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# TEST CELL FOR POLARIZATION AND DEPOLARIZATION CURRENT TEST OF TRANSFORMER INSULATION OIL

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**Abstract**. Polarization and Depolarization Current (PDC) analysis is normally used to determine the water content in the oil-paper insulation barrier and also oil conductivity inside the transformers. PDC measurement onsite was performed by injecting the DC Voltage at one side of the transformer and current measurement will be carried at the other side of the transformer, in which the transformers are required to be isolated from services to be tested. PDC test normally run up to 10000s for polarization and had to wait for other 10000s for depolarization measurement. Because of the long duration of the test, applications of this method to monitor transformer on service become less popular. In this research, a cell was designed and developed to perform PDC on insulation oil samples. The PDC pattern of insulation oil obtained by testing using the cell was found to have same pattern with the test done onsite. Predictions for transformers in service can be made by performing PDC tests on oil samples taken from the transformer tank and then comparing its pattern, conductivity level and measured capacitance value against a PDC fingerprint.

*Keywords:* Polarization; depolarization; oil insulation; transformer; cell

**Abstrak.** Polarisasi dan depolarisasi Arus (PDA) analisis biasanya digunakan untuk menentukan kadar air dalam di antara penebat minyak-kertas dan juga konduktiviti minyak di dalam pemboleh ubah. Pengukuran PDA ke atas pemboleh ubah di tapak dilakukan dengan menyuntikkan Voltan DC pada satu sisi pemboleh ubah dan pengukuran arus akak dilalukan pada sisi yang lain, di mana semasa pemdukuran dijalankan pemboleh ubah ini harus dipisahkan dari operasi. Ujian PDC biasanya berjalan sehingga 10000s untuk polarisasi dan harus menunggu 10000s lagi untuk pengukuran depolarisasi. Kerana tempoh ujian yang lama, aplikasi kaedah ini untuk memantau pemboleh ubah yang sedang beroperasi menjadi kurang popular. Dalam kajian ini, sel direka dan dibangunkan untuk melakukan ujian PDA pada sampel minyak penebat. Pola PDA minyak penebat diperoleh dengan ujian menggunakan sel tersebut didapati memiliki pola yang sama dengan ujian dilakukan di tapak. Ramalan kondisi pemboleh ubah dalam perkhidmatan dapat dilakukan dengan melakukan ujian PDA pada sampel minyak penebat yang diambil dari tangki pemboleh ubah dan kemudian membandingkan polanya, tahap konduktiviti dan nilai pemuat berkadar terhadap pola asal PDA minyak penebat tersebut.

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*Kata kunci*: Polarisasi; depolarisasi; minyak penebat; pemboleh ubah dan sel

## 1.0 INTRODUCTION

The PDC method is a simple and reliable analysis tool to monitor transformer insulation systems. The Polarization and Depolarization Current (PDC) analysis is a non-destructive dielectric testing method for determining the conductivity and moisture content of insulation materials in a transformer [1-4]. It is a technique that is based on time domain measurement and has been in use since the 1990's[5]. PDC can provide information about the Response Function (f (t)) of the dielectric and the conductivities of oil and paper. On the basis of this analysis, it is possible to take further actions such as oil refurbishment or drying or replacement of the transformer.

According to [2, 3, 5-8] Return Voltage Measurement (RVM) and PDC are two time-based dielectric diagnosis techniques that have become popular in recent years. According to [9, 10], the RVM technique can generally provide the clearest indication of the overall condition of the oil, and it is a simple technique to perform. However, according to Saha [5] and Kuchler [11], this technique needs a substantial amount of expertise in order to arrive at the correct interpretation. Moreover, RVM results are found to be strongly affected by the geometry of the insulation system, temperature, ageing by-products and moisture.

Besides using the time domain approach, dielectric diagnosis can also be done by frequency domain analysis which is known as Frequency Domain Spectroscopy (FDS). This technique monitors the insulation condition by analyzing the dissipation factor and the complex capacitance of the insulation as a function of frequency, typically ranging from 0.1mHz to 1kHz. FDS allows for the distinguishing of different materials at different frequency ranges [8, 11]. However, it requires the measurement to be carefully carried out under stationary conditions.

PDC measurement has gained immense popularity due to its ability to assess the condition of oil and paper separately without opening the transformer tank [12]. PDC gives information about the oil conductivity within the first seconds after a DC step application and about the barrier conductivity over a long period of time. PDC measurement can be used to distinguish different materials at different times [2, 13]. PDC involves step response measurement and contains all this information. From the PDC results, frequency domain quantities for FDS can be derived at low field strength with linear behavior of the material. Other than that, from PDC system response, the recovery voltage can also be measured directly [7]. However, the drawback of this method is the transformers are required to be isolated from services to be tested. Indeed, the nominal testing time are also considered have long duration, in which normally the test will be run up to 10000s for polarization and had to wait for other 10000s for depolarization measurement.

In this paper, a cell was developed to run the PDC test on oil sample from transformer. By using test cell, transformer in service will not be interrupted. This experiment was carried out to find the dielectric responsive function and maximum conductivities of mineral transformers oil samples. Each sample has different moisture levels (dried, normal, or wet). The dried condition was achieved by processing the oil in a dry-out plant to evacuate the moisture. Normal condition refers to the oil as taken directly from the drum while wet condition is the oil after 200ppm of moisture has been added. The polarization and depolarization current at test DC voltage of 1000V was recorded for 10,000 seconds. Each test was repeated for five to ten times to collect the most consistent PDC data and to check the repeatability of each PDC pattern. The pattern then will be compared and verified with the PDC test run onsite.

## 2.0 TEST CELL DESIGN

Figure 1 shows the test cell for the PDC test. The test cell was designed to eliminate environmental moisture that would affected the test oil moisture content. The cell was also designed to have the shield guard connected to the negative electrode by using an external cable. This was done to minimize the effect of stray current.

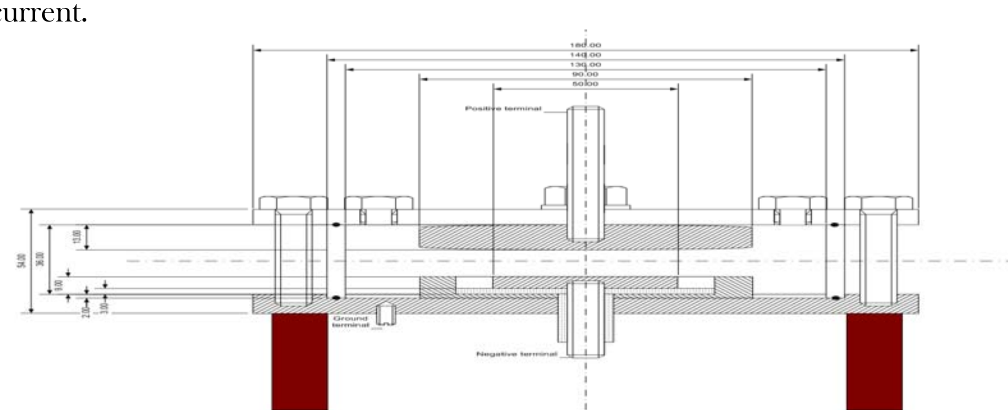


**Figure 1** Test cell for PDC test

A finite-element field plotting software (COMSOL Multiphysics) was used to simulate the polarization activities inside the cell. The simulation was done by selecting electric polarization, electric permittivity of the materials and setting the cell boundaries. Figure 2 shows the polarization concentration simulation result for the test cell. From this simulation result, the maximum polarization concentration in the test cell was $8.446x10^{-7}C/m^{2}$. The direction of the polarization inside the cell is shown in Figure 3.

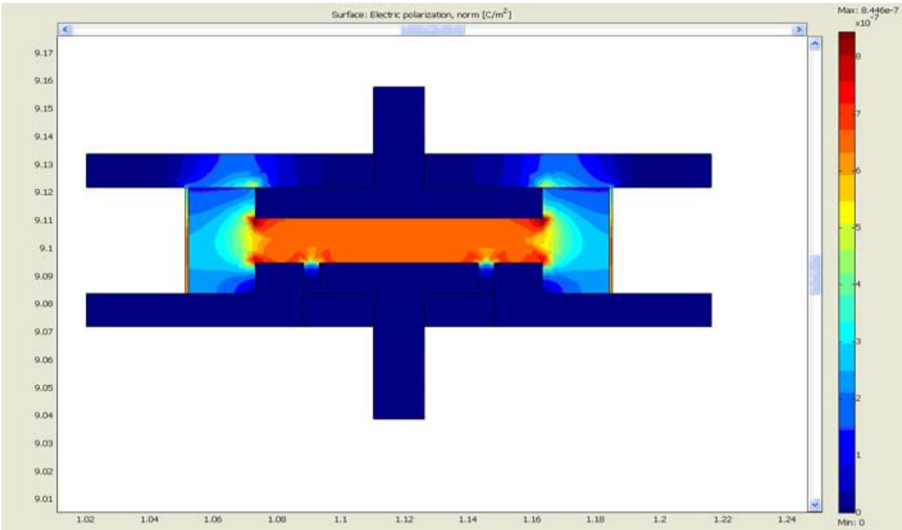


**Figure 2** Polarization concentration within the PDC test cell

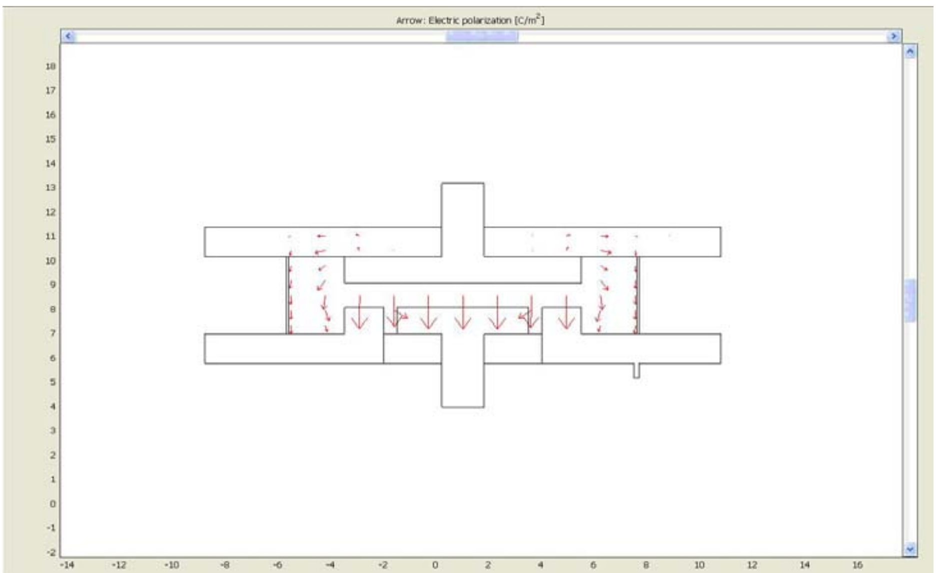


**Figure 3**. Direction of the polarization inside the PDC test cell

# 3.0 TESTING

## 3.1 Test Setup and Equipment

Figure 4 shows the basic circuit for the PDC test. The setup was equipped with a precision high voltage source and measurement devices. A computer was used to control the circuit switching and also to capture and record the measured currents by the high resistance electrometer. All the measurements were carried out at 1000V and 10,000 seconds for polarization and depolarization time.

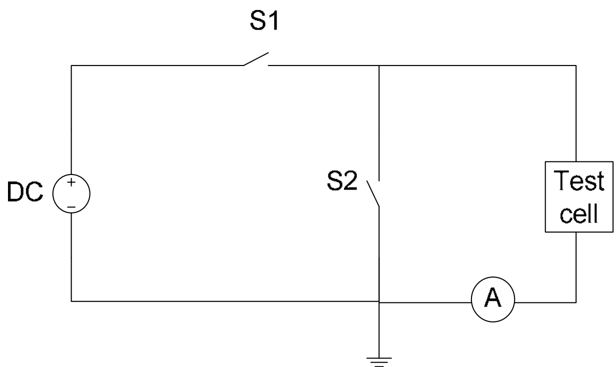


**Figure 4** PDC basic circuit

During charging process S1 will be closed and S2 will be opened. The charging current is measured by the ammeter and known as the polarization current. At the end of the charging time, S1 will be opened and S2 will be closed. The discharging process will start and the ammeter will measure the discharge current, known as the depolarization current.

## 3.2 Test Oil

Experiments were done using commercially available mineral oil. Table 1 lists the relevant properties of the oil tested.

**Table I**: Relevant properties of tested oils

| Properties | Standard | Mineral |
|---|---|---|
| Dielectric Breakdown Voltage (kV) | | |
| 1mm gap | ASTM D877 | ≥30 |
| 2mm gap | ASTM D1816 | ≥20 |
| 2.5mm gap | IEC60156 | ≥35 |
| Water Content (mg/kg) | ASTM D1533/IEC60814 | ≤35 |
| Dielectric dissipation factor(%) | | |
| 25°C | ASTM D924/IEC60247 | |
| 100°C | | ≤0.05 |
| | | ≤0.30 |
| Pour Point (°C) | ASTM D97 | ≤-40 |
| Flash Point (°C) | ASTM D92 | ≥145 |
| Fire Point (°C) | ASTM D92 | |

## 3.3 Test Oil Preparation

The ‘dried’ test oils were obtained by drying the oils in an oil dry-out plant for at least 48 hours until it reaches the standard moisture content as shown in Table 1. For testing wet oil condition, moisture was added into the dried oil using measured quantities of water for specified quantities of oil. A 2 litre beaker was used to hold the dried test oil and a small 3ml syringe was used to inject distilled water into the dried oil. A magnetic stirrer with hotplate was used for mixing water in the oil. The temperature was set to 50ºC to avoid vaporization of water and the oil was stirred for 24 hours before being used for the test. Figure 5 shows the setup for mixing water into the test oil.

**Figure 5**. Adding moisture into oil process

### 3.4 PDC Test Procedure

Firstly, the test cell is cleaned and then filled by gently pouring the test oil into the cell. The liquid is allowed to stand for 15 minutes. A standard LCR bridge is used to measure the geometric capacitance between the two terminals of the test cell. The cell is then connected to the power source and measuring devices as shown in Figure 4. On start-up, the control program will automatically discharge the cell for several seconds. This is to make sure the test oil was fully discharged before the first phase of the test (polarization) is allowed to commence.

From the screen panel, the user sets the charging voltage, the charging time and discharging time. The control program will charge and discharge the test object sequentially according to the specified time settings.

## 4.0 OIL CONDUCTIVITY

Oil conductivity is the ability of the insulation oil to conduct electric current. According to Ohm's law, the conductivity (G) is the inverse of resistance (R) and is determined from the measured voltage and current:

$$G = \frac{1}{R(\Omega)} = \frac{I(A)}{V(V)} \tag{1}$$

Water molecules present in the oil can have an effect on the movement of the charge in the oil (resistance) and thus it will directly affect the conductivity value of the insulation. The effect of moisture on insulation oil conductivity in PDC measurement is an important issue that requires investigation.

The basic unit of conductivity is Siemens (S) which is an equivalent of the $\Omega^{-1}$ unit. Since the cell geometry affects conductivity values, standardized measurements are expressed in specific conductivity units (S/m) to compensate for variations in electrode dimensions. Specific conductivity (C) is simply the product of measured conductivity (G) and the electrode cell constant (L/A), where L is the length of the column of liquid between the electrodes and A is the area of the electrodes. The formula can be written as below:

$$Conductivity(C) = \left( G \times \frac{L}{A} \right) \text{Sm}^{-1} \tag{2}$$

In this investigation, a fixed DC voltage was applied across the test cell for 10,000 seconds. The difference in the time constant of the charging current corresponds to different insulation materials and to the conductivity of the test object. After this so-called polarization current process, the current will reach a steady state, partly due to the DC conduction. When the voltage is removed and the test object is short-circuited, the depolarization current will flow in the other direction. The polarization current ($i_p$) and depolarization current ($i_d$) can be expressed using the following formulas:

$$i_p(t) = C_0 U_0 \left[ \frac{\sigma}{\varepsilon_0} + f(t) \} \right] \tag{3}$$

$$i_d(t) = C_0 U_0 [ f(t) - f(t + t_c)] \tag{4}$$

In this research both the above quantities were measured during the test. Based on these, it was possible to estimate the conductivity (σ) of the test oils. The oil was charged for 10,000 seconds, which is considered a sufficiently long charging time so that $f(t+t_c) \cong 0$ [14]. When the polarization and depolarization current equations are combined, the DC conductivity can be expressed as:

$$\sigma \approx \frac{\varepsilon_0}{C_0 U_0} \left[ i_p(t) - i_d(t) \right] \tag{5}$$

where $C_0$ is the geometric capacitance and $U_0$ is the external voltage used in the test. $C_m$ is the capacitance value measured between two main terminals of the insulation system under the test [15]:

$$C_0 = \frac{C_m}{\varepsilon_r} \tag{6}$$

Thus:

$$\sigma \approx \frac{\varepsilon_0 \varepsilon_r}{C_m U_0} \left[ i_p(t) - i_d(t) \right] \tag{7}$$

where $\varepsilon_0$ is the absolute permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. As in this test no pressboard was involved, so $\varepsilon_r = \varepsilon_{oil}$. In this investigation the voltage used for all tests was 1000V. The tested has relative permittivity of 2.2 . Hence:

$$\text{Mineral oil DC conductivity: } \sigma_r = \frac{\varepsilon_0 \varepsilon_r}{C_m U_0} \left[ i_p(t) - i_d(t) \right] \tag{8}$$

$$= \frac{1.946 \times 10^{-14}}{C_m} \left[ i_p(t) - i_d(t) \right] \text{ S/m}$$

The oil's maximum DC conductivity for each test can be calculated by applying the value of the maximum polarization and depolarization current ($i_{pd}$) gathered from the experiments. $i_{pd}$ is the difference between the polarization current ($i_p$) and the depolarization current ($i_d$). Both of these currents are measured in the time domain. The general response function for oil or cellulosic insulation material can be expressed as [14]:

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m} \quad \text{with A}, t_0 > 0, m > n > 0 \text{ and } m > 1 \tag{10}$$

The dielectric response function *f(t)* of the tested insulation oil is estimated from a depolarization current measured ($i_d$) . It is assumed that the dielectric response function is a continuously decreasing function in time. As in this experiment, the depolarization is considered as sufficiently long (10,000 seconds), so $f(t+t_c) \cong 0$. *f(t)* is proportional to the depolarization current. From equation 4, the following equation is used [14]:

$$f(t) = \frac{-i_d(t)}{C_0 U_0} \tag{11}$$

Based on equation 11, an empirical formula for *f(t)* can be obtained by using MATLAB software to generate a 10[th] degree polynomial curve that best fits the experimental results.

## 5.0 RESULTS AND ANALYSIS

### 5.1 Normal Oil Condition Test

In this test, mineral oil was extracted directly from the oil drum delivered by the supplier. It had moisture content at 31ppm and measured $C_m$ value at 21.7pF. Figure 6shows results of the PDC test for normal mineral oil. The charging current was recorded and the polarization curve was plotted. The curve shows that the peak current is at 0.173μA after 3 seconds of being charged while the minimum current occurs at end of the charging time with a current value of 0.145μA. In the discharging process, this oil has a maximum depolarization current of 24.66nA after 1 second being discharged. This oil takes a longer time to be fully discharged. At the end of the depolarization period the current was not fully discharged, its value at this time was 0.121nA. When the PDC curve was plotted, the maximum current achieved was 0.173μA at 3 seconds and the minimum current was 0.145μA at the end of the curve. The difference between the maximum and minimum PDC values was 27.8nA.

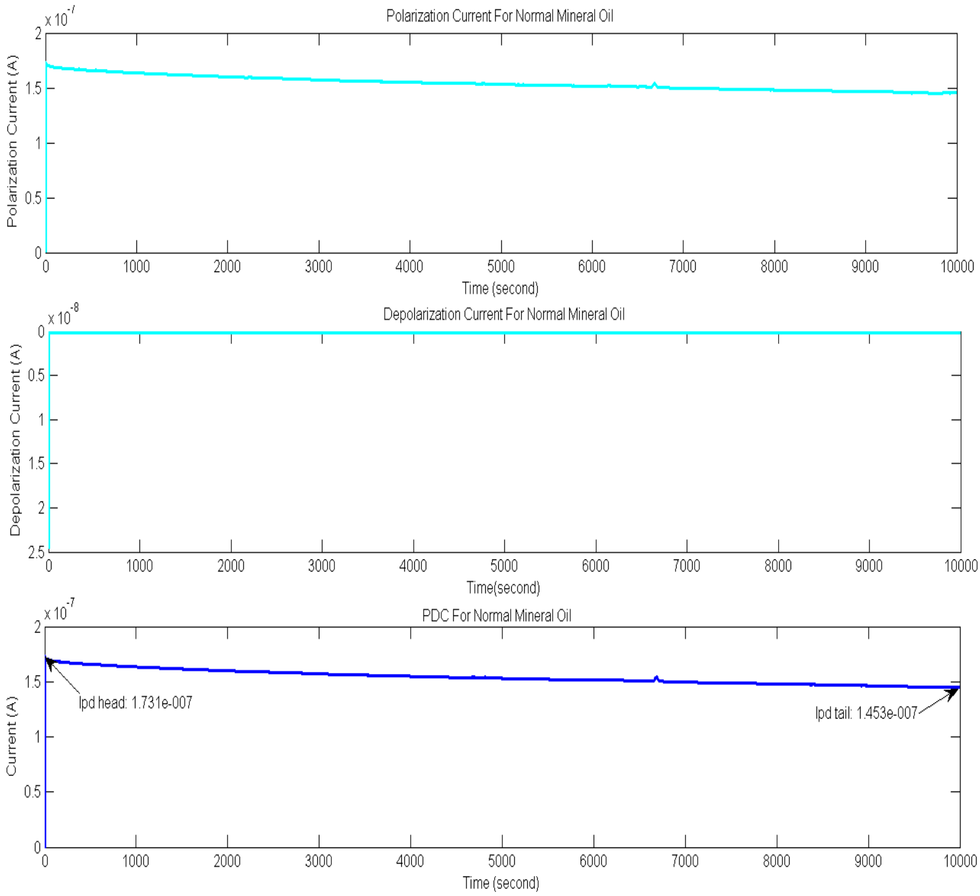


**Figure 6** PDC test result for normal mineral oil

Based on the measured values above, the maximum DC conductivity of the normal mineral oil is calculated as below:

$$C_m = 21.7\text{pF}, \ \ Maximum\ i_{pd}(t) = i_{pd}(3) = 0.173\mu\text{A}$$

Hence:

$$\sigma_r = \frac{1.946\times10^{-14}}{21.7\times10^{-12}}(1.73\times10^{-7}) \ = 0.1552\text{nS/m}$$

Using curve-fitting, the dielectric response function *f(t)* of this oil can be expressed as:

$$f(t) = \frac{-\begin{pmatrix} 8.4\times10^{-46}t^{10} - 4.4\times10^{-41}t^{9} + 9.9\times10^{-37}t^{8} - 1.3\times10^{-32}t^{7} + 9.8\times10^{-29}t^{6} - 4.8\times10^{-25}t^{5} \\ +1.5\times10^{-21}t^{4} - 2.9\times10^{-18}t^{3} + 3.1\times10^{-15}t^{2} - 1.7\times10^{-12}t \ + 4.6\times10^{-10} \end{pmatrix}}{21.7\times10^{-12}(1000)}$$

## 5.2 Dried Oil Condition Test

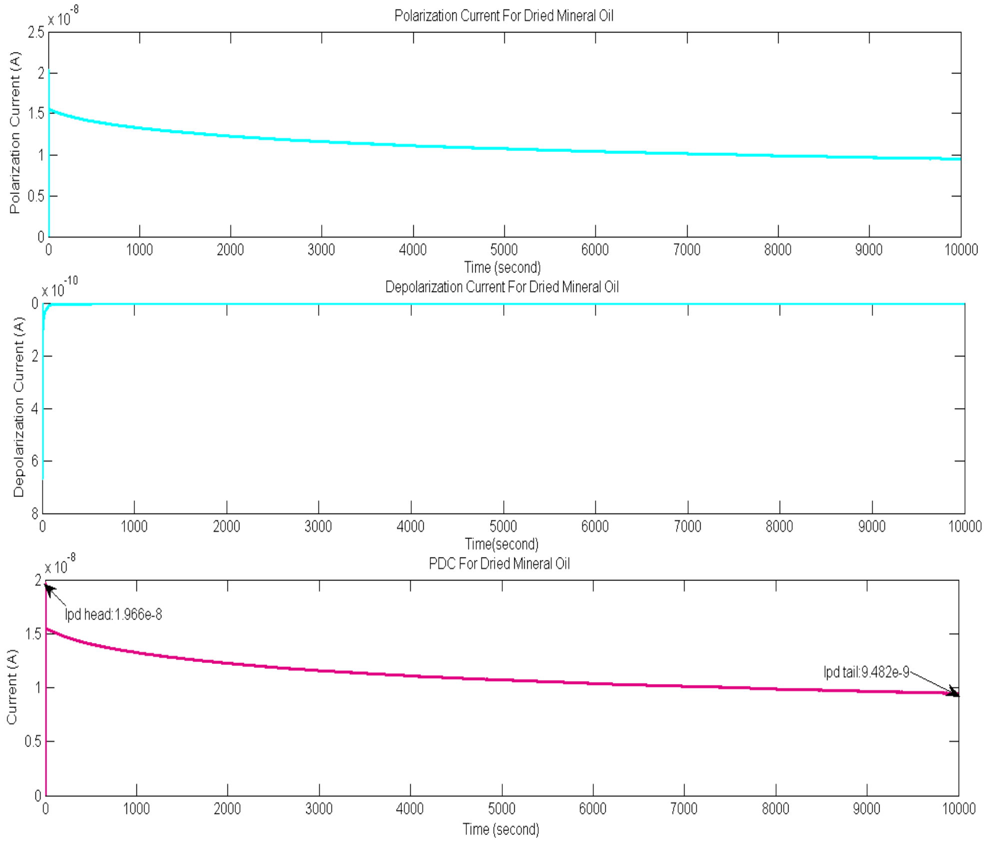


**Figure 7**. PDC test result for dried mineral oil

The dried mineral oil had a moisture content of 14ppm and measured $C_m$ at 26.1pF. The charging and discharging current was recorded and the polarization and depolarization curve of the oil was plotted in Figure 7. The polarization curve shows that the peak current of this oil is 20.33nA after 2 seconds of being charged while the minimum current occurs at the end of the polarisation period (10,000 seconds) with a value of 9.474nA. For the depolarization curve, the maximum current occurred after 2 seconds of being discharged with a value of 0.667nA. As in the preceding case with normal mineral oil, here the current was also not fully discharged at the end of the depolarization period. The end depolarization current achieved was 0.63pA. The PDC curve had a maximum current of 19.66nA at 2 seconds while the minimum current occurred at the end of the curve with a value of 9.482nA. The difference between the maximum and minimum PDC values was 10nA.

Based on the measured values above, the maximum DC conductivity of the dried mineral oil is calculated as below:

$$C_m = 26.1\text{pF}, \; \textit{Maximum}\; i_{pd}(t) = i_{pd}(2) = 19.66\text{nA}$$

Hence:

$$\sigma_r = \frac{1.946\times10^{-14}}{26.1\times10^{-12}}(1.966\times10^{-8}) \;= 14.66\text{pS/m}$$

Using curve-fitting, the dielectric response function *f(t)* of this oil can be expressed as:

$$f(t) = \frac{-\begin{pmatrix} 1.0\times10^{-46}t^{10} - 5.5\times10^{-42}t^{9} + 1.2\times10^{-37}t^{8} - 1.6\times10^{-33}t^{7} + 1.2\times10^{-29}t^{6} - 6.1\times10^{-26}t^{5} \\ +1.9\times10^{-22}t^{4} - 3.7\times10^{-19}t^{3} + 4.1\times10^{-16}t^{2} - 2.2\times10^{-13}t \; + 4.3\times10^{-11} \end{pmatrix}}{26.1\times10^{-12}(1000)}$$

## 5.3 Wet Oil Condition Test

Figure 8 shows results of PDC test on wet mineral oil. The oil moisture level before the test was at 40ppm and its measured $C_m$ was 18.8pF. The polarization current curve obtained had a peak current value of 0.245µA after 3 seconds of being charged and a minimum current of 0.162µA at the end of the charging period. The depolarization current curve had a peak current of 13.05nA after 2 seconds of being discharged. This oil was not fully discharged at the end of the discharging period, with a remnant of 31.31pA at the end of the experiment. The PDC curve of this oil is shown in Figure 8. This PDC curve had a maximum current of 0.239µA after 4 seconds at the head of curve, while the minimum current was 0.162µA at end of the curve. The difference between the maximum and minimum PDC values was 77nA

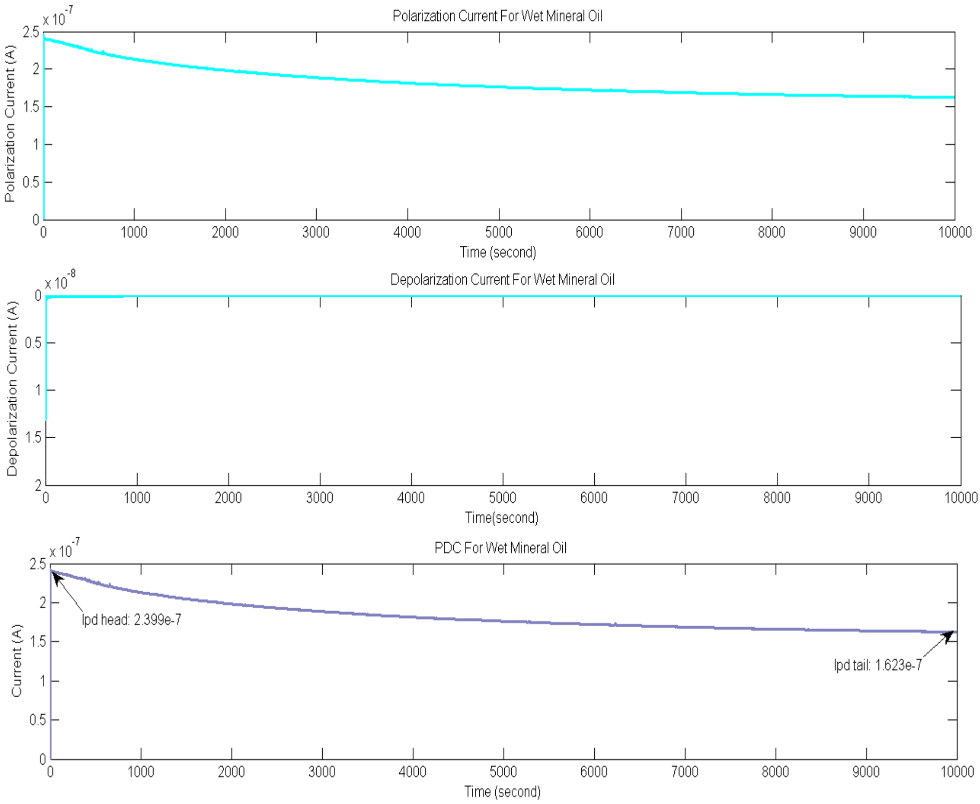


**Figure 8**. PDC test result for wet mineral oil

Based on the measured values above, the maximum DC conductivity of the wet mineral oil is calculated as below:

$$C_m = 18.8\text{pF}, \ \textit{Maximum}\ i_{pd}(t) = i_{pd}(4) = 0.239\mu\text{A}$$

Hence:

$$\sigma_r = \frac{1.946\times10^{-14}}{18.8\times10^{-12}}(2.39\times10^{-7}) \ = 0.248\text{nS/m}$$

Using curve-fitting, the dielectric response function *f(t)* of this oil can be expressed as:

$$f(t) = \frac{-\begin{pmatrix} 6.9\times10^{-46}t^{10} - 3.6\times10^{-41}t^{9} + 8.2\times10^{-37}t^{8} - 1.0\times10^{-32}t^{7} + 8.1\times10^{-29}t^{6} - 4.0\times10^{-25}t^{5} \\ +1.3\times10^{-21}t^{4} - 2.4\times10^{-18}t^{3} + 2.7\times10^{-15}t^{2} - 1.4\times10^{-12}t \ + 3.8\times10^{-10} \end{pmatrix}}{18.8\times10^{-12}(1000)}$$

## 6.0 DISCUSSION

The summary of the PDC pattern for this test is shown in Figure 9. At first, the pattern was plotted in linear scale for both axes. However, in order to have a better view, the log scale for the vertical axis was applied in the second plot. The wet oil condition (aged insulation oil) has the highest polarization and depolarization current, followed by the normal and then dried oil conditions.

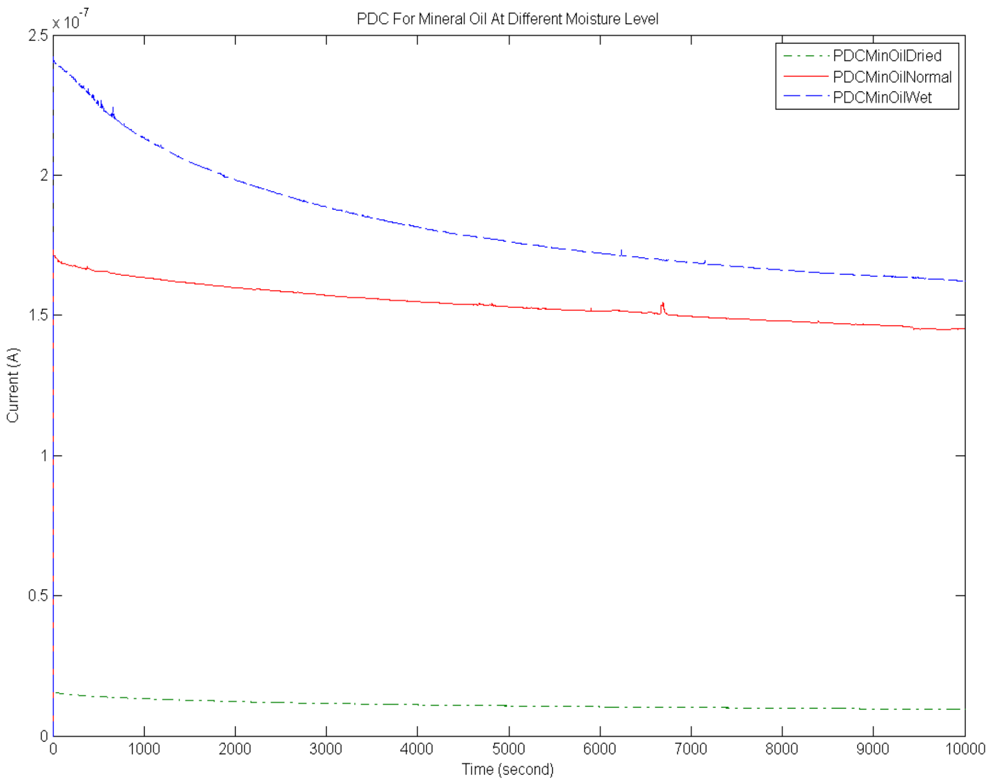


**Figure 9**. Summary of PDC pattern obtained during test using test cell

The result obtained during the PDC test using test cell have same pattern as result of the PDC test done on the transformer in services by researchers [16] as shown in figure 10 and the transformer insulation properties tested by the researcher was shown in Table II below. Both test result show that the oil that have highest moisture content will polarization and depolarization current value.

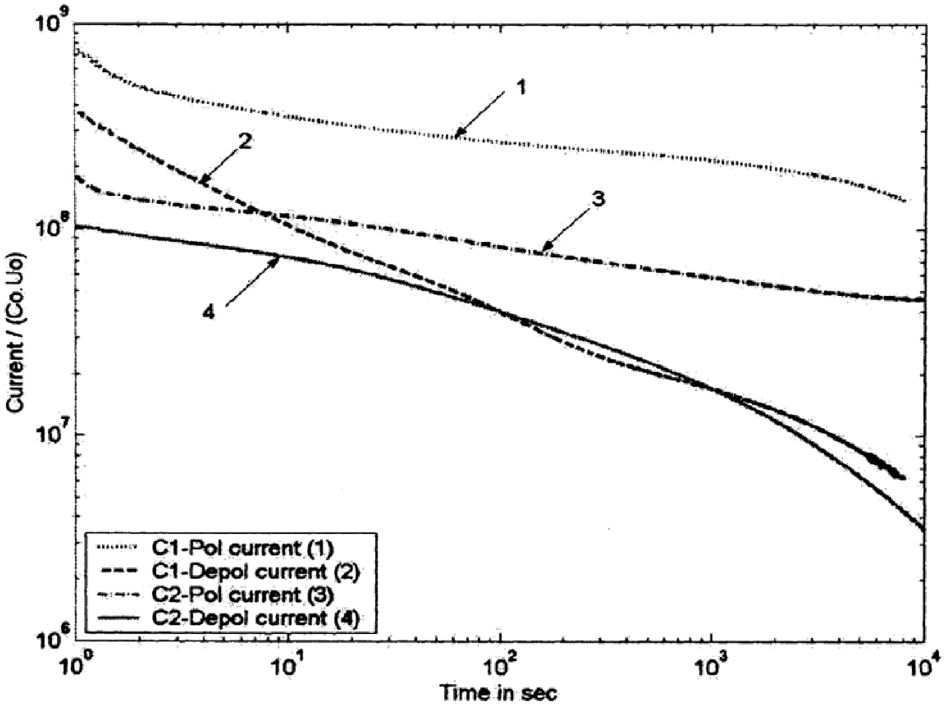


**Figure 10** PDC pattern of oil insulation for transformer in services

**Table 11** Insulation condition of tested transformer in services

| Transformer | | C1 | C2 |
|---|---|---|---|
| Conductivity (S/m) | Oil | $31.0\times10^{-12}$ | $3.6\times10^{-12}$ |
| | Paper | $2.3\times10^{-12}$ | $3.8\times10^{-13}$ |
| Capacitance (nF) | | 9.2 | 10.2 |
| 2-Furfuraldehyde (ppm) | | 1.87 | 3.81 |
| Moisture Content | Oil (ppm) | 36 | 26 |
| | Paper (%) | 4.2 | 3.2 |
| Oil Sampling Temp. (°C) | | 40 | 40 |

## 7.0 CONCLUSION

The designed test cell can be used to perform the PDC testing to monitor condition of the oil-filled transformer insulation. This method of testing show same PDC result pattern with the on-side testing. Both test PDC show that increased moisture content in the insulation oil will increase the polarization and depolarization current value. PDC test using test cell give an advantage of saving the service down time of running the PDC test on transformer on-side. Indeed, unlike the on-side testing that have PDC result inform of mixing of insulations oil and paper degradation, PDC testing using the test cell give independent degradation value of the oil. Because of this, the insulation oil assessment gives more accurate result on its condition compared to on-side testing

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