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Study on Influences and Elimination of Test Temperature on PDC Characteristic Spectroscopy of Oil-Paper Insulation System

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Abstract – Test temperature is an important factor affecting the measurement results of dielectric response of field power transformers. In order to better apply the polarization and depolarization current (PDC) to the condition monitoring of oil-paper insulation system in power transformers, the influences and elimination method of test temperature on PDC characteristic spectroscopy (PDC-CS) were investigated. Firstly, the experimental winding sample was measured by PDC method at different test temperatures, then the PDC-CS was obtained from the measurement results and its changing rules were discussed, which show that the PDC-CS appears a horizontal mobility with the rise of temperature. Based on the rules, the "time temperature shift technique" was introduced to eliminate the influence of test temperature. It is shown that the PDC-CS at different test temperatures can be converted to the same reference temperature coincident with each other.

Keywords: Test temperatures, Oil-paper insulation system, PDC characteristic spectroscopy (PDC-CS), Time temperature shift technique

1. Introduction

The safe operation of power transformers is of great significance. According to relevant statistics, operation faults of transformers are mainly caused by the failure of insulation system [1, 2]. The main insulation system of power transformer containing oil and paper will degrade under a combined action of thermal, electrical, mechanical and chemical stresses during transformer routine operation [3,4]. Therefore, accurate assessment for insulation condition of power transformers turn out to be significant, based on which, effective strategies like maintenance or replacement then can be taken.

Correlative data [5] have indicated that the lifetime of transformer insulation is determined by the solid insulation (insulation paper and pressboard). In other words, the evaluation of insulation cellulose condition will be the key to access the aging states of transformers. So far, three kinds of traditional diagnosis methods for transformer oil-paper insulation aging status have been recognized widely as the follows: Dissolved Gas Analysis (DGA) [6], test of furfural content in the oil [7], and test of degree of polymerization of insulation cellulose [8]. However, there are obvious deficiencies about these methods. For example, due to the oil replacement for transformers, the method of physical-chemical inspection focused on insulation oil may not reflect the facts. On the other side, although DP can reflect the most reliable aging status of insulation cellulose, it will damage insulation system in turn and needs removing the transformer covers to get test samples.

In recent years, new diagnosis methods including Return Voltage Method (RVM) [9], Polarization and Depolarization Current (PDC) [10, 11], Frequency Domain spectroscopy (FDS) [12] based on dielectric response, have drew much attention with the advantages of no sampling and non-invasive measurement, etc. Contrasting the above methods with each other, we can see that: RVM method can't distinguish the different influences of insulation oil and paper on characteristic spectroscopy which makes it difficult in practical application; FDS method performs without the problems in RVM, but it takes too much time for measurement limited to field test; PDC method with advantages of short test time and abundant information of insulation is very suitable for noninvasive diagnosis of field transformer oil-paper insulation ageing status which will be discussed in this paper.

It is worth mentioning that the test temperature is one of the most important factors affecting measurement results of dielectric response [13, 14]. That is to say, PDC measurement results onsite will be possibly different at different time one day, and in different seasons due to the changing temperatures. So it needs further research on this issue, otherwise the application of PDC method will be hard. Many scholars have done relevant research. Reference [15] discovered that dielectric response measurement is greatly affected by test temperature, which will result in inaccurate state assessment of oil-paper insulation. It is shown in [16] that with rising temperature, conductivity and polarization/depolarization current of oil-paper insulation gradually

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increase. Analogously, the effect of test temperature on PDC measurement was studied in [17] with the conclusion that with the rise of test temperature, polarization/depolarization current of test object also gradually increase and decay more quickly with test time passing by. However, the study didn't mention how to eliminate the influence of test temperature. Reference [18] proposed a new method calling "stable depolarization charge quantity" to access aging status of oil-paper insulation which had similar conclusions with [17]. But it also hasn't studied the influence of test temperature on "stable electric quantity depolarization" and its elimination method.

Going further with the current studies, this paper focuses on the influence and elimination of test temperature on PDC characteristic spectroscopy of oil-paper insulation. The following work have been done: firstly, experimental sample was measured by PDC method under different test temperatures; then, the PDC-CS was obtained from the test results by a new method and the influence of test temperature on it was exposed; lastly, a method called "time temperature shift technique" was introduced to eliminate the influence of test temperature on the PDC-CS.

2. Preparation of Test Sample and PDC Measurement

2.1 Preparation of oil-paper insulation

The test object-winding model was shown in Fig. 1.

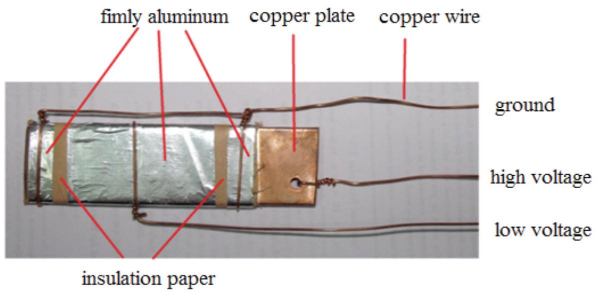


Fig .1. Geometric construction of measured winding

The copper plate was wrapped by ten layers of insulation paper, and the insulation paper was wrapped by three sections of aluminum foils to get a good measurement result. Insulation materials used in the experiment included 25# transformer oil from Karamay Sinkiang, insulation paper made from ordinary cellulose each with a thickness of 75μm and winding from Chongqing ABB.

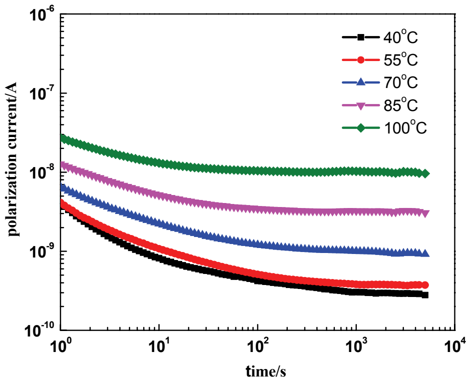
2.2 Process of PDC measurement

The process of PDC test was conducted as follows: firstly, the winding sample was placed in fresh oil for impregnation, then it was put into a flask which, in the next, was kept in oil bath with initial temperature of 40°C. After sample reached the target temperature, the flask was sealed and kept for two days until the moisture content between insulation oil and paper reached balance. After that, PDC measurement was carried out with the parameter setting: measurement voltage was set as U_0=200V, and polarization and depolarization time were both set to 5000s. The winding sample was measured by PDC-Analyser-1MOD from company ALFF ENGINEERING in Switzerland. After measurement, high and low voltage electrodes of winding were shorted to release the residual charges in sample. Then, test temperature was raised and kept at 55°C also for two days. Analogously, the above steps were repeated for the next measurement. As a rule, test temperature was 15°C higher than the former one for each new measurement. Through the process, we got PDC measurement results of sample at different test temperatures of 40°C, 55°C, 70°C, 85°C and 100°C.

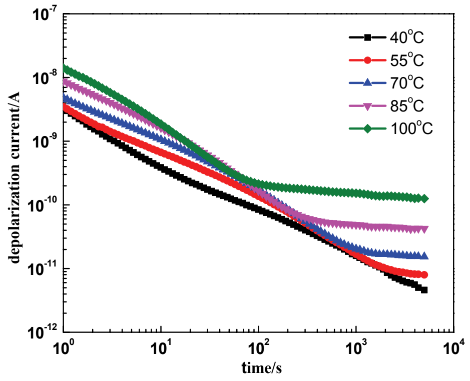
3. Test results and analysis

3.1 PDC measurement results of winding sample with different test temperatures

Fig. 2 shows the polarization and depolarization current of winding sample with different test temperatures. It can be seen that test temperature has great effect on



(a) Polarization current



(b) Depolarization current

Fig. 2. PDC curves with different test temperatures

measurement results. With the rise of test temperature, polarization and depolarization current gradually increase with faster attenuation and higher stable value in the end of the test. Moreover, the depolarization current appears an inflection point at high temperature. The rules above can be explained by: with rising temperature, average kinetic energy, movement speed, and migration rate of polarization and conductive particles in samples increase, leading the increase of the sample conductivity [15, 19].

3.2 Acquisition of PDC-CS and the influences of test temperature

Since there aren’t obvious rules between test temperature and PDC measurement results directly, one or more characteristic quantities should be obtained from the measurement results for the further study.

Reference [20] proposed a characteristic parameter-“depolarization charge quantity” to access the aging status of transformer oil-paper insulation defined as Eq. (1).

$$Q_{dep}(t)=\int_1^t I_{dep}(t)\,dt,\left(1\le t\le 5000s\right) \tag{1}$$

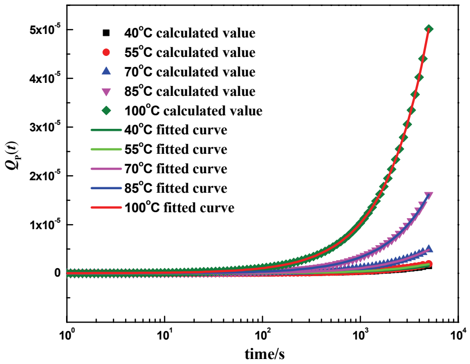
Some research had been taken on the influence of aging on the PDC-CS with the conclusion that depolarization charge quantity-$Q_{dep}(t)$ appears exponential growth with oil-paper insulation gradually aging. However, the quantitative connection of test temperature and $Q_{dep}(t)$ was not discussed. So $Q_{dep}(t)$ will be chosen as a characteristic quantity to study the influence and elimination of test temperature on PDC measurement.

Before discussing test temperature, a new characteristic parameter will be first introduced. Referring to the definition of $Q_{dep}(t)$ in Eq. (1), computing the integral for polarization current gets the polarization charge quantity - $Q_p(t)$ shown as Eq. (2).

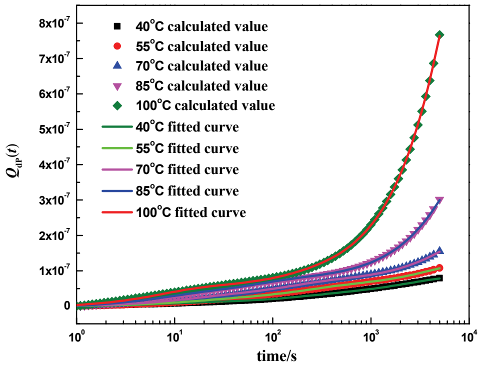
$$Q_p(t)=\int_1^t I_p(t)\,dt,\left(1\le t\le 5000s\right) \tag{2}$$

Compared with $Q_{dep}(t)$, $Q_p(t)$ carries more insulation information by the reason of polarization current contenting both conduction current and polarization current. This new characteristic parameter can play an important role in accessing oil-paper insulation condition of power transformers, meanwhile, provide a comparison to the former one to verify the effectiveness of the elimination method for the influences of test temperature.

Fig. 3 shows the varying pattern of PDC-CS of $Q_p(t)$ and $Q_{dep}(t)$ with different time and test temperatures(logarithm for abscissa, and linearity for ordinate).



(a) Polarization charge quantity $Q_p(t)$



(b) Depolarization charge quantity $Q_{dep}(t)$

Fig. 3. Calculated and fitted values of polarization and depolarization charge quantity with different temperatures

We can see that with test temperature rising, $Q_p(t)$ varies little in test period 10^0~10^2s, but increases in 10^2~5×10^3s significantly. While $Q_{dep}(t)$ increases in the whole period of depolarization, and also increase much more quickly in 10^2~5×10^3s. This is because polarization and depolarization current become slow to decay in 10^2~5×10^3s.What’s more, both $Q_p(t)$ and $Q_{dep}(t)$ increase faster with higher test temperature and appear a horizontal mobility with the rise of temperature. Superior to polarization and depolarization current, the PDC-CS collects more insulation information along with a period of test time, and will be more reliable compared to a series of test points. So, the PDC-CS is influenced by test temperature more strongly and regularly.

According to [21], the relaxation currents can be modeled by exponentials. As the integral of relaxation currents, the PDC-CS also meets the general model. Table 1 and Table 2 show the fitting relationship between $Q_p(t)$ and $Q_{dep}(t)$ and test time under different test temperatures which meet the exponential function with the goodness of fit up to 0.99.

Table 1. Fitting relation between polarization charge quantity $Q_p(t)$ and test temperature

Temperature	Fitted equation	R^2
40°C	$Q_p(t)$=5.19*10^{-6}-5.18*10^{-6}exp(-6.79*10^{-5}*t)	0.99
55°C	$Q_p(t)$=8.78*10^{-6}-8.77*10^{-6}exp(-4.87*10^{-5}*t)	0.99
70°C	$Q_p(t)$=2.27*10^{-5}-2.27*10^{-5}exp(-4.77*10^{-5}*t)	0.99
85°C	$Q_p(t)$=3.46*10^{-4}-3.46*10^{-4}exp(-9.53*10^{-6}*t)	0.99
100°C	$Q_p(t)$=9.38*10^{-4}-9.38*10^{-4}exp(-1.10*10^{-5}*t)	0.99

Table 2. Fitting relation between depolarization charge quantity $Q_{dep}(t)$ and test temperature

Temperature	Fitted equation	R^2
40°C	$Q_{dep}(t)$=8.57*10^{-8}-9.75*10^{-9}exp(-t/7.77)-2.11*10^{-8}exp(-t/184.75)-5.52*10^{-8}exp(-t/2496.14)	0.99
55°C	$Q_{dep}(t)$=1.31*10^{-7}-1.67*10^{-8}exp(-t/14.74)-3.66*10^{-8}exp(-t/192.35)-7.80*10^{-8}exp(-t/4341.75)	0.99
70°C	$Q_{dep}(t)$=2.87*10^{-7}-2.51*10^{-7}exp(-t/12.29)-4.38*10^{-8}exp(-t/139.72)-2.19*10^{-7}exp(-t/10089.12)	0.99
85°C	$Q_{dep}(t)$=1.02*10^{-6}-3.37*10^{-8}exp(-t/6.71)-4.31*10^{-8}exp(-t/62.74)-9.44*10^{-7}exp(-t/18201.96)	0.99
100°C	$Q_{dep}(t)$=2.94*10^{-6}-5.48*10^{-9}exp(-t/6.98)-2.48*10^{-8}exp(-t/126.23)-2.87*10^{-6}exp(-t/18199.58)	0.99

3.3 Elimination method for influences of test temperature on PDC-CS

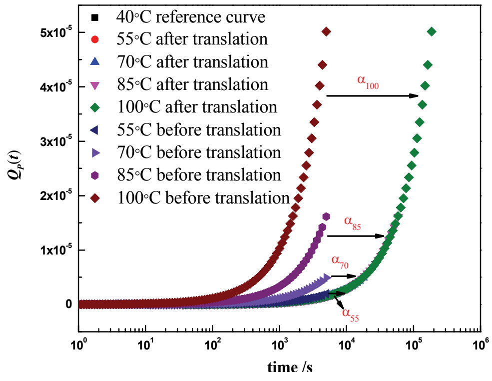
In the research of aging characteristics and aging mechanism of transformer oil-paper insulation, reference [22] found an idea called "time- temperature superposition [23]", which can be used as a guidance to improve the thermal aging model of oil-paper insulation by introducing the second order kinetics model. Based on the above thoughts and the change rule discussions of PDC-CS in section 3.2, a method of eliminating the influences of test temperature will be introduced, called "time temperature shift technique".

Firstly, the $Q_p(t)$ curve under 40°C is chosen as the master curve -"S_1". Then, the rest of the $Q_p(t)$ curves under 55°C, 70°C, 85°C and 100°C are moved along time axis to S_1 horizontally, so does the treatment of the $Q_{dep}(t)$ curves. Through the translation, different curves almost coincide with each other. The combination of these curves form a new feature curve called "S_2". In this way, differences of the PDC-CS caused by test temperatures have been basically eliminated. The curves before and after translation are shown in Fig. 4.

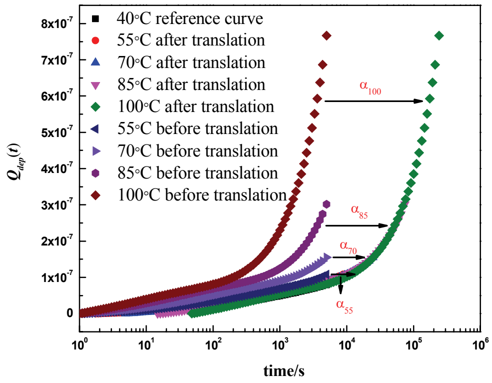
For the purpose of forming the new feature curve S_2, a variable-"time temperature shift factor" is defined as:

$$\alpha_T = \frac{t_{ref}}{t_T} \tag{3}$$

Where: t_{ref} is the time corresponding to a certain point on PDC-CS after translation; t_T is the time corresponding to the same point before shift. In other words, α_T is equivalent to the change of length of curves for the horizontal translation. The following will focus on the compute of α_T by the example of $Q_p(t)$. The "time temperature shift factor" with 40°C is defined as α_{40}=1. Based on the change of time axis in Fig. 4(a) during the translation, computing the ratio of the time of one point in the curve before and after move, gets the "time temperature shift factor" α_T as: α_{55}=1.2656, α_{70}=3.5473, α_{85}=11.8059, α_{100}=37.1810, which are shown in Fig. 4(a).



(a) $Q_p(t)$



(b) $Q_{dep}(t)$

Fig. 4. Formation of master curve of PDC characteristic spectroscopy

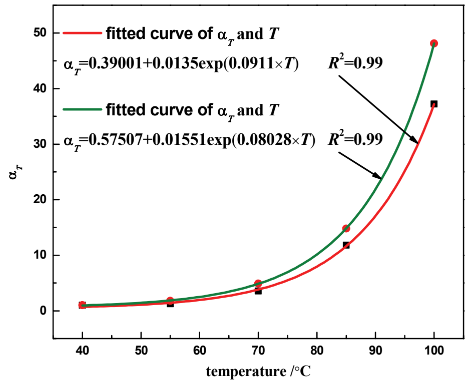


Fig. 5. Fitting relation between time temperature shift factor and test temperature

Fitting α_T with test temperature gets the exponential relationship as Fig. 5 shows, from which, the PDC-CS under any test temperature can be formed to the new feature curve to be classified into the same reference temperature. Conversely, once providing α_T at any test temperature and the PDC-CS with reference temperature so called the master curve, the PDC-CS with all test temperatures can be figured out. So this method eliminates the influence of test temperature on PDC-CS and improves the reliability of transformer oil-paper insulation condition assessment.

It is worth mentioning that, through the method "time temperature shift technique", the time horizon of the PDC-CS is expanded from 10^0~5×10^3s to 10^0~10^5s, which means, without any increase in test time, it can be realized to collect more information of PDC-CS. It is of great advantage to field test.

Obviously, before applying the PDC-CS-$Q_p(t)$ and $Q_{dep}(t)$ into condition assessment of field transformer oil-paper insulation, a large quantity of essential data of PDC features at different test temperatures should be collected and "time temperature shift factor" α_T need to be further modified to ensure the accuracy.

4. Conclusion

In this paper, transformer winding sample was measured by PDC method at different test temperatures, and the PDC-CS was obtained from original data. Then the influences and elimination of test temperature on the PDC-CS were discussed. The conclusions are made as follows:

(1) Test temperature has great effect on polarization and depolarization current. With the rise of test temperature, polarization and depolarization current gradually increase and come to the stable value more quickly. An inflection point appears in depolarization current at high temperature.
(2) With rising test temperature, in the test period 10^0~10^2s, $Q_{dep}(t)$ significantly increases, but $Q_p(t)$ basically keep unchanged. $Q_p(t)$ and $Q_{dep}(t)$ both increase in the test period 10^2~5×10^3s, which appear a horizontal mobility.
(3) By introducing "time temperature shift factor" α_T and constructing the new feature curve, the PDC-CS at any test temperature can be classified into the same reference temperature, thus the influence of test temperature can be eliminated.

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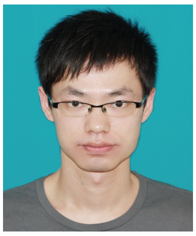

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