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A Novel, Compact Instrument for the Measurement and Evaluation of Relaxation Currents conceived for On-Site Diagnosis of Electric Power Apparatus

Jean-Jacques Alff *, Vahe Der Houhanessian * and Walter S. Zaengl * and #
Adolf J. Kachler §
* Presco AG, CH-8104 Weiningen, Switzerland
# High Voltage Laboratory, Swiss Federal Institute of Technology, CH-8092 Zurich, Switzerland
§ Siemens AG, Power Transformer Division, EV T, D-90027 Nuremberg, Germany

Abstract: **Ageing of insulation materials and systems may well be detected by quantitative measurements of their dielectric response. Such measurements can be performed in the frequency or time domain. In this contribution, a novel type of equipment based on relaxation current measurements is introduced which is designed for on-site tests of high voltage power apparatus. The Introduction outlines the reasons for the development. Then, the technique of the instrument is briefly explained. Finally, some examples of on-site measurements on power transformers are presented and post-processing and interpretation of the results is demonstrated.**

INTRODUCTION

Ageing, i.e. the deterioration of essential properties of insulation materials and insulation systems, is inherently accompanied by alterations of the molecular structure and often also by changes of the material's aggregation. Therefore, ageing phenomena are detectable at once by changes of the chemical composition, later on by changes of mechanical properties, and last but not least by significant variations in the *dielectric properties*. All known methods related to the detection and diagnosis of ageing in insulation materials or systems can thus be classified to record alterations of chemical, mechanical, optical or dielectric properties.

The measurement of some specific quantities related to dielectric properties or the "*dielectric response"* of insulation belong therefore to standard diagnostic techniques to assess the quality of dielectrics. Since many decades, the measurement of the *capacitance* and of the *loss factor* (tanδ) at one single frequency, namely power frequency (50/60 Hz), was and still is successfully applied and acknowledged as a non-destructive method for assessing the quality of high voltage insulation. But such a single value is only a more or less arbitrary fingerprint of the complete dielectric response in the "*frequency domain*". In this case, a sinusoidal voltage is applied to the test object and the complex values of the permittivities are determined from the amplitudes and phase shifts of the currents flowing through the sample. But dielectric properties can also be measured in the "*time domain*" by applying a dc voltage step across the sample and recording the transient currents flowing through the sample after voltage application and after short-circuiting. Examples for quantifying again only such arbitrary and isolated fingerprints in the time domain are the common and well known measurements of the insulation resistance and the polarisation index. With ageing, however, the numerical values of dielectric properties will change in specific ranges of frequency or time domain. Therefore much more information can be gained if measurements are expanded to at least wider frequency- or time- ranges. For each method the selection of such ranges shall be based on an already known or suspected correlation of individual results with the inherent and specific changes of the dielectric response. Although much knowledge was gained about such a correlation during the last decade, more investigations will be necessary for the many kinds of dielectrics as used in power apparatus. The instrument as presented in this paper is aimed to support such investigations.

This instrument is based on "time domain" measurements and was developed in connection with investigations concerned with on-site diagnosis of especially high voltage power transformers [1]. The working principle is based on the following, known effects: When an electric field is suddenly applied to a dielectric, it interacts with the free and the different kinds of bound charge within the dielectric. Now, the motion of the charge manifests itself as a current flow in the external circuit. Generally, this current depends on the time elapsed after voltage application to the electrodes between which the dielectric is placed, falls off at first for usually a quite long time and then may become steady ("polarisation-", "absorption-" or "anomalous charging current"). If the voltage generating the electric field is switched off by replacing the voltage source by a short circuit, a current of opposite polarity will flow, again depending on the time elapsed after short circuit ("depolarisation-", "resorption-" or "anomalous discharging current"). For very long times of polarisation, the difference between both time dependencies of these currents is only due to a pure conduction current, apart from the opposite polarities of these "relaxation currents" (polarisation *and* depolarisation currents). As already shown by our own and other investigations (see e.g. [2, 3]), relaxation current measurements starting at time-delays of only 1 s after voltage application or after short circuit are already sufficient to identify the oil-paper insulation system of transformers. The results of the time domain measurements can also be transformed into frequency domain dependencies. Here, significant changes of the dielectric properties by ageing are manifested in the low and very low frequency range, for which frequency-domain measurements become much more time consuming. The instrument performs thus also a "time-domain spectroscopy" as applied for fundamental dielectric investigations. A well known "Precision Time-Domain Dielectric Spectrometer" [4] demonstrates the advantages of this method; however, it can not be used for the demanding and robust on-site conditions in substations.

Relaxation current measurements are already and become more and more a tool for diagnostic insulation testing of motors, generators and cables. Recent developments in testing of stator windings have been summarised by V. Warren and G. Stone [5]. For such tests, the measurement of the "polarisation index" (PI), a value also provided by the new equipment described in the paper has been standardised for a long time. The interpretation of relevant parameters as gained from the relaxation currents is progressing [6]. Also the application of dielectric response measurement for condition assessment of cables increased considerably during recent years [7, 8]. Although relaxation currents of water-treed XLPE-insulation are often non-linear with respect to voltage, the currently applied dc voltage source of up to 2 kV of the new instrument may well identify also such effects.

An alternative to relaxation current measurements is provided by the measurement of the "recovery voltage", a method which can be traced back to the last century. By well known theory, the results are linked to relaxation current measurements [9]. One disadvantage of this technique is its inability to subdivide an insulation system into different sections which are accessible otherwise. During recent years, also a special procedure for recovery voltage measurements was promoted [10, 11] and its equipment was especially designed for transformer testing. However, the stated interpretation of a so-called "polarisation spectrum" related to the water content of the cellulose in power transformers as provided by the measurement procedure is not correct as the complex structure of the insulation system is not taken into account [12, 13].

In the following, the technique used within the new instrument, named "PDC-analyser", is briefly described and some typical measurements on high voltage power transformers are displayed together with evaluations concerning other quantities which can immediately be derived thereof.

PDC-ANALYSER HARDWARE AND MEASURING TECHNIQUE

The compact, portable instrument for measuring polarisation and depolarisation currents as presented in figures 1 and 2 comprises a voltage source, a sophisticated current measuring circuit and a computer for timing and recording the measurements as well as displaying graphically already acquired values while the measurement is going on. The built-in computer is compatible to the PC-standard. So, all Windows® compatible software can be used for onsite post-processing of the data and most PC compatible methods can be applied for transferring measured data to other PC's for further processing, for documentation purposes and for data storage.

The measuring technique used by the PDC-analyser is a so called "two active electrodes" technique according to figure 2. For this technique, the insulation to be analysed must be located between two electrically accessible electrodes which form a capacitor with the insulation as a dielectric. One of the electrodes is arbitrarily chosen as "excitation electrode" and a test voltage is applied to it referenced to ground; the second electrode called "sensing electrode" is shorted to ground via a sensitive ampere meter. In this "two active electrodes" arrangement, stray capacitances and insulation properties between the electrodes and ground as well as cable capacitances and cable insulation properties do not interfere with the measurement as compared to the "single active electrode" technique used by [10, 11] and by common insulation resistance meters, where one single electrode is used for excitation and sensing.

Important parameters for the voltage source of the PDC-analyser are drift and jitter, both should be low enough not to provoke significant displacement currents through the insulation under test. Another parameter is transient stability as the voltage source is switched to a capacitive load.

Figure 1 – External view of the PDC-analyser.

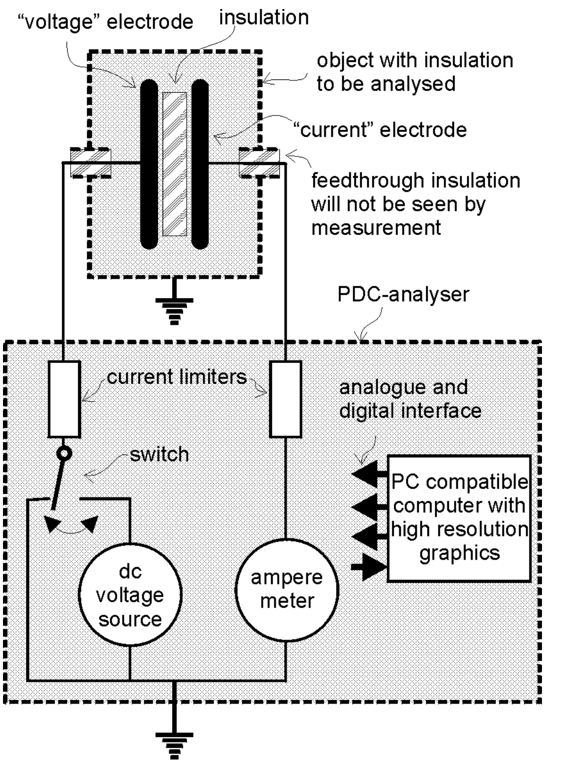

Figure 2 – Sketch of the PDC-analyser circuit with a typical "two active electrodes" object to analyse.

The current limiter is supposed to limit the transient currents to safe levels during switching. A non-linear, time dependent limitation gives the best results, because any electrostatically induced currents on the voltage electrode side are divided according to the impedance ratio of the current limiter and the capacitance of the insulation under test. So, after the switching transients are over, the impedance of the current limiter for the "voltage" electrode should be as low as possible.

The most challenging part of the PDC-analyser is the ampere meter. Normally the polarisation and depolarisation currents are quite small and the values for different test objects can range over many decades. The measurement of these tiny currents is further aggravated by superposed ac currents electrostatically induced by nearby high voltage installations and by the transient currents when switching the voltage source.

The basic working principle of the ampere meter is sketched in figure 3, obviously the actual electronic realisation is much more complicated. The opamp regulates its output voltage to the value needed to keep the node labelled "virtual ground" at zero volt; thus the impedance of the ampere meter is zero ohms (plus the impedance of the current limiter which is not shown here). To measure currents in the range of pA to mA and to have an over current protection up to 100 mA or so requires an opamp with input current drift over time and temperature of less than 1 pA, low input offset voltage drift and output current capability of at least 100 mA.

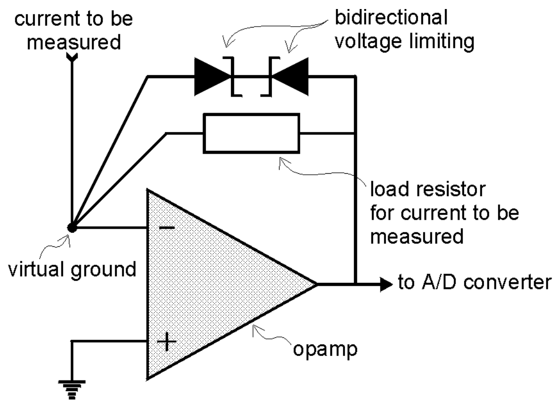

Figure 3 – Simplified schematics of the ampere meter of the PDC-analyser.

The bi-directional voltage limiting needs a special electronic circuit, ordinary zener diodes are far too "leaky" for this low current application.

For each digital sample, the load resistor is chosen instantaneously from 10 kΩ to 10 GΩ so as to have the highest possible unclipped output voltage for the A/D converter. For the user, the meter has only one single current range of ±1 mA with a resolution of about 0.5% of the measured value, the maximal drift and the lowest resolution are better than 1 pA. So, the ratio of the lowest measurable current to the highest one is $1{:}10^{9}$.

The signal filtering is done on several levels. Analogue filtering is used to keep the signal bandwidth low enough to make meaningful A/D conversions and to prevent voltage limiting of the opamp by hum and noise. However, analogue filtering is kept to a minimum as the capacitors as needed for further analogue filtering would exhibit relaxation current phenomena such like the insulation to be analysed.

Digital filtering consists of oversampling, notch filtering at mains frequency, low pass filtering and mean value computation. Digital filtering has several advantages for this application; filter quality is independent of the signal amplitude which embraces so many decades, changing filter properties and resetting filters can be done just by software.

The PDC-analyser is able to record currents in the time range 1 s to 200'000 s after switching the voltage source; the inherent properties of the PDC-analyser provide the means to shift the lower limit in the future to as little as 0.02 s.

Besides from directly measuring the relaxation current as described before, the PDC-analyser also integrates the current with fast analogue electronics to measure charge. By dividing the charge resulting from a voltage step by the step voltage amplitude, the "power frequency" capacitance of the insulation to be analysed is immediately obtained.

EXAMPLES FOR APPLICATION AND EVALUATION (DIAGNOSIS TOOLS)

The measurement of polarisation and depolarisation currents and their evaluation offers a powerful method of quality control of insulation systems in electric power apparatus. In fact, the recent investigation concerning the dielectric behaviour of oil-paper insulation systems in power transformers [2, 3, 12, 13, 14] have clearly shown that the quantification of dielectric response function [15] with relaxation currents and its analysis with simple models based on the theory of linear dielectric response permits a very good judgement of the quality of such insulation systems. Therefore, examples only related to high voltage power transformers are presented below.

The diagnosis tool as integrated in the PDC-analyser is implemented in an evaluation software based on linear models. This program offers a quantitative interpretation of measured relaxation currents and permits the calculation of other dielectric quantities such as dc insulation resistance, polarisation index, recovery voltage and "polarisation spectrum" related to the time domain or even the complex capacitance and the derived loss factor (tanδ) in a wide frequency range. The capabilities of this diagnosis tool are presented by means of some representative results (figures 4 to 9).

All measurements have been made with the "two active electrodes" technique as defined before and consisted on the application of a selectable magnitude of the (charging) dc voltage on selected high voltage windings and the sensing of generated currents from low voltage windings, which are surrounded by the first ones [2, 16]. The investigated main insulation between these windings consisted of a series of pressboard barriers with oil ducts in between and axial pressboard spacers, which fasten the barriers mechanically [2]. Evidently the shape of measured relaxation currents of a power transformer is dependent on dielectric properties of oil and pressboard material and on their geometrical arrangement.

Figure 4 presents the results of measured relaxation currents performed on-site on a *new* 3-phase 241±11×3.5/120/16.5 kV 160 MVA power transformer. The measurements have been performed between the 241 kV and 120 kV windings with charging voltages of 200 V and 1'000 V and charging duration of 1'500 s and 5'000 s. The oil temperature during the tests was about 15 °C. The characteristic, initially predominant exponential shape of the relaxation currents of power transformers is due to the exponential time dependence of the interfacial polarisation and depolarisation currents generated by the series arrangement of the oil ducts and pressboard barriers. For long times of voltage application, the dielectric response of pressboard barriers becomes more apparent due to the completion of the interfacial polarisation. The small contribution of the relaxation currents of spacers influences mainly the shape of currents at long times [12]. The initial differences between the polarisation and depolarisation currents with a charging voltage of 200 V is caused by a charging duration of only 1'500 s still insufficient to complete the interfacial polarisation. In case of the measurement with a charging voltage of 1'000 V and a charging duration of 5'000 s, the initial differences between the polarisation and depolarisation currents are larger in spite of longer charging duration. This effect is, however, due to a slight non-linearity (change of oil conductivity) caused by the somewhat too high excitation voltage level [13]. For the measurements of relaxation currents on new transformers with low oil conductivity, it is therefore very important to keep the charging voltage as low as possible to remain in the linear domain.

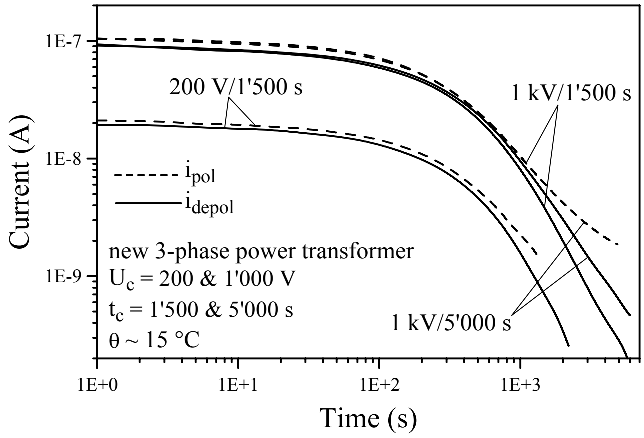

Figure 4 – Relaxation currents of a new 3-phase 241±11×3.5/120/16.5 kV 160 MVA power transformer, measured in function of charging voltage and charging duration.

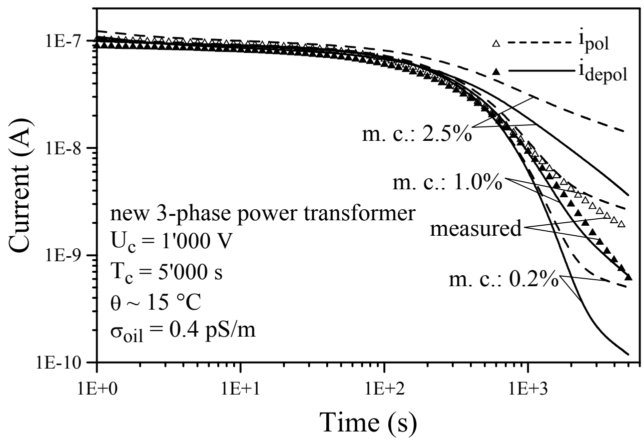

Figure 5 – Comparison between measured and calculated relaxation currents as a function of moisture content (m. c.) in the pressboard barriers and spacers of the new transformer of figure 4.

Based on extended linear models which take the geometrical composition of the main insulation into account [2, 12, 13], it is possible to distinguish between the dielectric properties of oil and pressboard and consequently to simulate the relaxation currents for different quality of oil and pressboard. Figure 5 presents the results of the simulation based on such an extended model. In this figure are compared the measured relaxation currents of this new transformer obtained with 1'000 V charging voltage and 5'000 s charging duration with a set of simulated currents at 15 °C as a function of different moisture content in the pressboard barriers and spacers. For these simulations the required dielectric quantities of oil (i.e. conductivity and power frequency permittivity) are taken to be constant and those of pressboard, i.e. dc conductivity, power frequency permittivity and dielectric response function, are changed as a function of the moisture content [2, 12].

From the time dependence of the simulated currents it can be seen that the moisture content of pressboard influences mainly the shape of currents at long times. The initial time dependence of relaxation currents is very sensitive to the conductivity of the oil. In figure 5 the amplitude coincidence between the measured and simulated relaxation currents was reached with a conductivity value of 0.4 pS/m.

To show the high sensitivity of the initial exponential shape of relaxation currents due to a change of oil conductivity, additional simulation have been performed with different oil conductivity values but holding now the properties of the pressboard constant. The results of these simulation are presented in figure 6. Here, a constant moisture content of pressboard of 1% was taken. These results show that the predominant influence of oil conductivity on the initial amplitudes of relaxation currents can be used to estimate the oil conductivity of a transformer even without performing direct conductivity measurements on its oil sample.

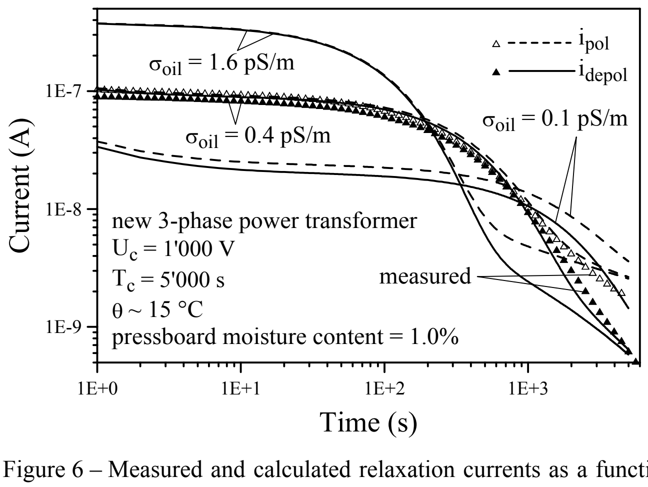

Figure 6 – Measured and calculated relaxation currents as a function of oil conductivity σ_{oil} of the new transformer of figure 4.

In summary, the results as presented in figures 5 and 6 disclosed that the moisture content of the pressboard used in this transformer was less than 1%.

The relaxation currents are directly related to the fundamental dielectric quantities, i.e. dielectric response function and dc conductivity. This permits the calculation of other derived dielectric quantities. Quantities as polarisation and absorption index, which are important for generator and motor insulation diagnosis [17] can directly be "read" from the polarisation and depolarisation current values. Other quantities as e.g. recovery voltage, "polarisation spectrum" [10] or complex capacitance [15] can be calculated using a simple equivalent circuit of parallel RC-elements determined from *a single* measurement of the relaxation currents [12, 13, 14].

Results of such calculations are presented in figures 7 and 8. Figure 7 shows calculated values of capacitance and tanδ for the new transformer already characterised in figure 4. The maximum in the tanδ-curve and the significant increase of capacitance at low frequencies confirm again the predominant influence of interfacial polarisation on the total dielectric response of the main insulation.

Figure 8 presents the calculated "polarisation spectrum" of the same transformer. Shown in this figure are also the relaxation currents used for determination of equivalent circuit. This special representation shows that the time position of the main maximum in the "polarisation spectrum" corresponds to the position of the main exponential decay in the relaxation currents. In fact, the investigation performed in [2, 12] have clearly shown that the main maximum in the "polarisation spectrum" is due to interfacial polarisation between oil ducts and pressboard barriers and its positions in time corresponds to the time constant of interfacial polarisation.

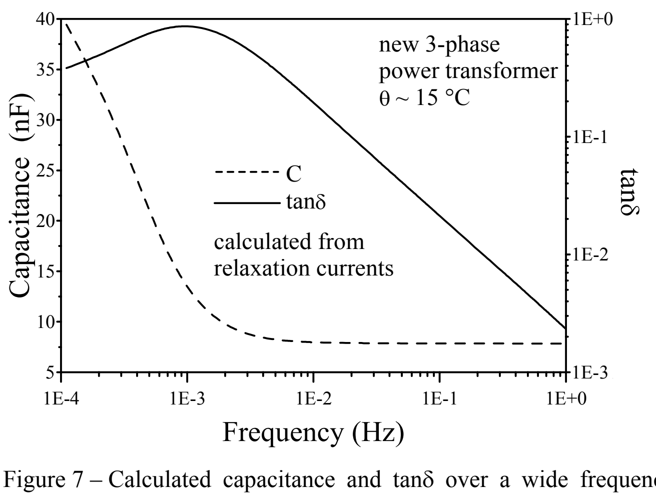

Figure 7 – Calculated capacitance and tanδ over a wide frequency range of the new transformer of figure 4. Calculated curves are obtained from measured relaxation currents.

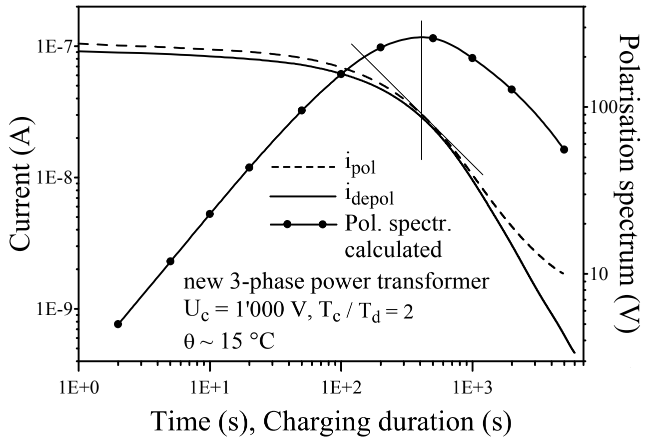

Figure 8 – Calculated "polarisation spectrum" of the new transformer, obtained from measured relaxation currents according to figure 4.

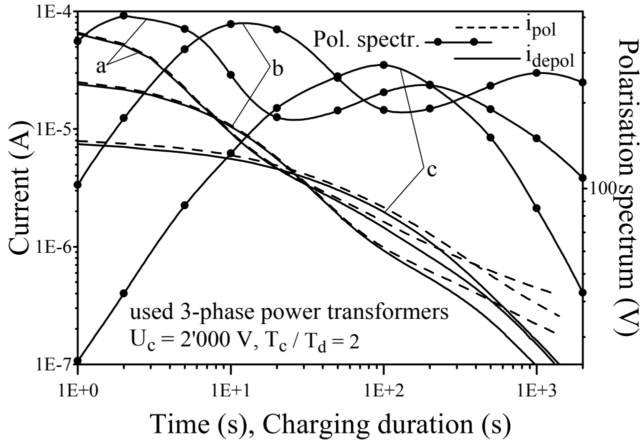

Figure 9 – Comparison between measured relaxation currents and measured "polarisation spectra" of three used identical 3-phase 410±2×10.3/17.5 kV 700 MVA step-up transformers.

As this time constant is very sensitive on the change of oil conductivity (see figure 6), the time position of this maximum in the "polarisation spectrum" cannot be considered as an unique criterion for the moisture and ageing assessment of pressboard material as used within a power transformer. In fact, the published "Software for analysis" [11], which is supposed to give the moisture content as derived from the time position of this maximum of the "polarisation spectrum", delivers a moisture content value of 1.67% for this new transformer at 15 °C, which is evidently not correct.

Finally, figure 9 compares the measured values of "polarisation spectra" and relaxation currents for three identical already used 3-phase 410±2×10.3/17.5 kV 700 MVA step-up transformers as manufactured between 1973 to 1976. The charging voltage for all measurements was 2'000 V and the charging duration for relaxation currents was limited to 1'500 s. Although here the investigated insulation systems during the "polarisation spectrum" measurements (with its "single electrode" technique [11]) and relaxation current measurements (with the "two electrodes" technique) are not fully identical, again, for each transformer, a correspondence between the time position of the main maximum of the "polarisation spectrum" and the time constant of the initially predominant exponential decay in the relaxation currents can be found. Measurements of the oil conductivity [18] performed on samples taken from these transformers provided values of 35 pS/m, 25 pS/m and 6 pS/m for transformers "a", "b" and "c", respectively. These differences in oil conductivity values can again very well be seen from the time position of the main (first) maximum of "polarisation spectra" and the initial exponential time dependence of relaxation currents.

Figures 8 and 9 show again that the dielectric response of barriers and spacers appears mainly at long times in form of a second maximum in a "polarisation spectrum" and a more flat time dependence in the relaxation currents; therefore, the necessity of measurements with charging duration which are long enough to identify the quality of the pressboard is confirmed. It is observed that in case of transformer "c" the main (first) maximum covers the second one. These results revealed also that *a single* measurement of relaxation currents contains the *total* information of a "polarisation spectrum", which otherwise results from a multiple set of several time consuming individual charging and discharging steps [10].

CONCLUSIONS

The "two active electrode" measuring technique as applied in the new PDC-analyser permits a selective investigation of single insulation systems in a complex apparatus consisting of several insulated components and it is insensitive to the leakage or surface currents which are inevitable in real test objects.

Relaxation currents are very sensitive to the change of dielectric properties. Due to their simple relationship to the fundamental dielectric quantities, i.e. dielectric response function and dc conductivity, they can easily be evaluated and non-linear effects, which could have been appeared during their measurements can clearly be distinguished.

Other dielectric quantities can easily be calculated from relaxation currents using models based on the theory of linear dielectric response.

In comparison to other dielectric response measurement methods as e.g. frequency domain dielectric spectroscopy [19, 20], for the same amount of information, the duration of the measurement of relaxation currents is shorter due to their high information rate.

Finally, it can be concluded that measurement and evaluation of relaxation currents is a simple and efficient method to quantify the quality of insulation systems. The actual measuring technique permits a reliable application of this method under on site condition on electrical power apparatus.

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