic mineral oil, which is provided by Chongqing Chuanrun Petroleum Chemical Co., Ltd. (Chongqing, China). These mineral oil specimens can satisfy the standard of ASTM D3487-2000(II).

2.1. Preparation of Experimental Specimens

To acquire the oil-impregnated pressboard specimens with various insulation statuses, a vacuum chamber is firstly used for drying the new cellulose pressboard specimens, which is shown in Figure 2, at 105 °C/50 Pa for 48 h. In drying process, the weights of pressboard specimen are strictly monitored using a high precision electronic balance for determining whether these pressboard specimens can satisfy the experiment requirement or not. Secondly, the dried and degassed insulation oil is heated to 40 °C/50 Pa. After that, a sealed vacuum chamber is used for the oil impregnation activities of these dried pressboard specimens for 48 h at 40 °C/50 Pa. Then, several oil-impregnated pressboard specimens are randomly sampled to obtain the moisture level by using the known Coulometric Karl Fischer Titration techniques in terms of IEC 60814 and the initial moisture content of unaged pressboard specimens is equal to 1.11%. Finally, the experimental pressboard specimens are acquired with four insulation statuses (ageing 0 day and water content 4.02%, ageing 8 days and water content 2.82%, ageing 21 days and water content 3.71%, ageing 42 days and water content 1.17%). Moreover, the degree of polymerization (DP) of cellulose pressboard specimen is measured according to IEC 60450 for representing the degradation status of new and degraded cellulose pressboard specimens.



Figure 2. Vacuum oil impregnation tank.

2.2. PDC Measurement Platform (Three Electrode Test Cell and DIRANA Using the PDC Measurement)

A sealed three electrode test cell embedded in transformer oil is shown in Figure 3. These experimental cellulose pressboard specimens are placed in the sealed three electrode test cell. This instrument includes a voltage electrode, a measuring electrode, and a guard electrode. The voltage electrode disc and measuring electrode disc adopt the cylinder structure with the diameters of 141 mm and 113 mm, respectively. The voltage electrode disc is connected to an additional weight (a copper plate) to ensure the close contact between cellulose pressboard specimen and the electrodes. In addition, to ensure the good repeatability in each test, the air bubbles between the electrode and the pressboard are removed using the specialized bleeder hole. The PDC measurements on oil-impregnated pressboard specimens are measured by DIRANA (Chinese version, OMICRON, Electronics GmbH, Klaus, Austria), which is shown in Figure 4.

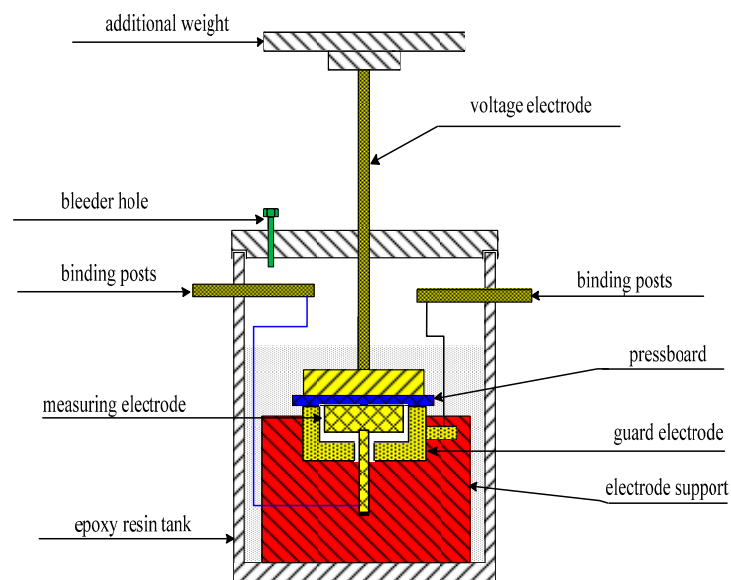


Figure 3. Schematic diagram of three-electrode test cell.



Figure 4. DIRANA.

3. Measurement Results of Polarization and Depolarization Current (PDC)

3.1. Polarization Current

It is a fact that the insulation temperature in transformer tank gradually decreases after de-energizing the transformer, and the PDC measurement is usually performed during the process of decreasing insulation temperature. Therefore, in order to stimulate this general process, we launch the PDC measurement under a condition of decreasing insulation temperature. The measurement results of polarization current on experimental pressboard specimens with four insulation statuses, at four different insulation temperatures (90, 75, 60, and 45 °C), are provided in Figure 5, in a log-log scale. It can be seen that the magnitudes of polarization current decrease with decreasing insulation temperature. Moreover, the ‘inflection point’ of polarization currents will occur with an insulation temperature decrease. Similar results are observed in the literatures [21,22]. This inflection point phenomenon seems to be related to the relaxation time constant with temperature dependant. It is interesting to note that the inflection point of polarization currents will migrate from smaller measurement time point to larger measurement time point with insulation temperature decrease.

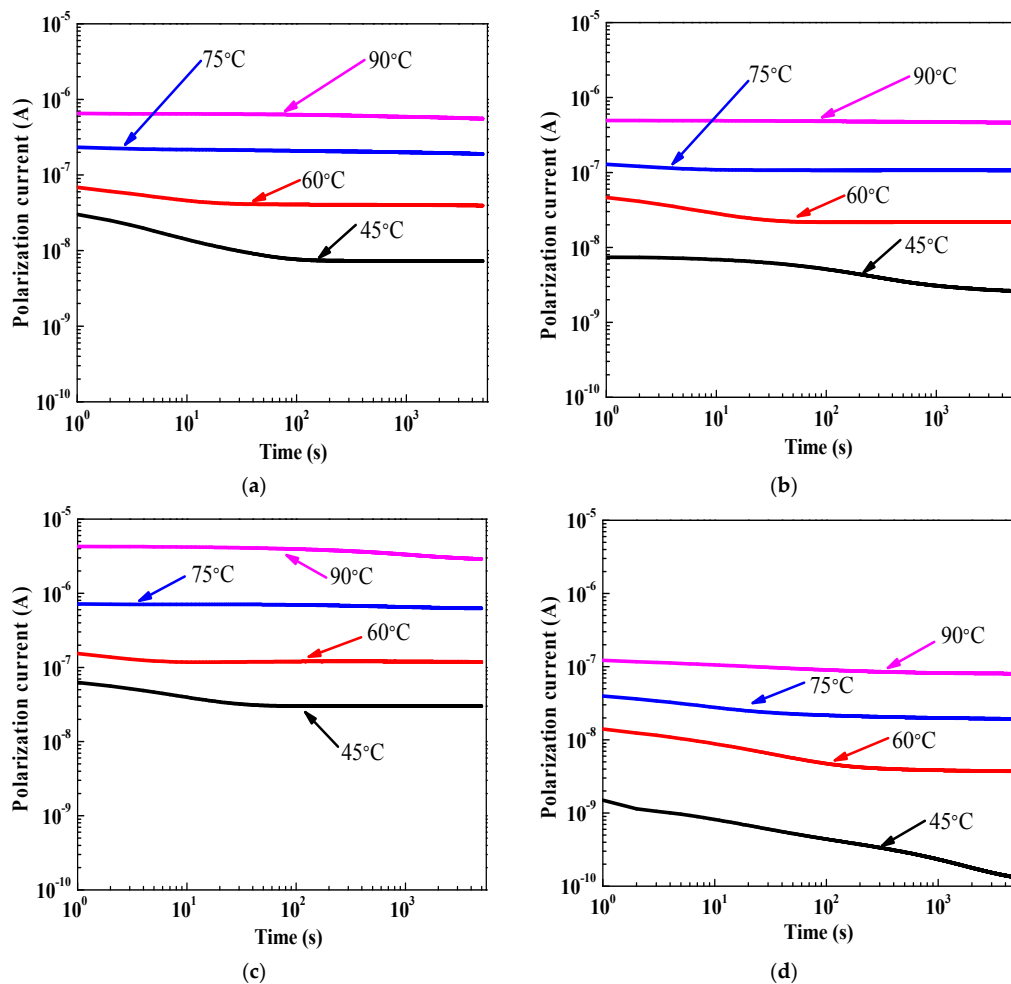


Figure 5. Measurement results of polarization current of oil-impregnated pressboard specimens with various insulation statuses. (a) Ageing 0 day (DP = 1285), moisture content 4.02%; (b) Ageing 8 days (DP = 994), moisture content 2.82%; (c) Ageing 21 days (DP = 841), moisture content 3.71%; and, (d) Ageing 42 days (DP = 415), moisture content 1.17%.

The authors believe that the variation of polarization current curves at any insulation temperature, as shown in Figure 5, depends on two elements. The first element is the conduction current. A lower

insulation temperature gives rise to a lower conduction current value due to the weak mobility of charge carrier in cellulose pressboard specimen. The decreasing conduction current contributes to decreasing the polarization current. The second element is the polarization behavior inside cellulose pressboard specimen. The decreasing insulation temperature can weaken polarization behavior, and then give rise to the decrease of relaxation current. In [4], it is reported that the PDC results mainly reflect the Maxwell-Wagner effect inside the cellulose pressboard specimen when the response duration is 5000 s and above. The polarization duration in our PDC measurement is exactly set to 5000 s, therefore we believe that the polarization behavior, as shown in Figure 5, is mainly attributed to the Maxwell-Wagner effect inside the cellulose pressboard specimen. Finally, we observed the phenomenon that the decreasing insulation temperature can result in the decrease of polarization currents.

3.2. Deolarization Current

The measurement results of depolarization current on experimental pressboard specimens with four typical insulation statuses, at four different insulation temperatures (90, 75, 60, and 45 °C), are presented in Figure 6, in a log-log scale. It is also observed that the depolarization current magnitudes decrease with decreasing insulation temperature. In addition, the more obvious ‘inflection point’ of depolarization current is found to migrate from a smaller measurement time point to larger measurement time point with insulation temperature decrease. In addition, the conclusion that the inflection point phenomenon seems to be related to the relaxation time constant with temperature dependant is more prominent. It should be noted that we observed the noise current of some depolarization currents shown in Figure 6a (45, 60 and 75 °C), Figure 6b (45 and 90 °C), Figure 6c (45 °C), and Figure 6d (60 and 90 °C). Similar results are also reported in the paper [4,11,23]. This phenomenon might be ascribed to the fluctuation of the weak electric field presented in our laboratory, which induces a current in measurement system cables. Therefore, when performing the PDC measurement, we suggest the researchers to take effective measures to reduce the noise current.

Due to the fact that the DC voltage is removed from the oil-impregnated pressboard, for the depolarization current results, as shown in Figure 6, it is believed that the variation of depolarization current curves under any insulation temperature only depends on the relaxation current. The decreasing insulation temperature can weaken depolarization behavior, and then give rise to the decrease of relaxation current. Finally, we observed the phenomenon that the decreasing insulation temperature can also result in the decrease of depolarization currents.

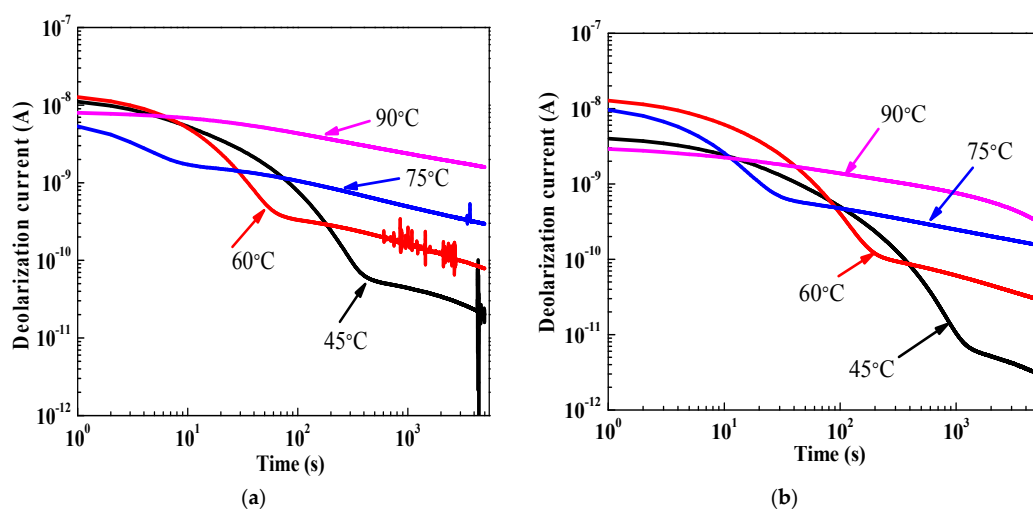


Figure 6. Cont.

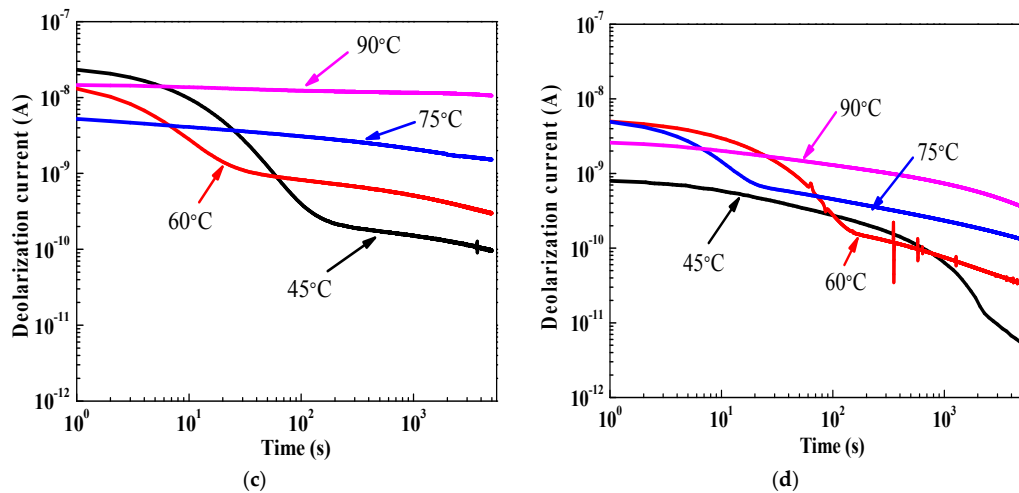


Figure 6. Measurement results of depolarization current of oil-impregnated pressboard specimens with various insulation statuses. (a) Ageing 0 day (DP = 1285), moisture content 4.02%; (b) Ageing 8 days (DP = 994), moisture content 2.82%; (c) Ageing 21 days (DP = 841), moisture content 3.71%; and, (d) Ageing 42 days (DP = 415), moisture content 1.17%.

4. Chemical and Electrical-Based Transformer Insulation Diagnostic Parameters Obtained from PDC Data

The transformer main insulation system, as a typical composite insulation, consists of a series of barriers, oil duct, and spacer, which is shown in Figure 7. Generally, in order to calculate the chemical and electrical-based transformer insulation diagnostic parameters (absorption ratio, polarization index, paper conductivity, oil conductivity, insulation resistance, etc.), the XY model [17,18,24,25], as shown in Figure 8, is introduced to indirectly obtain the oil and paper conductivity separately. While the polarization index, absorption ratio, and insulation resistance can be directly calculated from PDC data. It should be noted that the oil conductivity is not the focus of this contribution, while we pay more attention to the paper conductivity due to the fact that the status of paper insulation can determine the service duration of the whole transformer insulation. Therefore, we do not deduce the computational formula of oil conductivity. In the XY model, the X represents the ratio value of barriers to oil and the Y represents the ratio value of spacers to insulation oil, which can be, respectively, written as

$$X = \frac{\text{radial effective thickness of total barriers}}{\text{radial thickness of the duct}} \quad (1)$$

$$Y = \frac{\text{total effective width of the spacers along periphery of the duct}}{\text{periphery of the duct}} \quad (2)$$

The ranges of X and Y are typically 0.2–0.5 and 0.1–0.3, respectively, in a typical transformer insulation system [22]. It should be noted that the X value, in this work, is almost equal to 1, and the Y value is equal to 0 due to the test object is the only oil-impregnated pressboard specimens. In this section, we deduce the calculation formula of chemical and electrical-based transformer insulation diagnostic parameters.

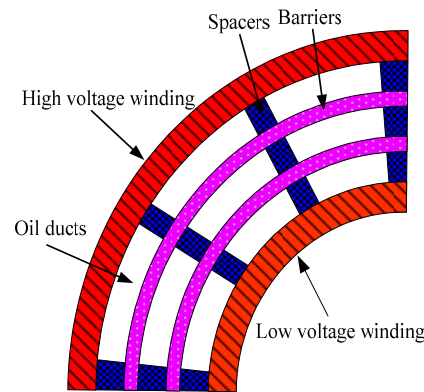


Figure 7. Cross-section diagram of the transformer main insulation system.

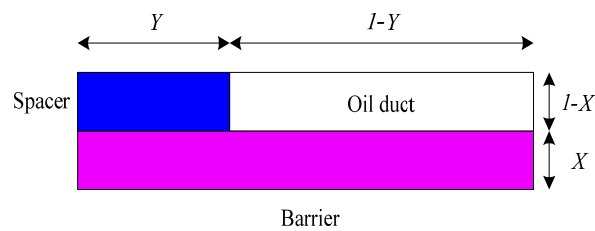


Figure 8. XY model of transformer main insulation system.

(a) Paper conductivity (σ_{paper})

① Method one of formula derivation [20,22]

Assuming that the insulation medium is charged for a sufficiently long time, and the final polarization current became the conduction current, which can be expressed as

$$i_{dc} \approx C_0 U_0 \frac{\sigma_r}{\epsilon_0} \quad (3)$$

where the C_0 represents the geometric capacitance, U_0 represents the step voltage applied to the insulation, ϵ_0 is the vacuum permittivity ($\epsilon_0 = 8.852 \times 10^{-12}$ F/m), and the σ_r is the dc conductivity of the dielectric medium.

As for the insulation arrangement presented in Figures 7 and 8 (as for a actual transformer insulation system, the spacers can be neglected due to the small ratio of spacers to insulation oil, that is to say, the Y value is equal to 0), the composite conductivity (σ_r) involved in oil conductivity (σ_{oil}) together with paper conductivity (σ_{paper}) can be written as

$$\sigma_r \approx \frac{\sigma_{paper}\sigma_{oil}}{\sigma_{paper}(1-X) + \sigma_{oil}X} \quad (4)$$

When $\sigma_{oil} \gg \sigma_{paper}$, the (4) can be written as

$$\sigma_r \approx \frac{\sigma_{paper}}{X} \quad (5)$$

According to (3)–(5), the paper/pressboard conductivity can be written as

$$\sigma_{paper} \approx \frac{\epsilon_0 X}{C_0 U_0} i_{dc} \quad (6)$$

In this work, as for the (6), due to the test object is the oil-impregnated pressboard, and the X value can be regarded to be equal to 1, therefore, the conduction current i_{dc} can be written as $i_{dc} = i_p(t_m) - i_d(t_m)$. Therefore, the σ_{paper} can be finally expressed as

$$\sigma_{paper} \approx \frac{\varepsilon_0}{C_0 U_0} [i_p(t_m) - i_d(t_m)] \quad (7)$$

where the $i_p(t_m)$ is the polarization current at the end of measure time, while the $i_d(t_m)$ is the depolarization current at the end of measure time.

② Method two of formula derivation [5,20]

The polarization current $i_p(t)$ applied to the insulation medium can be expressed as

$$i_p(t) = C_0 U_0 \left[\frac{\sigma_0}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t) \right] \quad (8)$$

In terms of principle of superposition, the sudden decrease of the voltage U_0 to zero is regarded as a negative voltage step at time $t = t_c$. Ignoring the second term in (8) due to the extreme transience of impulse current, the polarization current $i_d(t)$ can be written as

$$i_d(t) = -C_0 U_0 [f(t) - f(t + t_c)] \quad (9)$$

If the insulation medium is charged for a sufficient duration, that is to say, so that $f(t + t_c) \approx 0$, and the (9) can be written as

$$i_d(t) \approx -C_0 U_0 f(t) \quad (10)$$

According to (8)–(10), the paper conductivity can be finally written as

$$\sigma_{paper} \approx \frac{\varepsilon_0}{C_0 U_0} [i_p(t_m) - i_d(t_m)] \quad (11)$$

(b) Insulation resistance (R_{60s})

The insulation resistance at 60 s (R_{60s}) is the insulation resistance when the insulation medium is charged with a step voltage U_0 for the duration 60 s, which can be depicted as

$$R_{60s} = \frac{U_0}{i_p(60s)} \quad (12)$$

(c) Absorption ratio (AR)

Absorption (AR) is the ratio of the insulation resistance at 60 s to 15 s, which can be expressed as

$$K = \frac{R_{60s}}{R_{15s}} = \frac{i_p(15s)}{i_p(60s)} \quad (13)$$

(d) Polarization index (P.I.)

Polarization index (P.I.) is the ratio of the insulation resistance at 600 s to 60 s, which can be depicted as

$$P.I. = \frac{R_{600s}}{R_{60s}} = \frac{i_p(60s)}{i_p(600s)} \quad (14)$$

5. Temperature Effect Mechanism Together with Effectiveness Analysis on Chemical and Electrical-Based Transformer Insulation Diagnostic Parameters

(a) Paper conductivity (σ_{paper})

Figure 9 presents the calculation results of paper conductivity (σ_{paper}), it can be found that the paper conductivity obviously decreases with absolute temperature decrease. This indicates that the status of paper insulation become good with temperature decrease. According to the (6), (7), and (11), the authors believe that if the C_0 and U_0 are a constant, respectively, then the variation of paper conductivity at any insulation temperature only depends on the migration rate of charge carriers inside oil-impregnated cellulose pressboard. The decreasing insulation temperature can decrease the paper conductivity because the decreasing migration rate of charge carriers inside oil-impregnated cellulose pressboard can decrease the conduction currents, and thus finally decreasing the paper conductivity. It is interesting to note that this decreasing value of paper conductivity due to the decreasing insulation temperature does not represent permanent good condition of the paper insulation, because the temperature effect is inverted when insulation temperature in paper insulation increases. The present research findings reported that the paper conductivity varied with absolute temperature T , according to the well-known Arrhenius equation, which can be expressed in (15) [26].

$$\sigma_{paper}(T) \approx Ae^{(-E_a/RT)} \quad (15)$$

where E_a is the activation energy of experimental cellulose pressboard (J/mol), R is the molar gas constant ($R = 8.314$ J/mol), T is the absolute temperature in Kelvin, and A is a constant that is involved in ions mobility in the paper insulation. It is found that if taking natural logarithm on both sides of (15), it can be changed as

$$\ln \sigma_{paper}(T) \approx \ln A + \left(-\frac{E_a}{R}\right) \frac{1}{T} \quad (16)$$

It is observed from (16), there is linear relation between $\ln \sigma_{paper}(T)$ and $1/T$, and the slope is the $-E_a/R$. Figure 10 provides the relations between $\ln \sigma_{paper}(T)$ and $1/T$, it is observed that there is a better line relationship between $\ln \sigma_{paper}(T)$ and $1/T$, and the R-squared can be reached up to 0.957. In addition, according to the fitting equations between $\ln \sigma_{paper}(T)$ and $1/T$ shown in Figure 10, the values of activation energy E_a can be accurately obtained, which is provided in Table 1. It can be seen from Table 1 that the values of activation energy E_a with four insulation statuses were found to be in the range 93.75–135.59 kJ/mol. This is in agreement with the published works [26–28]. The variation values of activation energy E_a is unsystematic and the range most reflects the effectiveness of the chemical and electrical-based transformer insulation diagnostic parameters obtained from PDC measurement.

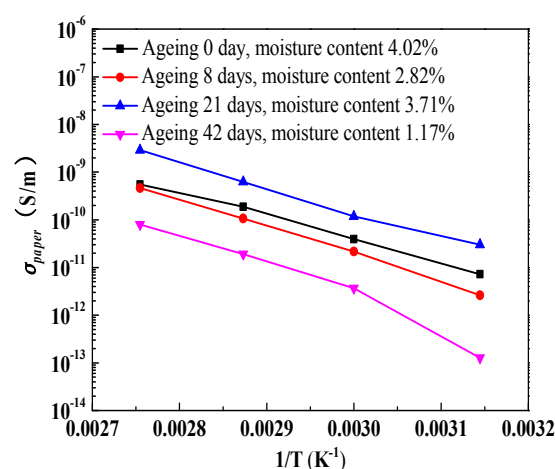


Figure 9. Variations of paper conductivity with the absolute temperature decrease.

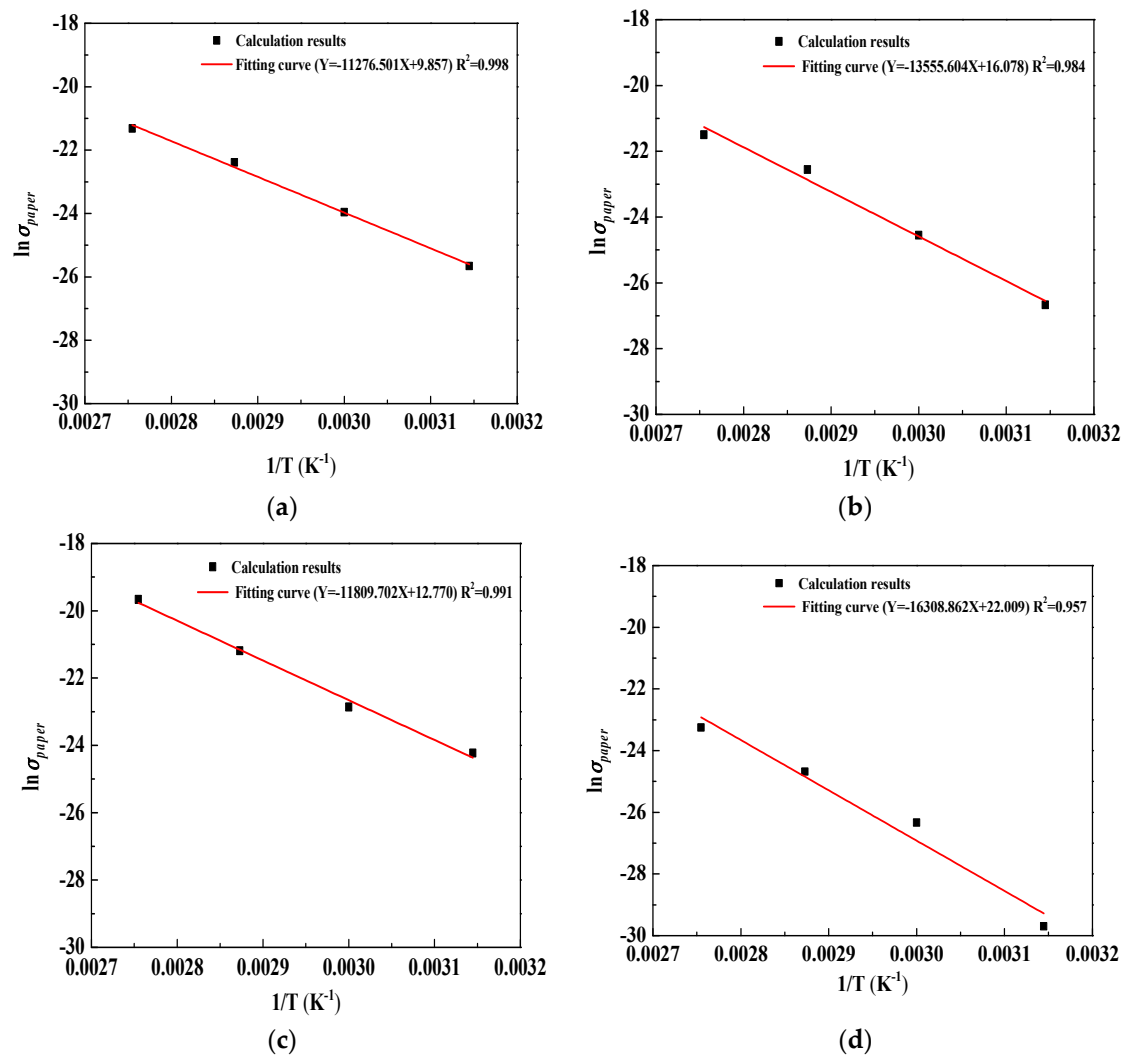


Figure 10. Relations between $\ln \sigma_{paper}$ and $1/T$. (a) Ageing 0 day (DP = 1285), moisture content 4.02%; (b) Ageing 8 days (DP = 994), moisture content 2.82%; (c) Ageing 21 days (DP = 841), moisture content 3.71%; and, (d) Ageing 42 days (DP = 415), moisture content 1.17%.

Table 1. Activation energy values of experimental pressboard specimens with various insulation statuses.

Insulation Status	E_a (kJ/mol)
Ageing 0 day (DP = 1285), water content 4.02%	93.75
Ageing 8 days (DP = 994), water content 2.82%	112.70
Ageing 21 days (DP = 841), water content 3.71%	98.19
Ageing 42 days (DP = 415), water content 1.17%	135.59

(b) Insulation resistance (R_{60s})

Figure 11 presents the calculation results of insulation resistance (R_{60s}), it is found that the values of R_{60s} increase with insulation temperature decrease.

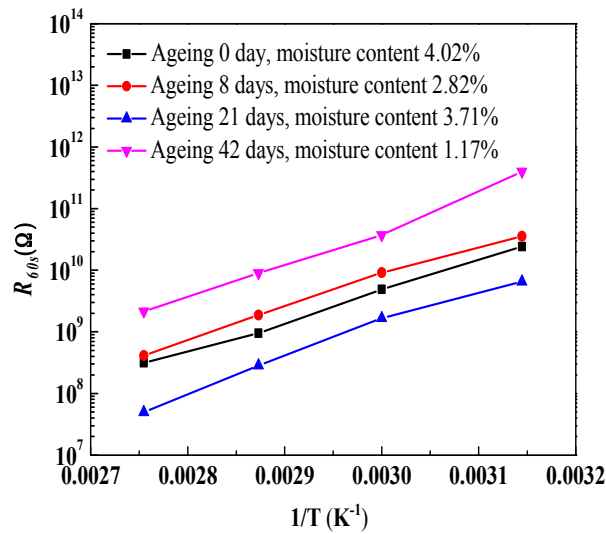


Figure 11. Variations of insulation resistance (R_{60s}) with the absolute temperature decrease.

Authors in [3] reported that the insulation resistance can present meritorious knowledge about the overall status of the transformer insulation. A lower value indicates a bad status of the transformer insulation that is caused by an insulation temperature increase, whereas higher corresponds to better status of the transformer insulation because of the temperature decrease [1,3]. From the calculation results of R_{60s} , as shown in Figure 11, the paper insulation can be restored to a good condition with insulation temperature decrease. In the work, we hold the view that the variation of insulation resistance at any insulation temperature depends on two elements. The first element is the migration rate of charge carriers inside oil-impregnated cellulose pressboard. The decreasing mobility of the charge carriers inside the oil-impregnated cellulose pressboard due to the decreasing insulation temperatures, evidently, results in the increase of insulation resistances. The second element is the process of migration, distribution, and equilibrium of moisture/conductive pollutant between dielectric oil and cellulose insulation. During the insulation temperature decrease, the relative saturation of water and conductive pollutant in dielectric oil decreases with the insulation temperature decrease, and thus moisture and conductive pollutant migrates from dielectric oil into cellulose until a new equilibrium state is achieved. The increasing moisture and conductive pollutant in paper insulation could slightly decrease the value of insulation resistance. It is interesting to note that the first factor contradicts with the second factor. However, the migration rate of charge carriers inside oil-impregnated cellulose pressboard is the predominant factor, and the insulation resistance therefore increases with insulation temperature decrease. In addition, it should be pointed out that the obvious increase of insulation resistance, in fact, also does not represent permanent good condition of the paper insulation, since the insulation performance of oil-impregnated cellulose pressboards is reversed once the temperatures increase. The insulation resistance is also vary with absolute temperature T , according to the well-known Arrhenius relationship, as shown in (17) [1].

$$R_{60s}(T) \approx R_{initial} e^{E_a/RT} \quad (17)$$

where E_a is the activation energy of experimental cellulose pressboard (J/mol), R is the molar gas constant ($R = 8.314$ J/mol), T is the absolute temperature in Kelvin, $R_{initial}$ is the initial insulation resistance related to an infinity high temperature and $R_{60s}(T)$ is the insulation resistance when the insulation medium is charged with a step voltage U_0 for the duration 60 s at the absolute temperature T . Similarly, if taking natural logarithm on both sides of (17), it also can be changed as

$$\ln R_{60s}(T) \approx \ln R_{initial} + \left(\frac{E_a}{R}\right) \frac{1}{T} \quad (18)$$

It is observed from (18) that there is linear relation between $\ln R_{60s}(T)$ and $1/T$, and the slope is the E_a/R . Figure 12 provides relations between $\ln R_{60s}(T)$ and $1/T$, it is found that there is a better line relationship between $\ln R_{60s}(T)$ and $1/T$, and all of the R-squared can be reached up to 0.984.

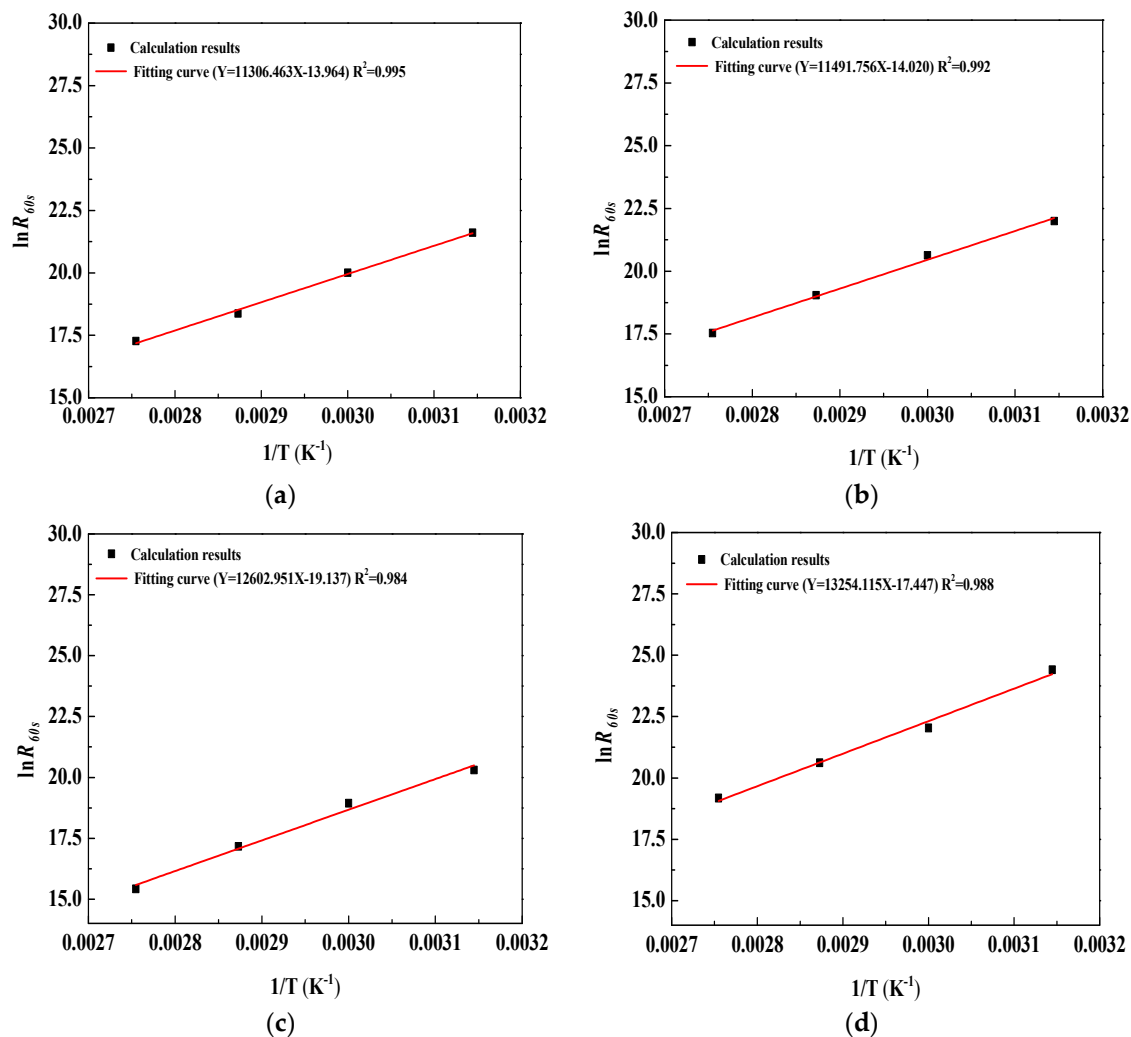


Figure 12. Relations between $\ln R_{60s}$ and $1/T$. (a) Ageing 0 day (DP = 1285), moisture content 4.02%; (b) Ageing 8 days (DP = 994), moisture content 2.82%; (c) Ageing 21 days (DP = 841), moisture content 3.71%; and, (d) Ageing 42 days (DP = 415), moisture content 1.17%.

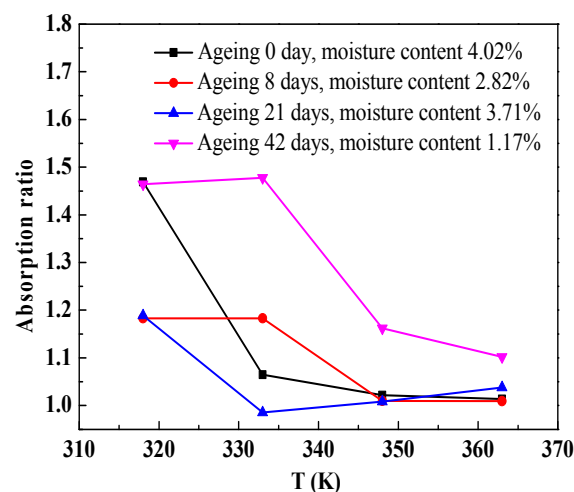
Furthermore, according to the fitting equations between $\ln R_{60s}(T)$, and $1/T$ shown in Figure 12, the values of activation energy can be accurately obtained, which is presented in Table 2. It can be seen from Table 2 that the values of activation energy of experimental cellulose pressboards with four insulation statuses were found to be in the range 94.00–110.19 kJ/mol. This is also in accordance with the published works [26–28]. When compared to the Table 1, it can be seen from Table 2 that the fluctuation range of the activation energy using the linear relation between $\ln R_{60s}(T)$ and $1/T$ is smaller than using the linear relation between $\ln \sigma_{paper}(T)$ and $1/T$ due to the better goodness of fit on fitting curves between $\ln R_{60s}(T)$ and $1/T$ presented in the Figure 12. It is also indicated that the variation values of activation energy are unsystematic and the small ranges may also reflect the effectiveness on chemical and electrical-based transformer insulation diagnostic parameters obtained from PDC measurement.

Table 2. Activation energy values of oil-impregnated pressboard specimens with various insulation statuses.

Insulation Status	E_a (kJ/mol)
Ageing 0 day (DP = 1285), water content 4.02%	94.00
Ageing 8 days (DP = 994), water content 2.82%	95.54
Ageing 21 days (DP = 841), water content 3.71%	104.78
Ageing 42 days (DP = 415), water content 1.17%	110.19

(c) Absorption ratio (AR)

Figure 13 presents the calculation results of absorption ratio (AR). It is observed that the AR value is a parameter that is greatly temperature dependent and there are no obvious change rules on the AR values. This phenomenon may attribute to the transient process of migration, distribution, and equilibrium of moisture and conductive pollutant between oil and cellulose material. In the early stage of measurement duration, the transient process is rather complicated. In the paper, we believe that the transient process can cause the fluctuation of polarization current, and thus result in the fluctuation of AR values. It is found that the AR value is rather unreliable when using the parameter to obtain the status of transformer cellulose insulation. Therefore, the absorption ratio is not a good insulation degradation indicator for the transformer cellulose material.

**Figure 13.** Relations between absorption ratio and absolute temperature T .

(d) Polarization index (P.I.)

Figure 14 presents the calculation results of polarization index (P.I.). Similarly, it is also observed that the P.I. value is a temperature dependent parameter and there are no obvious change rules on the P.I. values. The P.I. is different from paper conductivity, which is positive correlation with insulation temperature decrease and insulation resistance, which is negative correlation with insulation temperature. It is a fact that P.I. is the ratio of insulation resistance at 600 s to 60 s. Similarly, the transient process of the migration, distribution, and equilibrium of moisture and conductive pollutant between dielectric oil and cellulose paper/pressboard can cause the fluctuation of polarization current, and thus result in the fluctuation of P.I. values. In addition, it is also found that the P.I. value, obviously affected by temperature, is also rather unreliable when applying the parameter to obtain the status of transformer cellulose insulation. Similar conclusions are also observed in the papers [2,5]. Therefore, the polarization index is also not a good insulation degradation indicator for the transformer cellulose material.

To sum up, the temperature effect on paper conductivity, and insulation resistance can be effectively eliminated by using the well-known Arrhenius equation and the two parameters can

be used are suitable for field application, while the absorption ratio and polarization index obtained from polarization and depolarization current measurement are irregular and it is indicated that these parameters cannot be used for field application.

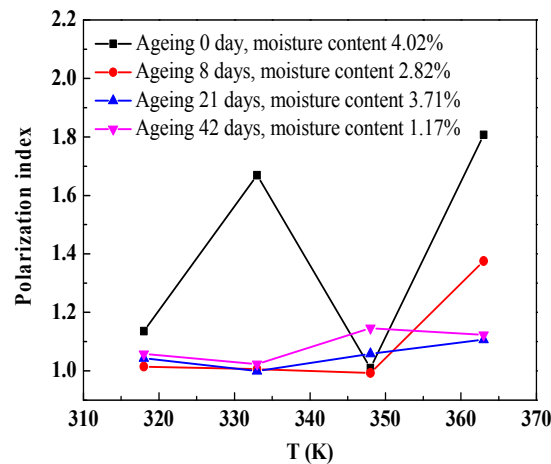


Figure 14. Relations between polarization index and absolute temperature T .

6. Conclusions

This aim of the contribution is to understand and interpret the effectiveness of chemical and electrical-based transformer insulation diagnostic parameters obtained from PDC measurement, as well as temperature effect mechanism on these parameters. The detailed conclusions in this paper are as follows:

- (1) The magnitudes of polarization/depolarization current obviously decrease with a decreasing insulation temperature. Moreover, the 'inflection point' of polarization/depolarization currents will occur with insulation temperature decrease. This inflection point phenomenon seems to be related to the relaxation time constant with temperature dependant. The inflection point will migrate from smaller measurement time point to larger measurement time point with an insulation temperature decrease.
- (2) The chemical and electric-based transformer insulation diagnostic parameters reported in this work can be calculated from PDC measurement and their effectiveness can be effectively verified by the activation energy obtained from the well-known Arrhenius relationship between paper conductivity/insulation resistance and absolute temperature. Moreover, the fluctuation range of the activation energy using the linear relation between $\ln R_{60s}(T)$ and $1/T$ is smaller than using the linear relation between $\ln \sigma_{paper}(T)$ and $1/T$ due to the better goodness of fit on fitting curves between $\ln R_{60s}(T)$ and $1/T$.
- (3) The temperature effect on paper conductivity and insulation resistance can be effectively eliminated by using the well-known Arrhenius equation. The two parameters are suitable for field application. While the absorption ratio and polarization index obtained from polarization and depolarization current measurement are irregular and it is indicated that these parameters are not suitable for field application.

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