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Low temperature and moisture effects on polarization and depolarization currents of oil-paper insulation

I. Fofana[a,b,*], H. Hemmatjou[a,b], M. Farzaneh[b]

[a] Canada Research Chair on Insulating Liquids and Mixed Dielectrics for Electrotechnology (ISOLIME), Université du Québec à Chicoutimi, 555 Boulevard de l'université G7H 2B1, Chicoutimi, Qc, Canada

[b] International Research Centre on Atmospheric Icing and Power Network Engineering (CenGivre), Université du Québec à Chicoutimi, 555 Boulevard de l'université G7H 2B1, Chicoutimi, Qc, Canada

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ABSTRACT

In the last decades, dielectric testing techniques are being used and investigated as potential tools for condition assessment of oil-paper insulation. From fields and laboratory investigations these techniques were found to be highly operating conditions (moisture, ageing, temperature, etc.) dependant. Because field measurements (generally performed after de-energizing the transformer), last hours after de-energizing the transformer, the ambient temperature may affect the results. Especially in cold regions of the world, extreme care is required to interpret the results when performing tests at surrounding low temperatures. A better understanding and analysis of the dielectric test results are therefore only possible with a clear understanding of the physical behaviour of the insulation system in response to the ambient conditions. In the current research project, a series of experiments have been performed under controlled laboratory conditions with preset moisture content inside the insulation. This paper reports the effects of low temperature on the time domain dielectric response of oil impregnated paper insulation.

1. Introduction

Power transformers are the single largest capital item in substations, comprising almost 60% of the total investment [1]. It is therefore crucial that they function properly for many years. This importance is raised due to the increasing demand of electric energy.

A large number of power transformers around the world are approaching the end of their design life. Replacing them with new ones – only because of their age – is clearly uneconomical, since some of these transformers are still in good condition and could be used for many more years. For these reasons, transformer life management gained the past decade an ever increasing interest, due to both economic and technical reasons.

Because the lifetime of a transformer is directly related to the quality of the insulation, condition monitoring of the insulation of transformers appeared to be an important issue. Indeed, condition monitoring can be utilized to attempt the prediction of the insulation condition and the remaining lifetime of a transformer. In this context, the adequacy of existing and the application of new diagnostic tools and monitoring techniques, have gained increasing importance.

Numbers of modern diagnostic techniques used to assess the insulation condition of transformers include, but are not limited to, dissolved gas analysis (DGA), degree of polymerization (DP) measurement, and high performance liquid chromatography (HPLC), the classical insulation resistance, power frequency dissipation factor, and polarization index measurements [2–9]. Over the last decades, increasing requirements for appropriate tools to diagnose power systems insulation non-destructively and reliably in the field drove the development of diagnostic tools based on changes of the dielectric properties of the insulation. Some of these modern diagnostic methods include the recovery voltage measurement (RVM), frequency domain spectroscopy (FDS) and polarization and depolarization current measurements (PDC) [2–9]. These studies have shown that dielectric response measurements could be used as an effective tool for insulation condition assessment.

Polarization and depolarization current (PDC) [3–9] measurement techniques provide indication of the general ageing status and moisture content of the oil-paper insulation of transformer. However, the results of these tests are severely influenced by several environmental factors, predominantly the temperature [3,4,9,10].

* Corresponding author at: Canada Research Chair on Insulating Liquids and Mixed Dielectrics for Electrotechnology (ISOLIME), Université du Québec à Chicoutimi, 555 Boulevard de l'université G7H 2B1, Chicoutimi, Qc, Canada.
E-mail address: ifofana@uqac.ca (I. Fofana).

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This temperature effect is more prominent in outdoor substations where the external environmental conditions are hardly predictable and controllable. In cold regions of the world, the annual average temperature can be as low as 0 °C (even lower in some regions) with only few summer weeks. The likelyhood for maintenance engineers to perform measurements under these situations (low outdoor temperatures) is seemingly high. For accurate interpretation of the measurement results in such situations, it is essential to understand the variations of PDC measurement results under low temperature. This contribution reports laboratory tests result on oil impregnated paper condenser bushing model with controlled variations of temperature; moisture content in the paper acted as parameter. A climate room chamber with ±0.1 °C accuracy was used to vary the temperature at −10, 5 and 20 °C. For each temperature, PDC measurements were performed after allowing sufficient time (2 weeks) for the oil-paper insulation to reach stable temperature and moisture equilibrium. To the best of the knowledge of the authors, such investigations have not yet been reported.

2. Time domain spectroscopy

Polarization and depolarization currents (PDC) measurement is a useful technique for assessing the condition of the insulation materials in transformers. The PDC measurement procedure consists in applying a DC high voltage across a test sample for a long time (∼10,000 s). During the charging time, the polarization current $i_{\mathrm{pol}}(t)$ 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.

This polarization (or absorption, or charging) current $i_{\mathrm{pol}}(t)$ through the test object can be expressed as [3–11]:

$$i_{\mathrm{pol}}(t) = C_0 U_c \left[\frac{\sigma_0}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t) \right] \tag{1}$$

where C_0 is the geometrical capacitance of the test object, U_c is the step voltage (charging voltage), σ_0 is the DC conductivity of the dielectric material, $\varepsilon_0 = 8.852 \times 10^{-12}$ As/Vm is the vacuum permittivity, ε_∞ is the high frequency component of the permittivity, $\delta(t)$ is the delta function arising from the applied step voltage at $t = t_0$. $f(t)$ is the response function of the dielectric material.

Following the polarization period, the test sample is short-circuited by removing the applied voltage at $t = t_c$, enabling the measurement of the depolarization current (or discharging, or desorption) $i_{\mathrm{dpol}}(t)$ in the opposite direction, without contribution of the conductivity [12].

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 $t = (t_0 + T_c)$ [3–10]:

$$i_{\mathrm{depol}}(t) = -C_0 U_c [f(t) - f(t + T_c)] \tag{2}$$

where T_c is the charging time of the test object.

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 [3,9].

From the PDC measurements currents, the DC conductivity σ_0, of the test object can be estimated. If the test object is charged for a sufficiently long time so that $f(t + T_c) \cong 0$, the dielectric response function $f(t)$ is proportional to the depolarization current. Using (1) and (2), it yields:

$$f(t) = \frac{i_{\mathrm{pol}}}{C_0 U_c} - \frac{\sigma_0}{\varepsilon_0} \tag{3}$$

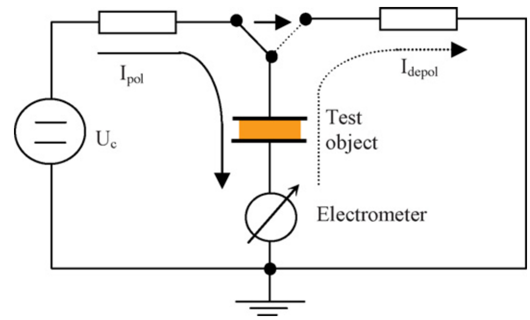

Fig. 1. Principle of test arrangement for the “PDC” measuring technique.

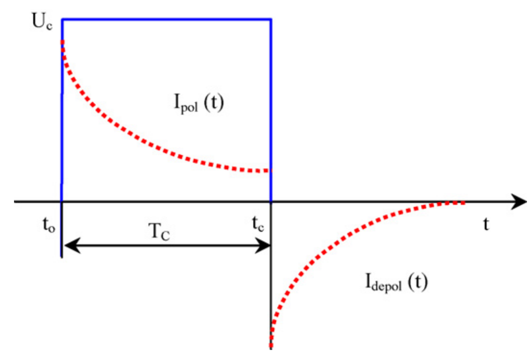

Fig. 2. Principle of polarization and depolarization current.

$$f(t) \approx \frac{-i_{\mathrm{depol}}}{C_0 U_c} \tag{4}$$

(1) and (2) can be combined to express σ_0 as:

$$\sigma_0 \approx \frac{\varepsilon_0}{C_0 U_c} (i_{\mathrm{pol}}(t_b) - i_{\mathrm{depol}}(t_b)) \tag{5}$$

Even without performing direct conductivity measurements on a oil sample, the oil conductivity can then be calculated with (5) where the $i_{\mathrm{pol}}(t_b)$ and $i_{\mathrm{depol}}(t_b)$ are the initial values in polarization and depolarization currents [13]. In the same way, the conductivity of the paper can be estimated from the long term values of the polarization and depolarization currents, by replacing the t_b with t_m, where t_m represents the largest value of time, for which the currents have been measured, that is $t_m = 10{,}000$ s for our investigations.

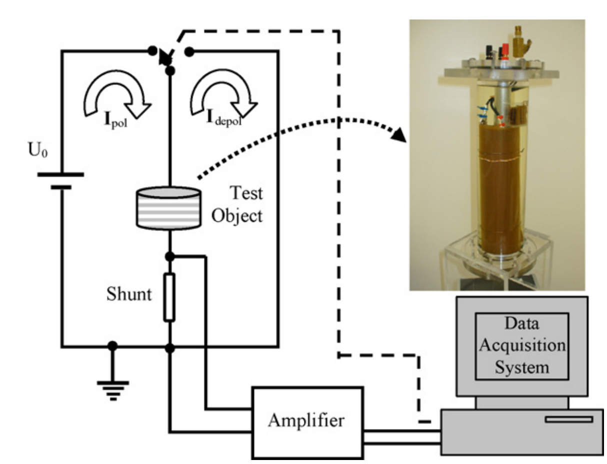

Fig. 3. Test arrangement for the “PDC” measuring technique.

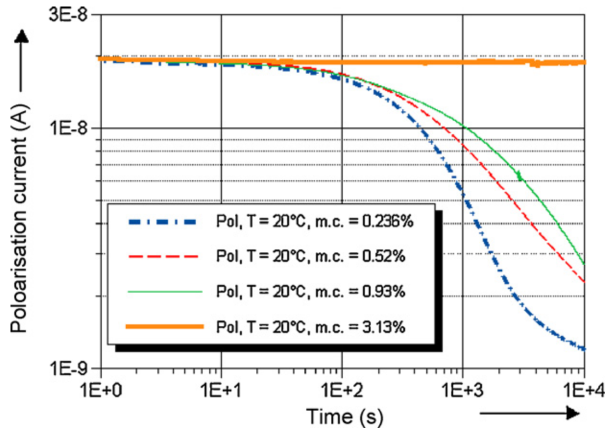

Fig. 4. Effect of paper moisture content on polarization current measured at 20 °C.

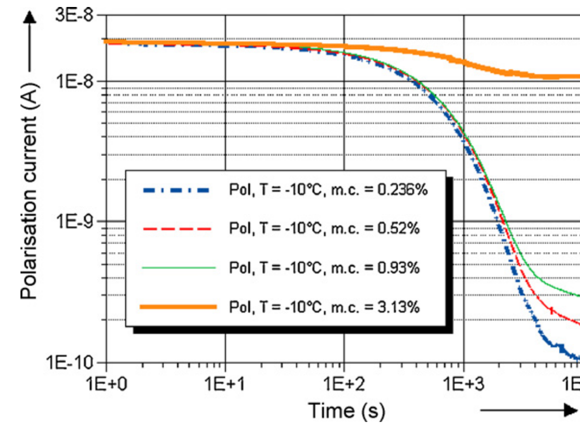

Fig. 6. Effect of paper moisture content on polarization current measured at −10 °C.

3. Experimental setup

An oil paper condenser model was designed as a test object. The bushing model was constructed by wrapping a conductor with cellulose paper and aluminium foils to get concentric capacitance layers in series. Cellulose paper used in the OIP laboratory bushing model was a TUK Paper manufactured by Weidmann [14] having a thickness $d_{\text{layer}} = 0.125$ mm and a dielectric value $V_{\text{B,layer}} = 8.5$ kV, performed according to ASTM D-202, Section 143.

Fig. 3 shows the test arrangement including the PDC measurements system, with a stabilised DC power source up to 2500 V.

The user-friendly interface developed under Labview, 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. Both currents (polarization and depolarization) are stored for analysis in the computer.

The oil paper condenser model was carefully dried and degassed under vacuum (<1 mbar, 48 h at 105 °C) before impregnation. Then, impregnation with degassed and dried commercial grade mineral oil (moisture content <5 ppm) was performed.

In order to access low temperatures effect on PDC measurements, an adiabatic climate chamber with ± 0.1 °C accuracy was used to vary the temperature at −10, 5 and 20 °C. The PDC measurements were performed under a 200 V DC voltage from 1 to 10,000 s. During temperature variations, a mass transfer process of water results from the consequent imbalance, where moisture transfers from the paper to the oil via diffusion. Performing the PDC measurements just after applying a specific temperature to the test object will not reflect the true insulation condition, since complex dynamic processes occur as moisture diffuses. Consequently, reasonable time delay (about 2 weeks) has been given before commencing measurements, to attain stable temperature and moisture equilibrium. As the time constant of moisture migration from oil to solid insulation and vice versa is about 333 h at 20 °C [15], samples were placed in a vessel, at the desired temperature, exposed to ambient air to reach the expected moisture level (as quantified by the moisture in paper), and stored – hermetically sealed – for weeks before starting tests. The moisture content was measured immediately after each measurement by Karl Fisher titration.

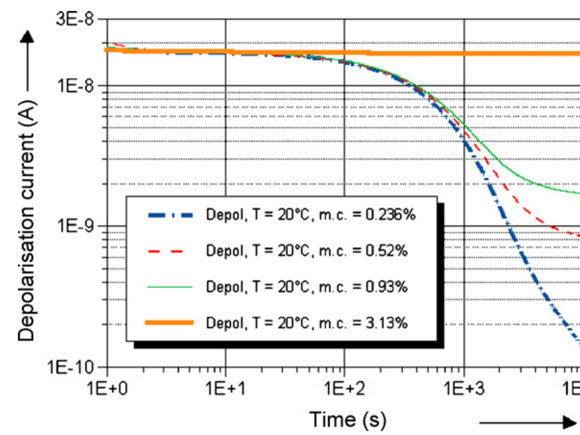

Fig. 7. Effect of paper moisture content on depolarization current measured at 20 °C.

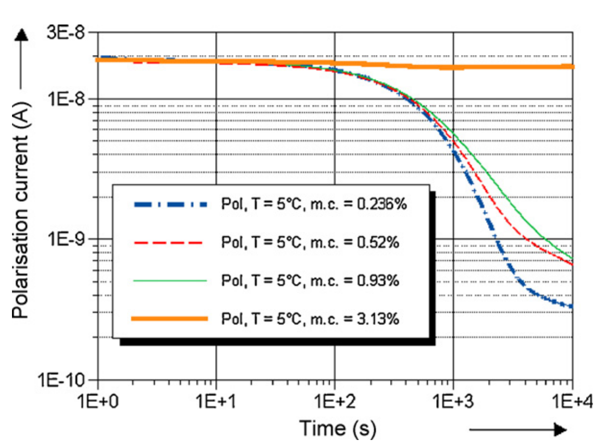

Fig. 5. Effect of paper moisture content on polarization current measured at 5 °C.

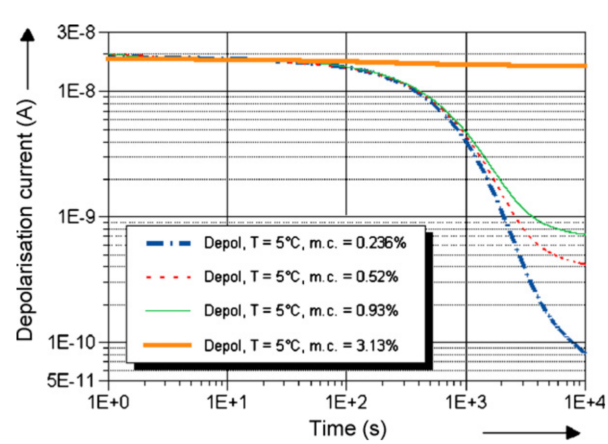

Fig. 8. Effect of paper moisture content on depolarization current measured at 5 °C.

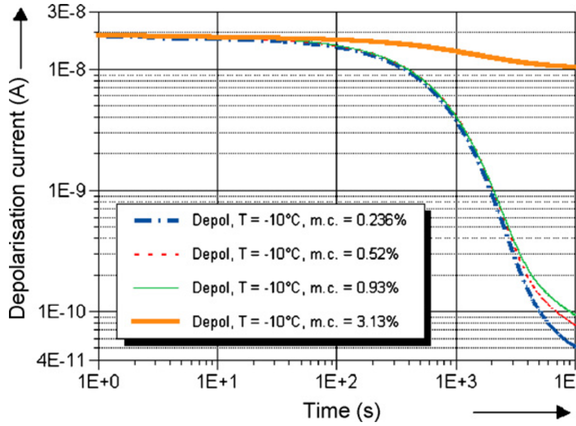

Fig. 9. Effect of paper moisture content on depolarization current measured at −10 °C.

4. Measurement results

4.1. Effect of moisture

Previous investigations have revealed that moisture content has a dominant influence on nearly all electrical based diagnostic techniques for assessing the condition of insulation [2–13]. The unit for moisture concentration in paper is typically expressed in %, which is the weight of the moisture divided by the weight of the dry, oil-free paper. For transformers with voltages not higher than 120 kV, the suggested limit of moisture content inside paper for reliable operation is about 3–4%, and for EHV transformers this limit is 2% [16]. For most application, a maximum initial moisture content of 0.5% is regarded as acceptable [16,17]. This limit is more stringent for modern EHV and UHV transformers, a maximum initial moisture content of 0.3% or less is recommended [17]. The moisture variation for the investigations (0.2–3.13) was selected in order to simulate normal operating conditions as well as critical situations in a transformer. The effect of moisture on PDC measurements at various temperatures is illustrated in Figs. 4–9.

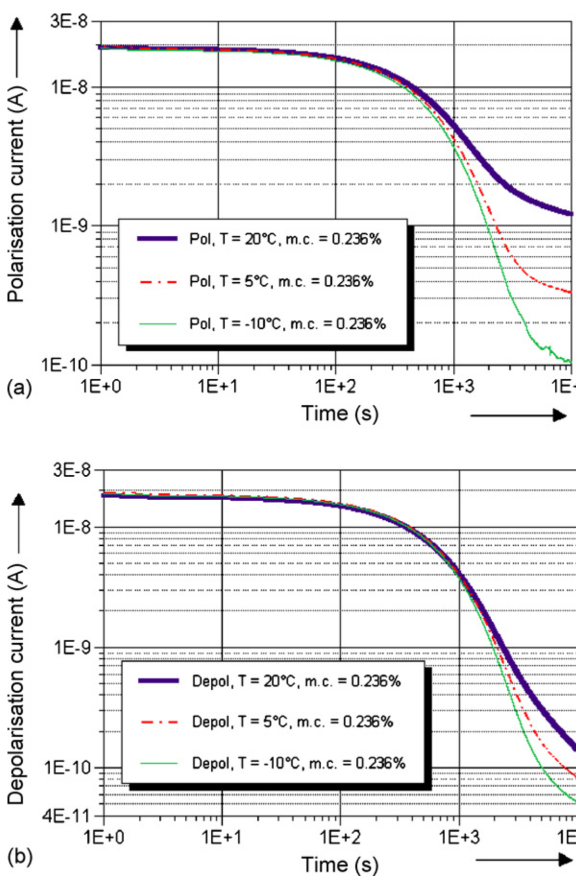

Fig. 10. PDC measurements on the test object at three different temperatures; the water content of the paper sample measured at 20 °C was 0.236%. (a) Polarization current and (b) depolarization current.

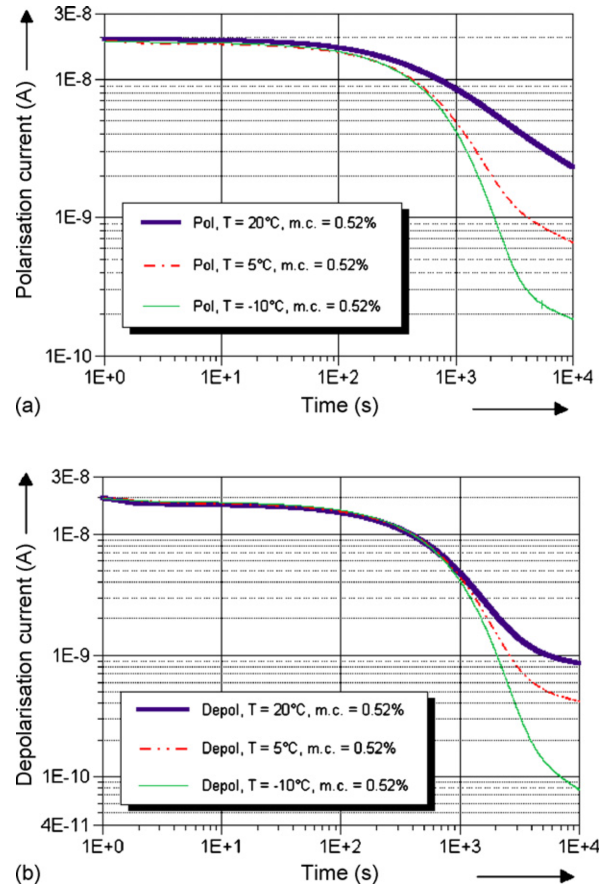

Fig. 11. PDC measurements on the test object at three different temperatures; the water content of the paper sample measured at 20 °C was 0.52%. (a) Polarization current and (b) depolarization current.

Out of these figures, it can be seen that the amplitude of long term dc polarization/depolarization current is very sensitive to the moisture content in paper. Any increase in moisture content shift upward the long term range of the dc polarization/depolarization current. This is in agreement with the common scheme for higher temperatures, reported by CIGRE Task Force 15.01.09 [18].

At 20 °C, the amplitude of long term dc polarization/depolarization current, the influence of moisture content can be easily distinguished. At −10 °C, for moisture contents lower than 1%, the effect of these later is hardly distinguishable. The variations at 5 °C, depict somewhat an intermediate behaviour.

4.2. Effect of temperature

The PDC measurements performed at three different temperatures on the test object, plotted in a log–log scale, are presented in Figs. 10–13. The polarity of the depolarization current values has been changed to positive values to ease representation in the same figure.

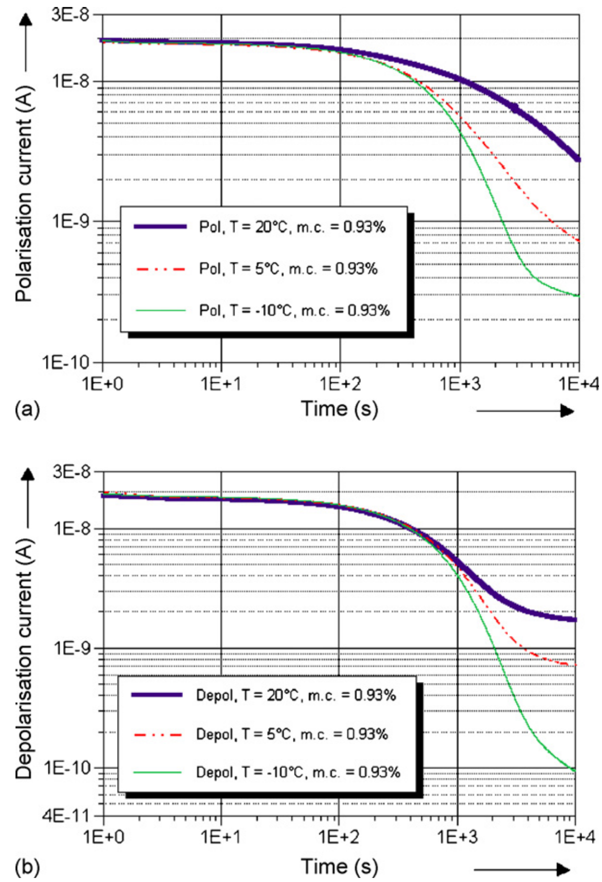

Fig. 12. PDC measurements on the test object at three different temperatures; the water content of the paper sample measured at 20 °C was 0.93%. (a) Polarization current and (b) depolarization current.

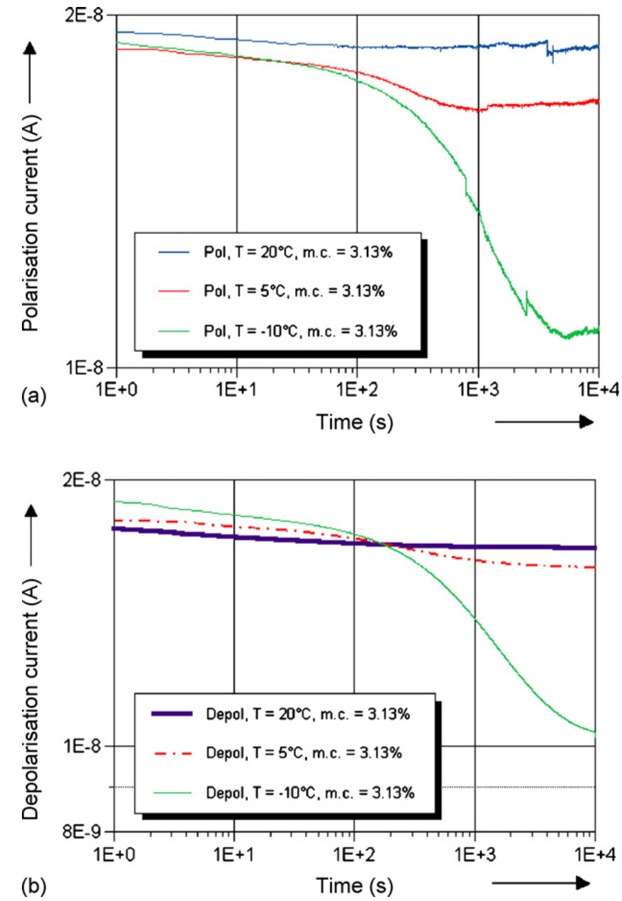

Fig. 13. PDC measurements on the test object at three different temperatures; the water content of the paper sample measured at 20 °C was 3.13%. (a) Polarization current and (b) depolarization current.

These results show that polarization and depolarization current increases with temperature increase, as observed at higher temperatures [3,4,9,10].

Spontaneous polarization is to be known as temperature-dependent. Any change in temperature causes a change of the dipole moments, measurable as a change of electric charges at both ends of the polar axis.

4.3. DC conductivity and the polarization index (P.I.)

Increasing temperature and/or moisture content changes the DC conductivity of the dielectric materials. The insulation conductivity is known to vary with temperature T (in Kelvin) according to the well-known Arhenius relationship [9,10,19]:

$$\sigma = A\exp\left(-\frac{E_{ac}}{kT}\right) \tag{7}$$

where E_{ac} is the activation energy and A is a constant related to ions mobility in the insulation. Both oil and paper conductivities are found to increase exponentially with temperature. The validity of this equation in fitting oil and paper conductivity vs temperature has been demonstrated by Saha and Purkait [10].

Conductivity values for both oil and paper have been calculated from the measured polarization/depolarization currents using (5) and are presented in Figs. 14 and 15. The linear scales of the graphs are consequently $\log\sigma$ vs $1000/T$. The slope of the representative lines provides the energy of activation E_{ac}. The problem with this approach is that E_{ac} is known to depend on moisture content and temperature [20].

The conductivity of both paper and oil increases as temperature increases. This means that at higher temperatures, the condition of insulation worsens. This is in agreement with observations reported by Saha and Purkait [10]. The behaviour at −10 °C produced some interesting results. The energy of activation increases for oil while it decreases for the paper insulation. Another mech-

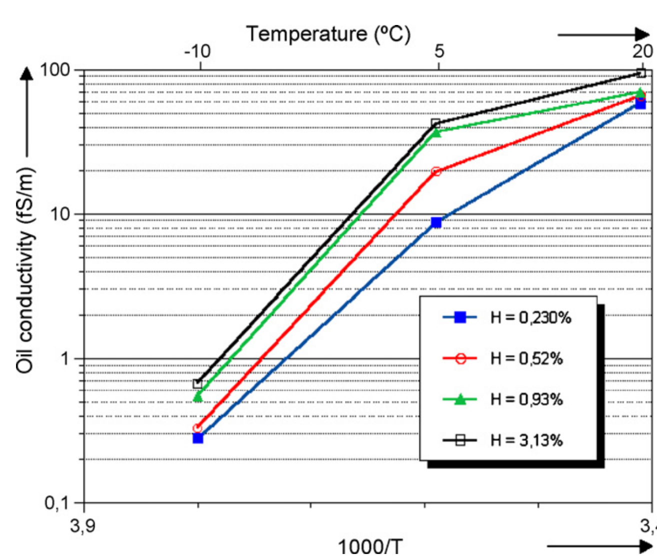

Fig. 14. Oil conductivity as function of temperature. The moisture content acted as parameter.

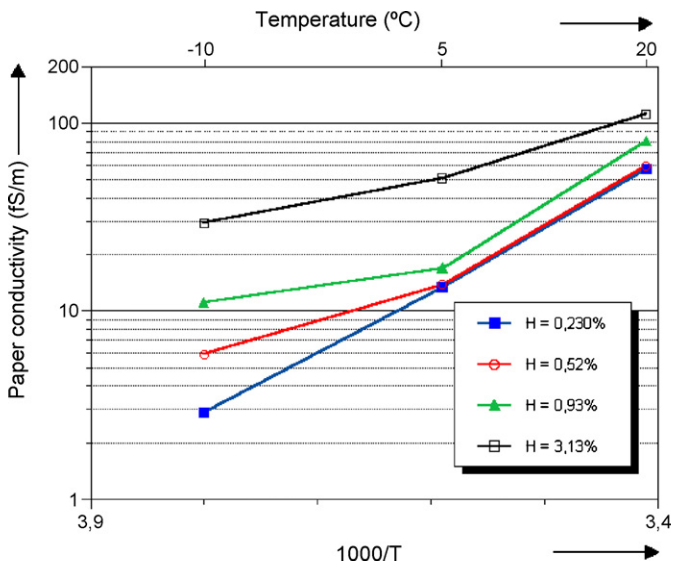

Fig. 15. Paper conductivity as function of temperature. The moisture content acted as parameter.

anism is superimposed. This mechanism might be related to moisture content. The activation energy is affected by two terms, which are crystallization and water migration [21]. Indeed, dielectric properties of liquid water are tremendously different from those of solid water: in the kilocycle frequency range, liquid water is conductive only, while solid water exhibits conduction together with a dipolar Debye-type dielectric relaxation [21]. When water freezes, there is a change in its dielectric properties which induces a time-dependent alteration of the dielectric behaviour [21].

At increasing temperature the relative water saturation of oil increases too. Thus water penetrates from cellulose into oil until an equilibrium state is reached. With decreasing temperature the water migrates back into the solid parts of the insulation. The increase/decrease in E_{ac} is more accentuated with moisture content increase/decrease. Investigations reported on bound water diffusion in wood revealed that activation energy decreases with moisture content increase [20].

From the PDC measurements, the apparent insulation resistance can be calculated from the polarization current and the constant applied voltage. As the polarization current is measured continuously up to the end of the charging time, an insulation resistance curve for the entire test duration can be drawn [10].

It is well known that P.I. is the ratio of insulation resistance at 600 s (10 min) to 60 s (1 min) or the ratio of polarization current at 60 s (1 min) to 600 s (10 min) [12]. P.I. is a temperature-dependent test. Unlike conductors where the resistance increases with temperature, insulation resistance is inversely proportional to temperature so insulation resistance decreases with temperature. Fig. 16 provides the results computed from the PDC measurements.

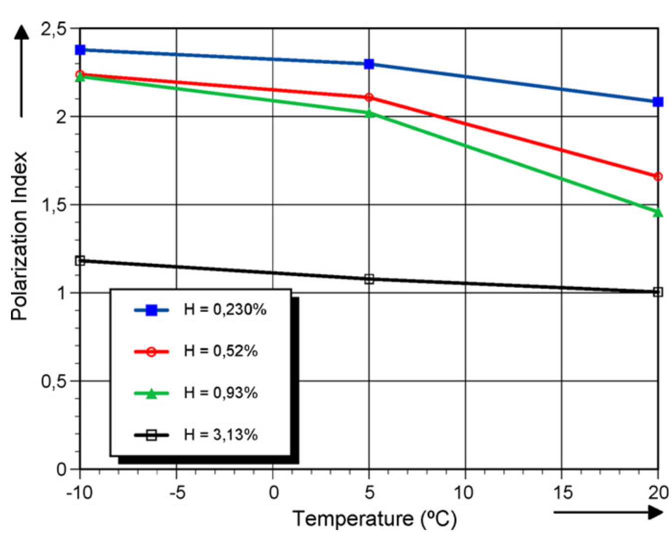

Fig. 16. Polarization index (P.I.) as function of temperature. The moisture content acted as parameter.

Obviously, the polarization index is not only affected by moisture content, but also by temperature. The P.I. decreases with temperature increase which means worse, but it is not true.

Therefore P.I. is not a good indicator for the state of the solid insulation condition, but the resistance itself is. Such observation has been already emphasized by previous investigators [6,12].

5. Conclusions

For correct interpretation of polarization and depolarization current (PDC) test results, it is essential that an understanding of temperature effects is available. In this contribution, low temperature effects on oil-paper insulation system have been investigated. The moisture content acted as parameter. From these investigations, it was found that:

- The polarization/depolarization current increases with temperature and/or moisture content increase.
- Although the PDC change consistently with temperature for all moisture content tested, the consistency and the diagnostic value of the information they provide about impending insulation condition depends very much on the temperature. Also, the shape of polarization current changes as temperature increases.
- For given moisture content, oil and paper conductivity deduced from PDC measurements show high temperature dependency.

Because PDC measurements last hours, investigations during cold days may affect insulation temperature. The strong dependency of the measurements with temperature, clearly indicates that, for on-site measurements, which are generally performed just after de-energizing the transformer, whereby the insulation inside the transformer may be seriously cooled down, careful analysis and interpretation of the dielectric response measurement are required.

Even though the behaviour at low temperature reflects those at higher temperatures, variations in activation energies indicate that extreme care is required when interpreting measurements performed at low temperatures.

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