Effect of Temperature, Water Content and Aging on the Dielectric Response of Oil-Impregnated Paper

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Abstract- In this contribution, Fourier transform of dielectric responses from Polarization and Depolarization Current measurements were investigated to evaluate temperature and aging effects on dielectric response of oil paper insulation system. Measurements of the dielectric response were performed at three temperatures and aging conditions. To provide quantitative analysis from measurements, the current curves were decomposed into basic exponential functions. Attempts have been performed to correlate the physical condition of the insulation and the equivalent model parameters. The obtained results indicate the feasibility of using the relaxation time constants and coefficients to depict the temperature, water content and aging effects.

I. INTRODUCTION

Condition monitoring of the insulation of transformers is an important issue since many transformers in electrical industries around the world are approaching the end of their design life. When power transformers fail, the fault can be traced usually to defective insulation. Since the quality of the insulation is a key element for reliable operation of a power transformer, condition monitoring can be utilized to attempt the prediction of the insulation condition and the remaining lifetime of a transformer.

Modern non-destructive, off-line techniques used by many engineers and researchers around the world include the Interfacial Polarization Spectra measurement by Frequency Domain Spectroscopy (FDS) and Polarization and Depolarization Current Measurements (PDC) [1-3]. However, their popularity has not been as well spread as anticipated due to the requirement of the expertise for their evaluation and analysis. In particular a number of factors need to be understood.

The main objective of this contribution is to report about the investigations concerning the time domain dielectric response (PDC) of an oil paper insulation system at different operating ranges of temperature, water content and aging. Measurements have been performed in laboratory, on some oil-impregnated pressboard samples. Temperature, water content and aging effects on the characteristic of the insulation system were investigated.

To obtain a quantitative data from PDC measurements for evaluating the temperature, moisture content and aging effects on the insulation, the polarization and depolarization currents were modeled with basic exponential functions. The polarization and depolarization currents were fitted with five exponential functions. The results show a relation between the relaxation time constants and coefficients to the temperature, water content and aging.

II. BACKGROUND KNOWLEDGE

The polarization and depolarization current indicated in the literature as “PDC” measurements is a non-destructive method for determining the condition of insulation materials in power equipments [1-3]. The measurement of PDC following a dc voltage step is a way in the time domain to investigate the slow polarization processes [1-4]. The dielectric memory of the test object must be cleared before the PDC measurement. The voltage source should be free of any ripple and noise in order to record the small polarization current with sufficient accuracy. The procedure consists in applying a dc charging voltage of magnitude \( U_c \) to the test object for a long time (e.g., 10,000 s). During this time, the polarization current \( i_{pol}(t) \) through the test object is measured, arising from the activation of the polarization process with different time constants corresponding to different insulation materials and to the conductivity of the object, which has been previously carefully discharged.

Then the polarization (or absorption, or charging) current \( I_{pol}(t) \) through the test object can be expressed by [2, 4 and 5]:

\[
I_{pol}(t) = C_o U_c \left( \frac{\sigma_o}{\varepsilon_o} \varepsilon_o \eta(t) + f(t) \right)
\]

where:

- \( C_o \) - geometrical capacitance of the test object,
- \( U_c \) - step voltage (charging voltage),
- \( \sigma_o \) - DC conductivity of the dielectric material,
- \( \varepsilon_o \) - vacuum permittivity,
- \( \varepsilon_o \) - high frequency component of the permittivity,
- \( \eta(t) \) - delta function arising from the suddenly applied step voltage at \( t = t_0 \),
- \( f(t) \) - response function of the dielectric material.

The voltage is then removed and the object is short-circuited at \( t = t_c \), enabling the measurement of the depolarization current (or discharging, or desorption) \( I_{depol}(t) \) in the opposite direction, without contribution of the conductivity. The polarization current measurement can usually be stopped if the current becomes either stable or very low. According to the superposition principle the sudden reduction of the voltage \( U_c \)
to zero is regarded as a negative voltage step at time \( t = t_c \). Neglecting the second term in (1) we get for \( t = (t_0 + T_c) \):

\[
I_{\text{depol}}(t) = -C_o U_c \left[ f(t) - f(t + T_c) \right]
\]

(2)

where \( T_c \) is the charging time of the test object. As \( f(t) \) is a monotonically decaying function, the second term in (2) can be neglected for large values of \( T_c \) and the depolarization current becomes proportional to the dielectric response function.

\[
I_{\text{depol}}(t) = C_o U_c f(t)
\]

(3)

Fig. 1 shows the schematic diagram of the PDC measuring technique while Fig. 2 shows the typical nature of these currents due to a step charging voltage \( U_c \) [2, 4 and 5].

\[
i(t) = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} + \ldots + C_n e^{-\lambda_n t}
\]

(4)

where \( 1/\lambda_i \) is the relaxation time constant and \( C_i \) is the coefficient related to charging voltage, charging duration and relevant relaxation branch parameters. In these contributions, relaxation time constant and coefficient belonged to the each exponential function is considered as a point \( (1/\lambda_i, C_i) \) in the frequency domain. Each fitted curve generates five points and these points are plotted in log-log scale. Comparison of these points or the curve which is formed of these points are investigated to evaluate insulation condition.

### III. Experimental Setup

Figure 3 shows the test arrangement with a stabilized DC power source up to 4000 V, a digital multimeter for the current measurements with an uncertainty of 1% and a number of relays in order to operate the test setup by a computer. The user-friendly interface of the developed software enables the operator to choose the voltage and time for charging and discharging. Once the operator sets the system into operation the measurement system becomes fully automated. For measurement purpose the switch \( S_1 \) is closed, so that the polarization current flows in the transformer and decreases to nearly zero during charging time. After polarization duration, which lasted 10,000 s, switch \( S_1 \) is opened and the specimen short circuited by switch \( S_2 \). Similar to the polarization duration, a depolarization current in this stage flows, but in opposite direction. Both currents are stored for analysis in the computer.

![Simplified Diagram of Dielectric Response Measurement (time domain)](image)

To study the influence of insulation aging on the PDC measurements, accelerated aging were conducted in laboratory. The calendared pressboard samples (15 x 15 cm² and 1 mm thick) were carefully dried under vacuum (<1 mbar, 48 hours at 105 °C) before impregnation. Then, impregnation with degassed and dried commercial grade mineral oil (moisture content < 5 ppm) was performed. Finally, the samples were exposed to ambient air to reach the desired moisture level (as quantified by the moisture in oil), and stored, hermetically sealed, for one week before starting the tests. The aging was then conducted by placing vessels of
impregnated paper specimens in a convection oven at 135°C and aging them for an extended specific period. The procedure involves ageing the new materials within unsealed vessels, and requires that the tested material include all other significant materials used in the system. To simulate the effects of metallic components in the transformer, metallic catalysts (each 3 g/l zinc, copper, aluminium, and iron of cuttings) were attached in a filter paper and immersed in the oil. The vessel is sealed to remain constant moisture equilibrium during the measurement periods.

IV. RESULTS AND DISCUSSIONS

Analysis of the PDC measurements can provide reliable information about the condition of oil-paper insulation condition. This non-destructive method can provide information about moisture content in the solid insulation material and the conductivity of the oil and paper separately. Other diagnostic quantities like \( \tan \delta \) (from Fourier Transform), polarization index and polarization spectra can be calculated from PDC measurements directly. Another method which might be used to evaluate insulation condition is the comparison of the relaxation time constants and coefficients of a fitted curve of the polarization current in each logarithm decade.

In these investigations, the relaxation time constants and coefficients of the fitted curve of polarization current are considered. To evaluate this method several pressboard specimens with different insulation condition (moisture, aging rate and insulation temperature) were considered.

A. Effect of Temperature on the PDC Measurements

Polarization currents measured at three different temperatures on the oil/paper insulation, plotted in a log-log scale, are presented in Figure 4. These results show that polarization current increases with temperature increase and it seems to be related to the loss of linearity at higher temperature.

![Fig. 4: Polarization currents measured on the specimens at three different temperatures. The water content of the oil sample measured at 17°C was 10.5 ppm.](image)

Each polarization current was fitted with five exponential functions and the constants of each exponential function were calculated by a MATLAB fitting program. Whereas the sampling time of PDC measuring system is about 1 minute, the accuracy of this fitting is valid for angular frequencies less than 0.5 Hz. The relaxation time constant and the coefficient related to charging voltage of the complex dielectric capacitance are presented in Fig. 5.

![Fig. 5: Coefficients of the polarization currents at three different temperature of the pressboards versus angular frequency \( \lambda_i \).](image)

Out of this Figure, it can be seen that, variation in temperature significantly affects the coefficients and \( \lambda_i \). This effect is more appreciable at low angular frequencies. The magnitude tends to shift to higher values with rising temperature at low angular frequency values (mHz).

B. Effect of Pressboard Aging on the PDC Measurements

To access the influence of the insulation aging of the coefficients and \( \lambda_i \), two aging durations were considered. The pressboard specimens were aging according to the procedure described in section III, for an extended period of 500 h and 2000 h. The polarization currents of these two specimens were measured and the relaxation time constants and the coefficients of the fitted curves computed.

![Fig. 6: Coefficients of the polarization currents at two different aging duration of the pressboards specimen versus angular frequency \( \lambda_i \).](image)
The variations of the coefficients and $\lambda_i$ versus the angular frequency are depicted in Figure 6. The results indicate that the coefficient values increase with pressboard aging in all frequencies range.

C. Effect of Oil Aging on the PDC Measurements

Oil and other materials in a transformer degrade with time in service. The cost of an unexpected failure of a power transformer can be several times its initial cost. Therefore, monitoring the qualities of oil, the maintenance planners can reduce the decline rate of internal insulation. To access the separate effect of oil degradation/aging onto the coefficients and $\lambda_i$, measurements were performed on two identical pressboard specimens immersed in two different oil qualities, that is new oil and a 500 h aged oil. The polarization currents of the pressboard specimens were measured and the relaxation time constants and the coefficients of the fitted curves derived and represented in Figure 7. The results indicate the increase of the coefficients and displacement of $\lambda_i$ in the low angular frequencies range for aged oil.

D. Effect of Moisture on the PDC Measurements

To evaluate the effect of moisture on the PDC measurements, three similar specimens having different water contents, that is 10, 20 and 30 ppm were considered. The procedures consisted in drying and impregnating pressboard samples with treated oil samples having different moisture contents. The polarization currents of these specimens were measured and the relaxation time constants and coefficients for each fitted polarization current curves were computed. From the results summarized in Figure 8, the effect of moisture on the coefficients and $\lambda_i$ is hardly quantifiable even though the polarization current has been found to be very sensitive to moisture [1-5].

V. CONCLUSIONS

The PDC measurement and analysis is a non-destructive method, which provides valuable information about the condition of a transformers insulation system. Interpretation of the test results still remains a difficult task as it is believed to be influenced by insulation ageing condition, moisture content and also by environmental condition like the operating temperature. Out of these investigations performed with the aim of providing quantitative analysis on the PDC measurements, the following conclusions can be drawn:

- An increase in temperature tends to increase the coefficients and displaces significantly the $\lambda_i$ in the low angular frequency range (below a few mHz).
- Also, coefficients increase with pressboard and/or oil aging rate in the low angular frequency range (below a few mHz).

Even though PDC measurements have been found to be very sensitive to moisture, the effect of this latter on the coefficients seems to be hardly distinguishable. Obviously, further investigations are needed to ascertain these observations. This point still constitutes a challenging part of our research activities.

VI. REFERENCES