ASSESSING AGEING CONDITION OF MINERAL OIL-PAPER INSULATION BY POLARIZATION/DEPOLARIZATION CURRENT

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Abstract: Accurately assessing the ageing status of oil-paper insulation in transformer is essential and important. Polarization and Depolarization Current (PDC) technique is effective in assessing the condition of oil-paper insulation system. Though the PDC behaviour of mineral oil-paper insulation has been widely investigated, there is no report about how to make the quantitative analysis of mineral oil-paper insulation ageing condition by PDC. The PDC characteristics of mineral oil-paper insulation samples were investigated over the ageing period at 110°C. A new method for assessing the ageing condition of mineral oil-paper insulation by calculating the depolarization charge quantity was proposed. Results show that the depolarization charge quantity of mineral oil-paper insulation sample is very sensitive to its ageing condition. The stable depolarization charge quantity could be used to predict the ageing condition of mineral oil-paper insulation.

1 INTRODUCTION

Power transformers play a vital role in the whole electrical power system. The main insulation system of power transformer consists of cellulosic material and insulation oil, which degrades under a combined action of thermal, electrical, mechanical and chemical stresses during transformer routine operation [1-2]. The degradation of the main insulation system in transformer is recognized to be one of the major causes of transformer breakdown [3-7]. Therefore, accurately assessing the status of the transformer insulation is essential and important.

In recent years, the need to assess the insulation system non-destructively and reliably has driven the development of dielectric response diagnostic tools, which are based on the changes in the dielectric properties of the oil-paper insulation [7-10]. Polarization/Depolarization Current (PDC) is not only a non-destructive dielectric method being widely used to assess the moisture content and the ageing condition of oil-paper insulation used in transformers, but also a diagnostic method which has attracted attention of a large number of scholars and engineers. There are many reports about the influence of moisture, ageing and testing temperature on the PDC characteristics of mineral oil-paper insulation [7, 11-15], because a combination of mineral oil with cellulose materials is widely used as the main insulation system in transformers.

The degradation of the cellulosic materials immersed in insulation oil determines the remaining life of transformer [1-2]. To fully utilize the PDC technique to assess the condition of oil/paper insulation system, how to make quantitative analysis of ageing status of mineral oil-paper insulation by the PDC method is required to be addressed.

In this paper, the influence of ageing on the PDC characteristics of mineral oil-paper insulation samples was provided. Modelling PDC data with R-C circuit parameters is one of the most common techniques utilized in insulation condition assessment [16-21]. The R-C circuit parameters of mineral oil-paper insulation samples with different ageing conditions were fitted by their depolarization current. And then the depolarization charge quantity changing with the ageing condition of the oil-paper insulation samples was analyzed. At last, a new method for making quantitative analysis of the ageing status of mineral oil-paper insulation samples by PDC method was proposed.

2 THEORY

2.1 PDC principle

The measurement of the polarization and depolarization current following a dc voltage step is one way in the time domain to investigate the slow polarization processes of dielectrics [7-15]. When an external voltage u(t) is applied on the dielectric material, the current through the dielectric material can be expressed as:

$$i(t) = C_0[\frac{\sigma}{\varepsilon_0}u(t) + \varepsilon_r \frac{du(t)}{dt} + \frac{d}{dt}\int_0^t f(t-\tau)u(\tau)d\tau] \quad (1)$$

where, C_0: geometrical capacitance of the dielectric material, u(t): the step voltage, σ : the dc conductivity of the dielectric material, ε_0: the vacuum permittivity 8.852*10^{-12} F/m, ε_r: the relative permittivity of the dielectric material, f(t) : the response function of the dielectric material.

Simplified diagram of the PDC measurement for the test object is shown in Figure 1(a) [7]. Figure 1(b) shows a typical polarization and depolarization current due to a step charging voltage U_C [7]. Assuming that a dc step voltage u(t) with the following characteristics is applied to a totally discharged test object.

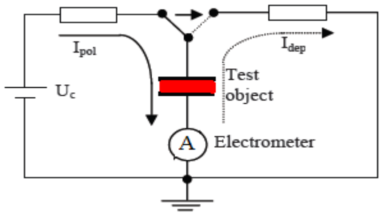
$$u(t)=\begin{cases} 0 & t<0 \\ Uc & 0\le t\le t_1 \\ 0 & t_1<t \end{cases} \tag{2}$$

As shown in Figure 1(b), T_p which is from t=0 to t_1 represents the polarization duration time, and T_d is the depolarization duration time. When t<0, the current through the test object is zero, and for time $0\le t\le t_1$ the so called polarization current is generated due to the conductivity and the various polarization processes of the test object. The polarization current can be written as:

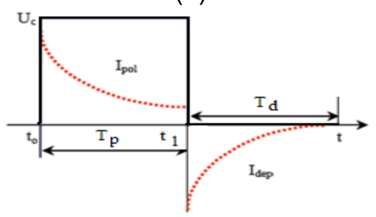
$$i_{pol}(t)=C_0U_c[\frac{\sigma}{\varepsilon_0}+f(t)] \tag{3}$$

At time $t=t_1$, the external voltage is removed and the test object is short circuited, the depolarization current can be expressed as:

$$i_{dep}(t)=-C_0U_c[f(t)-f(t+t_p)] \tag{4}$$



(a)



(b)

Figure 1: Principle of PDC measurement

2.2 R-C equivalent circuit model

It is commonly known that dielectrics with alternating layer of oil and paper can be simulated with R-C equivalent circuit model [16-21]. The polarization processes inside the oil-paper insulation structure can be modelled by a parallel arrangement of branches each containing a series connection of resistor and capacitor as shown in Figure 2.

The circuit parameters shown in Figure 2 can be derived from measured polarization and depolarization currents (i_{pol} and i_{dep}). The capacitance C_0 is determined by conventional capacitance measurement techniques at power frequency. The insulation resistance R_0 is calculated from the difference between polarization and depolarization current at larger values of time. These polarization processes, represented as R_i-C_i, are randomly distributed, and have associated time constants given by $\tau_i=R_iC_i$. The individual elements R_i-C_i with the corresponding time constants $\tau_i=R_iC_i$ can be determined by fitting the depolarization current with the following equation:

$$i_{dep}(t)=\sum_{i=1}^{n}(A_i*e^{-\frac{t}{\tau_i}}) \tag{5}$$

$$A_i=U_c*\frac{1-e^{-\frac{T_p}{\tau_i}}}{R_i} \tag{6}$$

Where, n is the number of R_i-C_i branches.

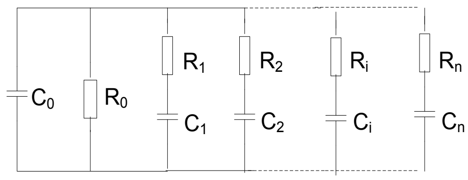


Figure 2: R-C equivalent circuit model

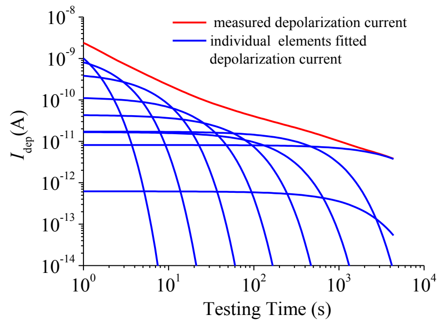


Figure 3: Individual elements of the depolarization current

Table 1: The fitting parameters of curve for simulating

Branches	τ_i(s)	A_i	$R_i(\Omega)$	C_i(F)
1	0.562	5.94×10^{-9}	3.36×10^{10}	1.67×10^{-11}
2	1.78	1.41×10^{-9}	1.41×10^{11}	1.26×10^{-11}
3	5.62	4.56×10^{-10}	4.39×10^{11}	1.28×10^{-11}
4	17.8	1.17×10^{-10}	1.71×10^{12}	1.04×10^{-11}
5	56.2	4.35×10^{-11}	4.6×10^{12}	1.22×10^{-11}
6	178	1.67×10^{-11}	1.2×10^{13}	1.49×10^{-11}
7	562	1.72×10^{-11}	1.16×10^{13}	4.84×10^{-11}
8	1780	6.20×10^{-13}	3.03×10^{14}	5.87×10^{-12}
9	5620	8.14×10^{-12}	1.45×10^{13}	3.88×10^{-10}

Figure 3 shows the result of the analytic fitting method. The red line in Figure 3 is the depolarization current of new short winding (Figure 5) immersed in new mineral oil measured at 27±

0.1ºC, U_c=200V, T_p=5000s. The blue lines in Figure 3 are the individual elements fitted the depolarization current according to equations (5) and (6), and the R_i-C_i values are shown in Table 1.

As can be seen from Figure 4, the depolarization current measured and the depolarization current simulated by equations (5) and (6) according to the data in Table 1 performs satisfactory. The results show that the experimental and R-C circuit model simulation is in good agreement with each other. In this paper, the depolarization current of oil-paper insulation samples with different ageing conditions were fitted according to equations (5) and (6), and the R-C circuit parameters were obtained to calculate the depolarization charge quantity.

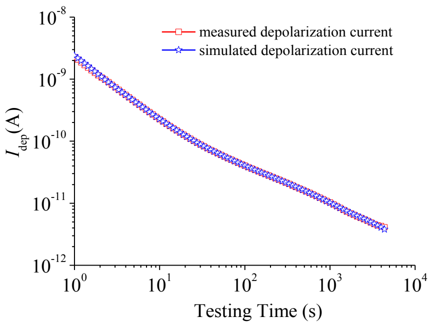


Figure 4: Comparison of measured and simulated curves of depolarization current

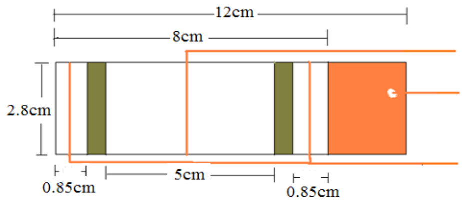
3 EXPERIMENTAL

3.1 Experiment materials

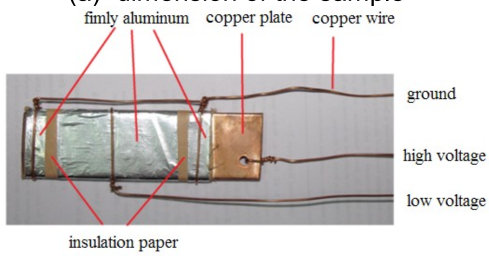
The mineral oil used in this experiment was Karamay 25# naphthenic mineral oil provided by Chuanrun Lubricant Co. Ltd, China. Its electrical index accords with the ASTM D3487-2000(II) standards. The insulation windings used in transformer were provided by ABB Chongqing Transformer Co. Ltd. There are ten layers insulation paper (75μm thickness) wrapped the copper plate (width 2.8cm, thickness 0.2cm). The windings were cut short according to the dimension shown in Figure 5(a), and the real winding sample used for PDC measurement is shown in Figure 5(b). The aluminum foil was wrapped outside the insulation paper to achieve a good measurement result. When the windings aged in oil were measured by PDC equipment, the windings were firstly dealt with in vacuum like the sample shown in Figure 5(b).

3.2 Thermal ageing experiment of oil-paper insulation samples

In this paper, accelerated thermal ageing experiment of windings immersed in mineral oil at 110°C was done. Firstly, in order to simulate the real ageing condition in modern sealed transformers, all winding samples and pressboards were put into a vacuum box and dried at 90°C for 48 hours. Then the temperature of the vacuum box was adjusted to 40°C. Secondly, the new degassed and dried mineral oil was infused into the vacuum box. The vacuum box was left for 24 hours at 40°C and then cooled down to room temperature. Thirdly, three winding samples and 38g pressboard samples were taken out of the vacuum box each time and put into a glass bottle (1000ml). Then new mineral oil was poured into each bottle at a mass weight ratio of liquid/cellulose materials equal to 10:1 (each bottle has 630g oil and 63g cellulose material). Then every bottle was filled up with nitrogen and sealed. These bottles were finally put into the ageing ovens and heated to 110°C for the accelerated thermal ageing experiment. The initial moisture content of new mineral oil is 13 mg/Kg. The initial moisture content of paper wrapped the cooper plate immersed in mineral oil is 2.0%.



(a) dimension of the sample



(b) real object

Figure 5: Sample for PDC measurement

3.3 PDC Measurement

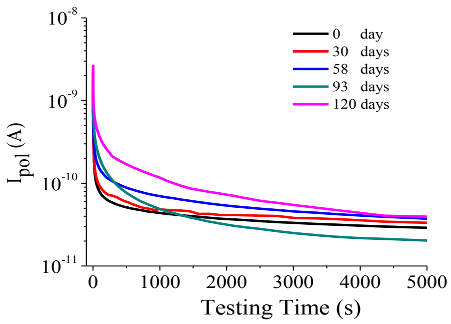
The PDC measurements of windings aged in mineral oil for different times were performed using PDC-analyser-1MOD, ALFF Engineering, Switzerland. The experiments were done at charging voltage U_c=200V, polarization duration T_p=5000s, depolarization duration T_d=5000s, and testing temperature T=27±0.1ºC.

Before taking samples for PDC test, the aged sample was gradually cooled down to room temperature in vacuum box for two months to obtain the room-temperature equilibrium distribution between cellulose and oil. When the PDC measurement was conducted, the winding and insulation oil together after ageing for different time intervals were contained in a column bottle (1000ml), and 400ml insulation oil was infused to immerse the winding. Then the bottle was sealed with plastic film. And the copper wire (Figure 5(b) was wrapped with plastic insulation pipe.

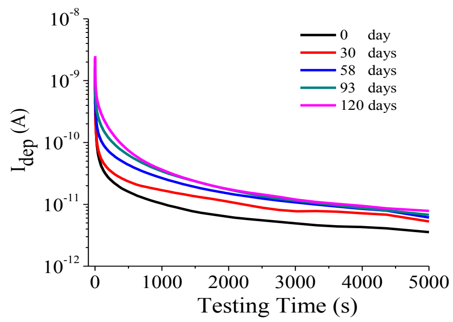
4 RESULTS AND DISCUSSIONS

4.1 PDC behaviours of oil-paper insulation samples with different ageing condition

PDC measured at different ageing intervals on the mineral oil-paper insulation samples are shown in Figure 6. The polarity of the depolarization current values has been changed to positive values for easy comparison. The polarization/depolarization current of mineral oil-paper insulation samples reaches a relative stable value with the testing time increased. The long term polarization current value increases with the ageing time apart from the sample aged for 93 days. While the long term depolarization current of mineral oil-paper insulation sample increases with the ageing time all the time. The initial polarization current values are dominated by the oil condition, whereas the long term current values are sensitive to the condition of paper insulation [7, 26]. It is noteworthy that the amplitude of long term depolarization current is sensitive to the ageing condition of oil-paper insulation samples (Figure 8(b)). The longer the ageing time, the higher amplitude of the depolarization current values of mineral oil-paper insulation sample.



(a) polarization current



(b) depolarization current

Figure 6: PDC measurements on the mineral oil-paper insulation sample with different ageing condition

The oil conductivity and moisture content of paper during the ageing process are presented in Table 2. The oil conductivity increases in the ageing process. While the moisture content of the paper in the ageing process increases firstly and then decreases.

Table 2: Oil conductivity and moisture content of paper during the ageing process

Ageing time (day)	0	30	58	93	120
Mineral oil conductivity (10^{-11} S/m)	0.58	2.77	1.87	2.65	4.57
Moisture content of mineral oil impregnated paper (%)	2.00	2.08	2.19	2.05	1.54

4.2 Relation between depolarization charge quantity and ageing status of oil-paper insulation samples

In order to explore the relationship between the depolarization current of oil-paper insulation samples and their ageing condition, the depolarization charge quantity of the oil-paper insulation samples aged for different times was investigated. Firstly, the R-C equivalent circuit model is validated by comparing the depolarization current simulated and the depolarization current measured, as shown in Figure 4. Secondly, the R-C equivalent circuit parameters for the mineral oil-paper insulation samples with different ageing condition were obtained. Then the depolarization charge quantity of mineral oil-paper insulation samples was calculated from their equivalent circuit parameters, as follows:

$$Q(t) = \int_{1}^{5000} I_{dep}(t)dt$$

Where t is the testing time, 1≤t≤5000s.

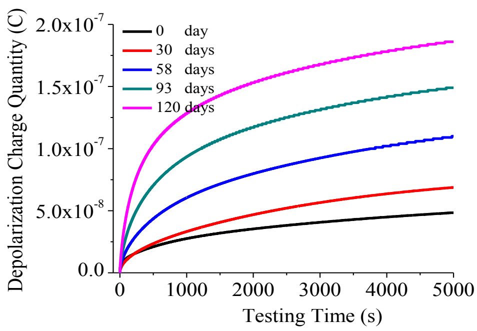


Figure 7: Depolarization charge quantity results of oil-paper insulation sample with different ageing condition

Table 3: Relation between the depolarization charge quantity and testing time for mineral oil-paper insulation sample in the ageing process

Ageing time (day)	Fitting equations Q(t)=C+A*exp(-t/B)	R^2
0	$Q_0(t)$=5.0634E-8-3.8789E-8exp(-t/2082.22)	0.991
30	$Q_{30}(t)$=7.6254E-8-6.6487E-8exp(-t/2413.37)	0.997
58	$Q_{58}(t)$=1.1253E-7-9.4359E-8exp(-t/1826.88)	0.992
93	$Q_{93}(t)$=1.4733E-7-1.1833E-7exp(-t/1371.97)	0.986
120	$Q_{120}(t)$=1.8078E-7-1.3487E-7exp(-t/1135.33)	0.974

The depolarization charge quantity results of mineral oil-paper insulation samples with different ageing conditions are shown in Figure 7. It can be that the depolarization charge quantity of oil-paper insulation samples is very sensitive to their ageing condition. The more deterioration the oil-paper insulation sample, the faster increasing rate the depolarization charge quantity, and the higher value the depolarization charge quantity. The relationship between the depolarization charge quantity and testing time is shown in Table 3. For each oil-paper insulation sample, it can be seen that the depolarization charge quantity increases in an exponential way Q(t)=C+A*exp(-t/B) with the testing time. R^2 is the coefficient of determination, which is used to measure how successful the fit is in explaining the variation of the data. R^2 value closer to 1 indicates a better fit. $Q_0(t)$ means the depolarization charge quantity of the oil-paper insulation sample aged 0 day, $Q_{30}(t)$ means the depolarization charge quantity of the oil-paper insulation sample aged 30 days, etc.

In order to make quantitative analysis of the depolarization charge quantity of oil-paper insulation sample and its ageing condition, the degree of polymerization (DP) of the paper on the winding aged in mineral oil was measured. DP values of paper aged in mineral oil decrease fast in the initial ageing stage due to the high moisture content of the insulation paper, as shown in Figure 8.

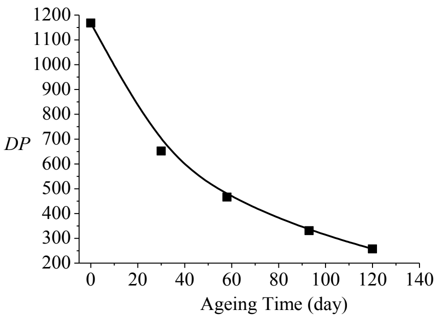


Figure 8: DP of paper aged in mineral oil

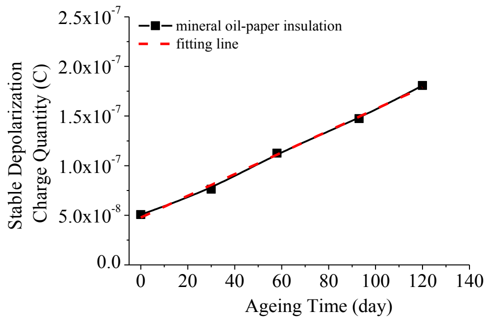


Figure 9: Q_{stable} of mineral oil-paper insulation sample and ageing time

Table 4: Q_{stable} of mineral oil-paper insulation sample and its ageing tine

Fitting equations $Q_{stable}(t)$= a*t+b	R^2
$Q_{stable}(t)$= 1.093E-9*t+4.773E-8	0.996

The constant C in Table 3 is defined as the stable depolarization charge quantity Q_{stable}. The relation-

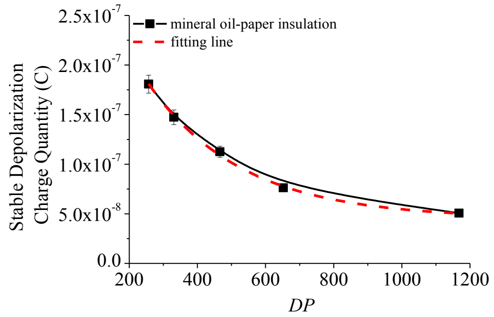


Figure 10: Q_{stable} of mineral oil-paper insulation sample and DP

Table 5: Q_{stable} of mineral oil-paper insulation sample and DP

Fitting equations $Q_{stable}(DP)$=E*exp(-DP/F)+D	R^2
$Q_{stable}(DP)$=3.442E-7*exp(-DP/275.81)+4.545E-8	0.997

ship between the stable depolarization charge quantity of oil-paper insulation sample and its ageing time, as well as DP of paper has been investigated, as shown in Figure 9 and Table 4, Figure 10 and Table 5, respectively. From Figure 9 and Table 4, it can be clearly seen that there is a linear relationship between the Q_{stable} and the ageing time of mineral oil-paper insulation samples. From Figure 10 and Table 5, it clearly shows that there is an exponential relationship between the Q_{stable} and DP of paper. Therefore, the stable depolarization charge quantity can be used to predict the ageing condition of oil-paper insulation.

5 CONCLUSIONS

The depolarization charge quantity of oil-paper insulation sample calculated from their depolarization current is very sensitive to their ageing condition. The more deterioration the oil-paper insulation sample, the higher the stable depolarization charge quantity.

The stable depolarization charge quantity Q_{stable} of mineral oil-paper insulation sample increases in a linear way with the ageing time. There is an exponential relationship between the Q_{stable} and DP of paper aged in mineral oil-paper insulation sample. The stable depolarization charge quantity can be used to predict the ageing condition of oil-paper insulation.

6 ACKNOWLEDGMENTS

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