Frequency Response of Oil Impregnated Pressboard and Paper Samples for Estimating Moisture in Transformer Insulation

Chandima Ekanayake, *Student Member, IEEE*, Stanislaw M. Gubanski, *Fellow, IEEE*, Andrzej Graczkowski, and Krzysztof Walczak

***Abstract*—Knowledge about moisture content in oil impregnated paper insulation is essential when estimating remaining lifetime of power transformers. Direct evaluation of moisture content is rarely possible due to inaccessibility of the internal insulation system in transformers. Therefore, various indirect estimation techniques are utilized. Frequency domain spectroscopy (FDS) measurements of transformer insulation belong to this group. To perform high quality interpretation of results of FDS measurements a good knowledge on dielectric responses in oil impregnated pressboard and paper is required, especially as it refers to their variation with water content and temperature. The aim of this paper is to provide an open access to the frequency domain spectra of oil impregnated paper and pressboard samples, which can then be used in modeling of the results of diagnostic measurements in power transformers.**

***Index Terms*—Conductivity, dielectric frequency response, modeling, moisture content, oil-paper insulation.**

I. Introduction

EVALUATION of moisture content in oil-paper insulated power transformer is an important issue. Water significantly accelerates ageing processes of cellulose and it is also a product of cellulose ageing. Therefore, knowledge about moisture content provides important information about the condition of the insulation and it is one of the parameters useful in predicting lifetime of transformers [1], [2].

Traditionally oil analyses (Karl Fischer titration—KFT) have been used for estimating moisture content in impregnated paper/pressboard insulation. Samples of oil are easily accessible in contrary to availability of paper/pressboard samples. If a transformer remains at a constant temperature for sufficiently long time, equilibrium in distribution of moisture between oil and paper/pressboard can be achieved. In such a situation, moisture content in impregnated paper/pressboard can be estimated from so called equilibrium curves [3]. Unfortunately, the equilibrium state is rather rare for a transformer in operation and this is one of the reasons for which the estimates are not always very accurate. In addition, when oil is sampled at low temperatures the equilibrium curves are not very accurate, which additionally introduces uncertainty in the estimates of moisture content.

During the last decade several new techniques based on analysis of dielectric response of the insulation were introduced for estimating moisture content in transformer pressboard [4]–[6]. Dielectric response of the whole transformer insulation system depends on three main factors i.e., on the properties of impregnated pressboard, the properties of oil and on the geometrical arrangement of the system components [7]. For this reason correct evaluation of measurement data involves mathematical modeling [8], which requires knowledge on variation of the mentioned parameters with temperature and moisture. Precise and reliable data from well-controlled oil impregnated samples of pressboard and paper are therefore necessary for performing the modeling to correctly evaluate moisture content in real transformer insulation systems. Presently such data are not available openly and the aim of this paper is to present dielectric response data in a broad frequency range for new and artificially aged samples. These should allow to perform modeling procedures on results of diagnostic measurements. In addition, the paper discusses the influence of oil layers between the electrodes and the samples on the measured responses.

II. Preparation of the Samples

The pressboard samples, which were used for the measurements, had a thickness of 1.5 mm and diameter of 160 mm. The diameter of the paper discs was also 160 mm, while their thickness was 60 μm. Ten paper discs were stuck together in a single copper holder to form a sample. The pressboard and the paper originated from H.Weidmann AG, Switzerland.

Sample preparation included the following activities: drying, moisturizing, impregnation with transformer oil and, in some cases, artificial thermal ageing. First, samples were dried at temperature 80 °C in a vacuum-thermal chamber for 2–3 days. During this process sample weights were continuously monitored using a precision scale for identifying whether they became dried out. After drying the samples were kept in an open atmosphere (in the laboratory) for absorbing moisture from air. Weight changes of the samples were again monitored using the same precision scale to obtain predefined levels of moisture intakes. Then the samples were put into containers filled with new

Manuscript received March 7, 2005; revised September 2, 2005. This work was supported by the European Union Project REDIATOOL ("Reliable Diagnostics of HV Transformer Insulation for Safety Assurance of Power Transmission Systems" under Contract NNE5/2001/472) and Sida/SAREC Sweden. Paper no. TPWRD-00112-2005.

C. Ekanayake and S. M. Gubanski are with the Division of High Voltage Engineering, Chalmers University of Technology, Gothenburg SE 412 96, Sweden (e-mail: chandima@ee.pdn.ac.lk; stanislaw.gubanski@elteknik.chalmerse.se).

A. Graczkowski and K. Walczak are with the Institute of Electric Power Engineering, Poznan University of Technology, Poznan 60-965, Poland (e-mail: andrzej.graczkowski@put.poznan.pl; krzysztof.walczak@put.poznan.pl).

Digital Object Identifier 10.1109/TPWRD.2006.877632

TABLE I
DEGREE OF POLYMERISATION OF SELECTED SAMPLES

Material	State	DP	Aging factor
Paper	New	1320	------
	Aged - 0.6%	490	63%
	Aged - 4%	340	74%
Pressboard	New	1230	------
	Aged - 0.6%	695	43%
	Aged - 4%	260	79%

mineral transformer oil, Nynas Nytro 10 GBN, for impregnation. The measured moisture content in the oil used was 12 ppm. Five groups of samples were prepared with moisture intake equal to 0.6%, 1%, 2%, 3%, and 4%.

Paper and pressboard samples were stored in separate containers. The containers were hermetically sealed and prepared to provide possibility for performing temperature treatment. Also special metal stands were designed for holding the samples at different elevations inside the container. Ten samples with the same moisture intake were placed in one container.

Paper and pressboard samples with moisture intake of 0.6% and 4% were artificially aged. Four of the containers were placed in two ovens kept at 130 °C. Total time of ageing was about 800 hours. Temperature distribution in the oven was regularly observed using an infrared camera. The temperature in the containers was found to be distributed uniformly. Furthermore, in order to maintain the same ageing conditions, container positions in the oven were regularly exchanged. The degree of polymerization of six samples (aged and unaged) were measured afterwards according to IEC 60450 in order to evaluate the degradation state of the aged samples. The results are shown in Table I.

As shown in the table the aging factor was significantly lower for the low moisturized samples than that of the high moisturized ones. For pressboard, the aging factor was almost double in 4% samples compared to 0.6% samples. This result clearly indicates the strong influence of moisture on the rate of degradation.

All samples were kept in the containers for more than six months at room temperature before making response measurements on them. This time has been considered sufficient for reaching moisture equilibrium between impregnated pressboard and oil at room temperature [3].

III. MEASUREMENTS

A. Dielectric Measurements

Dielectric responses of the impregnated paper and pressboard samples were investigated in frequency domain.

A sample was placed in a three-electrode test cell (ref. Fig. 1), filled with similar oil as the one used for the impregnation. Moisture content in this oil was also measured and it was equal to 12 ppm at 20 °C. The procedure was as follows. First, the test cell was cleaned with pure methanol and dried in a vacuum at 80 °C. Then, the cell was filled with oil through a bottom valve. After cooling the cell to room temperature, it was opened for a short time and the sample was placed between electrodes. Then the cell was hermetically closed and additional weight of 6.7 kg

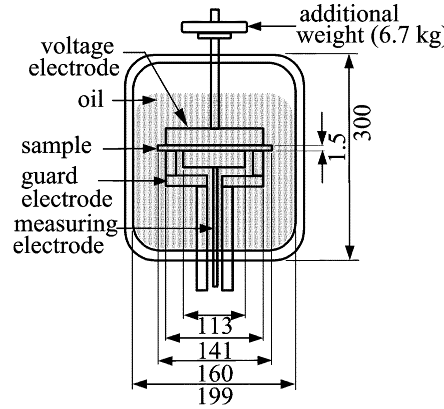

Fig. 1. Schematic diagram of the test cell (Not to scale. All of the dimensions are in millimeters).

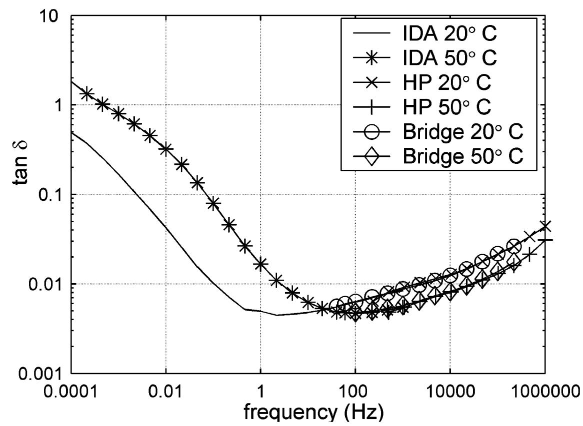

Fig. 2. Comparison of the FDS results for the pressboard samples with 1% moisture intake measured by instruments covering different frequency ranges at 20 °C and 50 °C.

was put on the upper electrode to equalize the pressure on the sample.

Dielectric response in frequency domain (FDS) was investigated in frequency range from 0.1 mHz to 1 MHz. In the low frequency range (i.e., from 0.1 mHz to 1 kHz), IDA 200 measuring system was utilized. In higher frequency range (i.e., from 40 Hz to 1 MHz), a manual General Radio capacitance bridge 1615A and HP 4192 A LF impedance analyzer were used. In first two cases the voltage applied was equal to 5 V_{rms} and in the last case it was 1 V_{rms}, which was the maximum possible voltage supplied by this unit. Accuracy of the measurements was checked by comparing the results at overlapping frequency ranges of the instruments. A good agreement between the results obtained was seen. It is illustrated in Fig. 2.

All the dielectric measurements were repeated at three temperature levels i.e., at 20, 50, and 80 °C, starting from the lowest one and increasing to 80 °C. Afterwards, additional measurement was performed at 20 °C again. This was done to observe the hysteresis of the dielectric response due to temperature changes. Before starting the measurements, samples were kept at each temperature for at least two days. At the initial stage of the study, the reproducibility of results was additionally checked by introducing a second measurement cycle at each temperature.

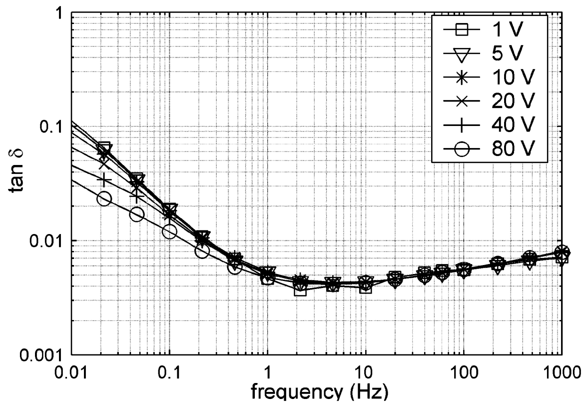

Fig. 3. Variation of loss factor with frequency (10 mHz–1 kHz) at different voltage levels for pressboard sample (0.6% of moisture intake) at 20 °C.

B. Karl Fischer Titration

Coulometric Karl Fisher titration technique was used for measuring moisture content in impregnated paper and pressboard samples according to IEC 60 814. In this study Metrohm 756 KF Coulometer instrument with a 832 Thermoprep oven was utilized. Procedure 4.4 of the standard was modified to obtain better results with the setup used. The errors associated with KFT measurements were within $\pm 2\%$, according to its manufacturer.

IV. Results and Discussions

A. Accuracy of Results

1) Influence of Applied Voltage: For selecting a proper voltage level for FDS measurements, investigations were performed on one of the impregnated pressboard samples (0.6% of water intake). Fig. 3 presents the obtained variation of loss factor of this sample at different voltage levels.

As shown in Fig. 3, the losses are decreasing in the low frequency range (below 10 Hz) with increasing voltage. This nonlinear behavior is mainly caused by the field dependent ionic oscillations, which are known as so called Garton effect [9]. As shown in the figure the nonlinearity is getting insignificant when the measuring voltage is lower than 5 V_{rms}. However, the results obtained for voltages lower than 5 V_{rms} were not well reproducible, mainly because of too low currents, which limited the measurement accuracy of the instruments. Consequently all the FDS measurements were made at 5 V_{rms}.

2) Influence of Oil Layers: Surface of the investigated impregnated pressboard samples was rough. As a result the actual area of direct contact between the sample and the electrodes was less than the surface area of the measuring electrode. An image of the pressboard surface and an enlarged view of electrode pressboard interface region are presented in Fig. 4. Since the measurements were performed in an oil bath a thin oil layer was always present in the valleys. This layer could influence results of the measurements and consequently its influence on the dielectric response of the impregnated pressboard sample was examined.

A model equivalent to the so called XY model of transformer insulation [8], as shown in Fig. 5, was used to represent the volume fractions of impregnated pressboard and free oil during

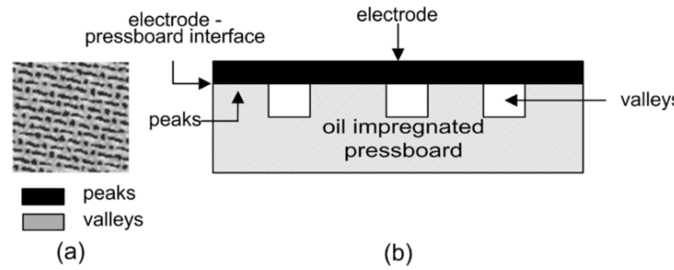

Fig. 4. Image of the pressboard surface (a) and enlarged view of a cross section around the region of the interface between one of the electrodes and impregnated pressboard (b).

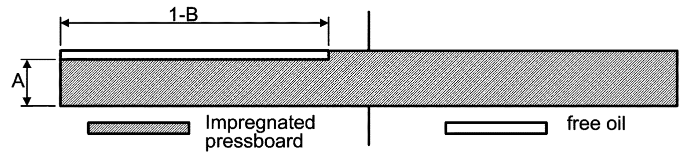

Fig. 5. Model representing the impregnated pressboard sample placed between the electrodes.

dielectric measurements. All the free oil in the valleys is together represented by a single oil layer of relative thickness (1-A) and of relative width (1-B), which could be estimated by measuring the relative depth and the area of the valleys on the impregnated pressboard sample.

By assuming a linear behavior, the dielectric response of this model could be calculated at a given frequency ω and temperature T as follows:

$$\varepsilon^*_{\mathrm{tot}(\omega,T)} = B\varepsilon^*_{PB(\omega,T)} + \frac{1-B}{\frac{1-A}{\varepsilon^*_{\mathrm{oil}(\omega,T)}} + \frac{A}{\varepsilon^*_{PB(\omega,T)}}} \tag{1}$$

where $\varepsilon^*_{\mathrm{tot}(\omega,T)}$ is the complex permittivity of the whole system, $\varepsilon^*_{PB(\omega,T)}$ is the complex permittivity of impregnated pressboard, and $\varepsilon^*_{\mathrm{oil}(\omega,T)}$ is the complex permittivity of oil.

The frequency response at 80 °C of the oil used is illustrated in Fig. 6. Since transformer oil is a nonpolar liquid, its dielectric losses under low electric field stresses are mainly caused by the conduction of ionic impurities [10], as can be seen in the plots presented. Consequently, frequency response of pure oil can be written in the form

$$\varepsilon^*_{\mathrm{oil}(\omega,T)} = 2.2 - j\frac{\sigma(T)}{\varepsilon_o \omega} \tag{2}$$

where $\sigma(T)$ is oil conductivity.

An image processing technique [11], which is similar to the one used in [12] for estimating biological growth area on composite insulators, was adopted to estimate the surface area covered by valleys and peaks. The estimated area covered by valleys was about 30% (i.e., $B \gg 0.7$). The estimate of sample thickness indicated that the depth of valleys should be less than 5% of the total thickness (i.e., $A \gg 0.95$). The oil conductivity $\sigma(T)$ was measured from the frequency response of the oil used. At 20 °C $\sigma(T)$ was equal to 0.23 pS/m and at 80 °C it was equal to 3.3 pS/m. The measured dielectric responses was then used to calculate the pure response of impregnated pressboard by means of (1). An example of the measured responses at 20 and 80 °C of the whole system, including the influence of the oil layers,

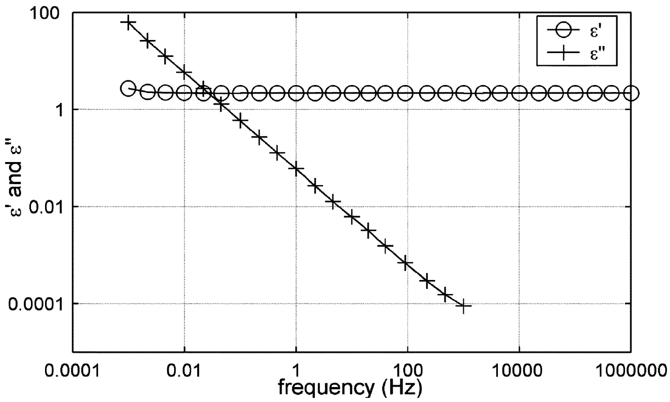

Fig. 6. Frequency response of oil (results of loss measurement above 1 kHz were not reliable as the loss tangent of oil was lower than the measuring limit of the instrument and, therefore, not presented in the plot).

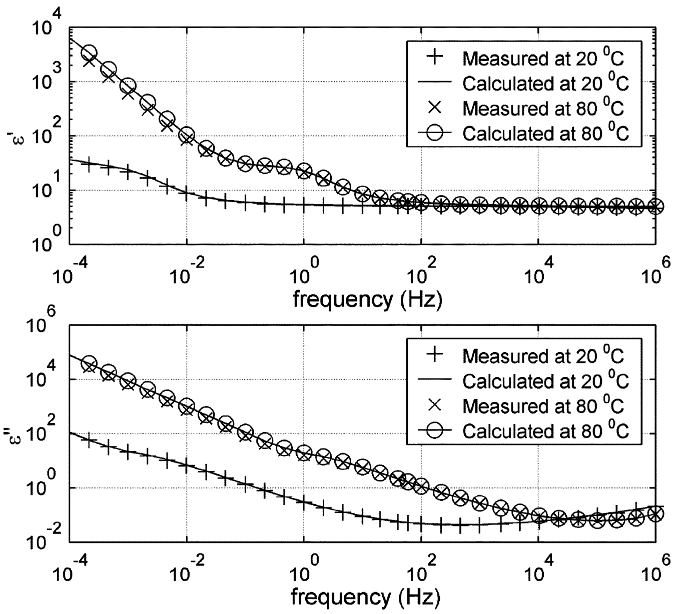

Fig. 7. Comparison of measured and calculated impregnated pressboard responses for a sample with 4% moisture intake at 20 °C and 80 °C.

and the calculated responses of pure impregnated pressboard are shown for a sample with 4% of moisture intake in Fig. 7. As can be seen, the differences between the responses are insignificant. Such behavior was observed on all the samples measured. The largest difference appeared at the low frequency range of the 4% sample at 80 °C, as the oil conductivity increased with temperature and its influence was most significant. This difference was about 30% of the calculated impregnated pressboard response. However, it is not clearly visible in the log—log plot. These results indicate that not too large mistakes can be made when using the measured responses of the investigated samples for modeling purposes and it is not necessary to make special corrections for the influence of the small oil gaps when conductivity of the oil is low.

Attempts were also made to introduce larger oil gaps during the measurements and to model the response of impregnated pressboard from the obtained results. Fig. 8 shows results of the measured and the modeled permittivity and loss curves for

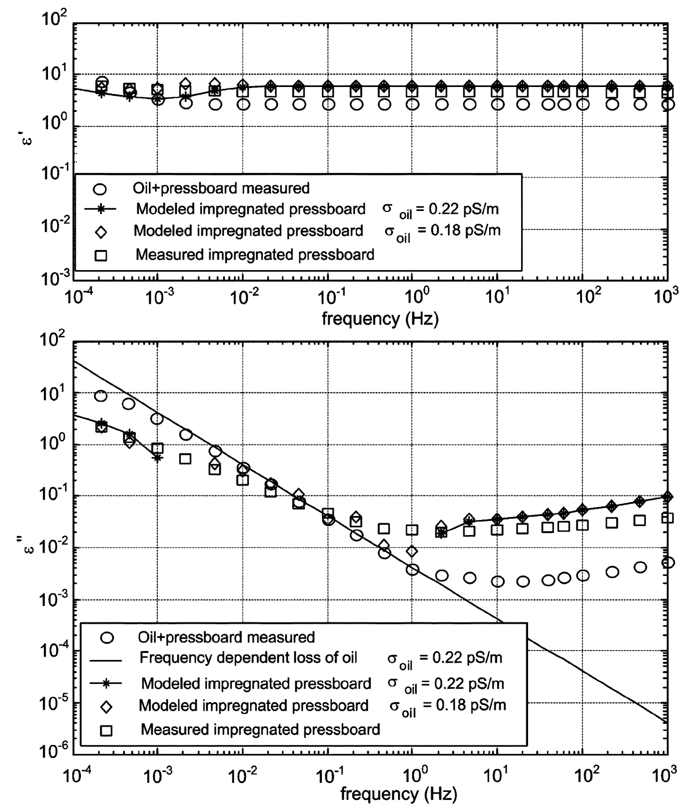

Fig. 8. Comparison of modeled and measured response of pressboard with 1% moisture intake. For the system with a 2 mm oil gap $A = 0.43$ and $B = 0$.

a case when 2 mm oil gaps were introduced on both sides of a pressboard sample in the test cell. Measured conductivity of this oil was 0.22 pS/m at 20 °C. As can be seen in the figure, the modeling ($\sigma = 0.22\ \mathrm{pS/m}$) did not provide a good representation of the impregnated pressboard response. In the frequency range 1 mHz–1 Hz the calculated response of impregnated pressboard deviated strongly from the measured one. Within the same region the dielectric loss of total system was almost similar to the loss of oil, which indicate a strong influence of the oil presence on the response of the whole system. An additional modeled response was also calculated with slightly lower oil conductivity value ($\sigma = 0.18\ \mathrm{pS/m}$), to examine the influence of error in measured oil conductivity on the derived response. As seen in Fig. 8 the slight change in conductivity shows a considerable improvement in the derived response.

In order to study the field/current distribution between the electrodes a simulation was made by means of Maxwell 2D electromagnetic simulation software. Fig. 9 shows the current distribution in the vicinity of electrode edge when 2 mm oil gaps existed between the sample and both the electrodes.

This simulation showed that there exists in such a case a small (less than 10%) current component J_X, flowing parallel to the electrode plane between the measuring and the guard electrode, which disturbs the measurement results. Similar distribution, but with higher current magnitudes, was found in simulations at higher frequencies (1 kHz and 1 MHz). Consequently the measurements with large oil gaps are not accurate enough for extracting the pure impregnated pressboard response, especially within the regions where oil dominates the total response.

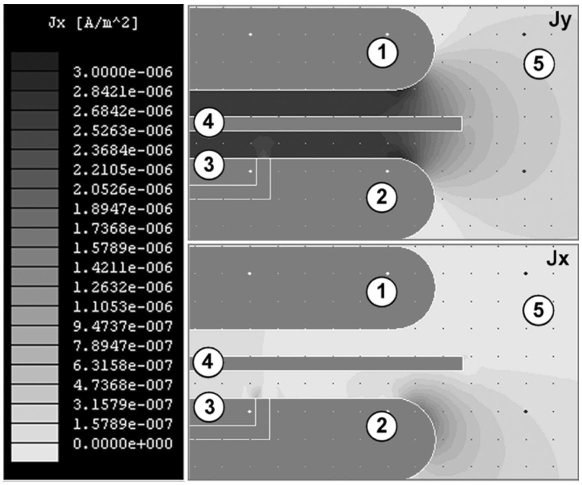

Fig. 9. Simulated current distribution in the vicinity of electrodes at 20 Hz. 1—voltage electrode, 2—guard electrode, 3—measuring electrode, 4—pressboard, 5—oil, J_Y—current perpendicular to the electrode plane, J_X—current parallel to the electrode plane.

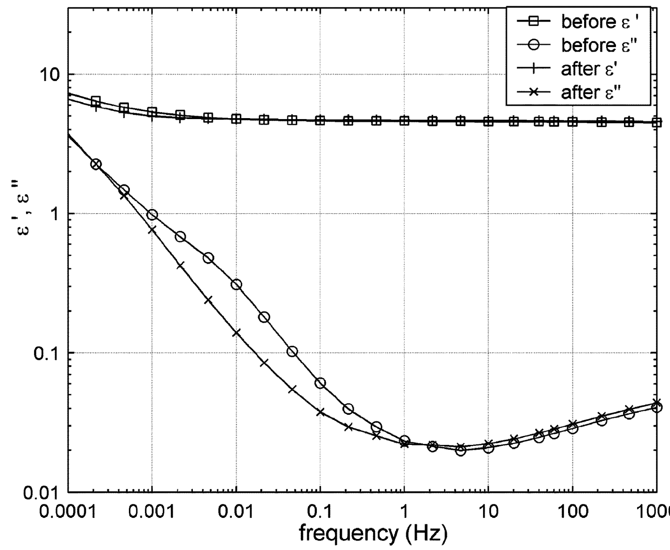

Fig. 11. Dielectric responses of pressboard having 1% moisture intake at 20 °C, before and after heat treatment.

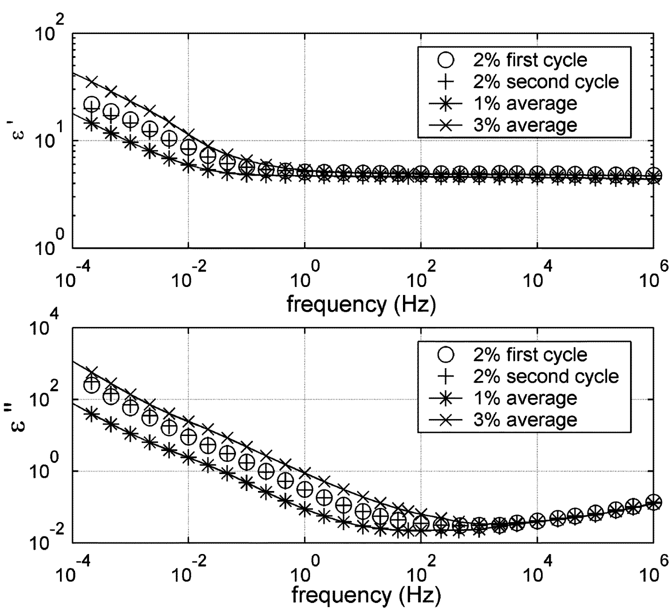

Fig. 10. Dielectric responses of pressboard at 50 °C: responses of 2% moisture intake at two consecutive measurement cycles, average responses of 1% and 3% moisture intake samples.

3) *Reproducibility of Measurements on Same Sample:* In Fig. 10, results of two consecutive measurement cycles at 50 °C on one of the impregnated pressboard samples having 2% moisture intake are presented. For the purpose of comparison, average responses of impregnated samples having 1% and 3% moisture intakes are also shown. As seen in the figure, the results of two measurement cycles were almost identical except for slight deviations at low frequencies. The maximum difference between the results of the two cycles is at 0.1 mHz and it is less than 10% of the mean value of the permittivity at the same frequency.

One can also notice that differences of the responses at two cycles are not significant compared to the variation of dielectric response due to changing moisture content by 1%.

TABLE II
ESTIMATED MOISTURE CONTENT IN DIFFERENT SAMPLES

Moisture intake (%)	Measured moisture content (%)			
	Sample 1	Sample 2	Sample 3	Average
1	1.0	1.0	1.0	1.0
2	1.9	2.0	2.0	2.0
3	2.7	2.9	3	2.9
4	4.0	4.2	3.9	4.0

A similar behavior was observed with few other samples and consequently in the later stage of the analysis the second measurement cycle was omitted, mainly to reduce the time needed for the measurements.

4) *Influence of Thermal Treatment:* Influence of thermal cycling on the dielectric response was examined by making response measurements at 20 °C in two different occasions; i.e., first measurement after the samples were placed in the cell and another measurement after temperature was reduced from 80 °C to room temperature. Results of such two measurements on a sample with 1% moisture intake are illustrated in Fig. 11. One can clearly see a significant difference between the curves, especially in the loss curves, in the range between 1 mHz and 1 Hz. It was also found that this difference is more significant for samples with small moisture content (e.g., 1%).

Two reasons may be responsible for the behavior shown in Fig. 11. First one could be related to inhomogeneous moisture distribution on surface or inside the sample, whereas the other one could originate from incomplete impregnation. It is difficult to judge at this stage which of them dominated, but it was decided that the after treatment characteristics would further be used for analyses.

B. Responses of Impregnated Pressboard and Paper

1) *Repeatability of Measurements on Different Samples:* The measurements were performed on 3 samples of

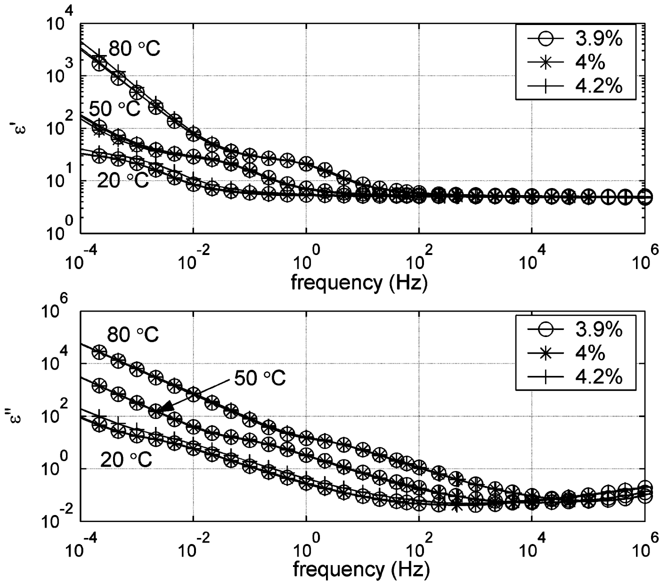

Fig. 12. Frequency response of three similar samples taken from the 4% moisture intake container.

each set, located in three different positions in the containers, i.e., in the top, in the middle, and at the bottom. Table II shows the measured moisture content in each of the selected samples. These values are the average of three KFT analyzes. As shown in the table, the KFT results agree well with the water intake determined by the weight change. The slight differences appearing could be due to inhomogeneous moisture distribution across the sample and to the minor errors linked to the KFT procedure. Fig. 12 shows the frequency responses of three similar samples having 4% moisture intake at 20 °C, 50 °C and 80 °C, which slightly deviate from each other, especially between 0.1 mHz and 0.1 Hz. Similar behavior was observed in the other samples. Average dielectric responses of pressboard at 50 °C calculated from the measurements on three similar samples are illustrated in Fig. 13 for different moisture contents. In the same figure error bars at each point indicate the maximum deviation of the measured response from the average. As seen in this figure, at low frequencies, at which each response corresponding to certain moisture content shows its unique shape and magnitude, error bars do not overlap. This indicates the possibility to use the average response for further modeling.

2) Influence of Moisture: As presented in Fig. 13, the dielectric losses in impregnated pressboard increase significantly with increasing moisture content when the frequency is lower than 100 Hz. However, there is no much difference between the loss curves corresponding to different moisture contents at frequencies higher than 10 kHz. Furthermore, a more rapid increase of permittivity ε' at low frequencies (below 0.01 Hz) can be seen in the samples with higher moisture intake (2%–4%). The increasing part of permittivity was modeled by an inverse power dependence on frequency, $A\omega^{-n}$, whereas the remaining section was modeled by Havriliak-Negami expression [13] as represented in (3)

$$\varepsilon'_{\text{tot}} = A\omega^{-n} + \varepsilon_\infty + \text{Re}\left((\varepsilon_s - \varepsilon_\infty)(1 + (j\omega\tau)^{1-\alpha})^{-\beta}\right). \quad (3)$$

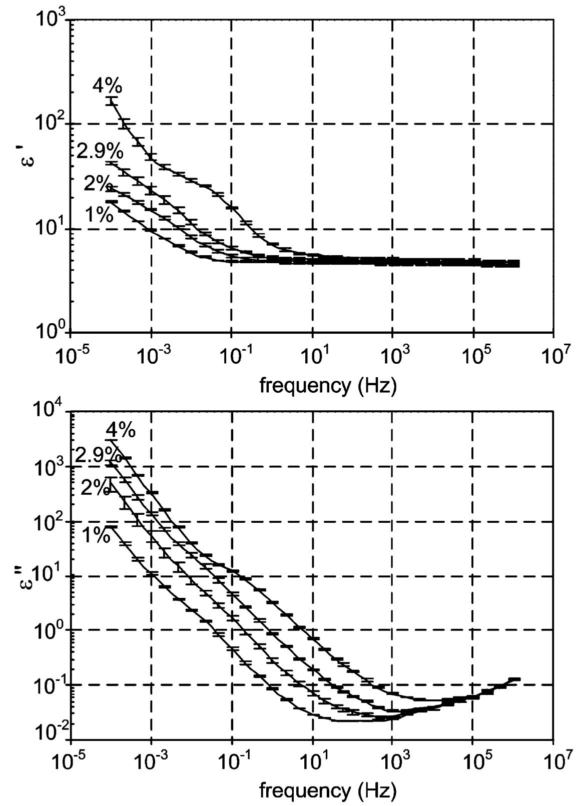

Fig. 13. Average dielectric response of pressboard containing different moisture contents at 50 °C with error bars, which represents the maximum deviation of the measured response from the average.

The imaginary part of the complex permittivity $\varepsilon''_{\text{tot}}$ was calculated by the addition of dc loss to the Kramers-Kronig (K-K) transformation of (3) as shown in (4)

$$\varepsilon''_{\text{tot}} = A\omega^{-n} \cot\left((1-n)\frac{\pi}{2}\right) + \text{Im}\left((\varepsilon_s - \varepsilon_\infty)(1 + (j\omega\tau)^{1-\alpha})^{-\beta}\right) + \frac{\sigma_{dc}}{\varepsilon_0\omega}. \quad (4)$$

The parameters $A, n, \alpha, \beta, \tau$, and ε_s in (3) were fit by means of least square technique to obtain the best fit of measured permittivity. ε_∞ was assumed as the permittivity value at the highest frequency measured.

Fig. 14 presents the measured and the modeled curves of complex permittivity of impregnated pressboard with the 4% moisture content at 50 °C. Similar fitting pattern was observed with the other pressboard samples having lower moisture contents. One can observe in the figure that the derived imaginary part of permittivity $\varepsilon''_{\text{tot}}$ does not match with the measured imaginary part at high frequencies (over 250 Hz). This inequality is mainly caused by end effects in the modeling that result from a lack of information on the response characteristics at higher frequencies [14]. According to the measured results, the loss above 10 kHz is rising with increasing frequency. One could expect a presence of drop of permittivity ε' at high frequencies to maintain the K-K compatibility between the real and the imaginary parts of the complex permittivity. However, such variation was not found below 1 MHz.

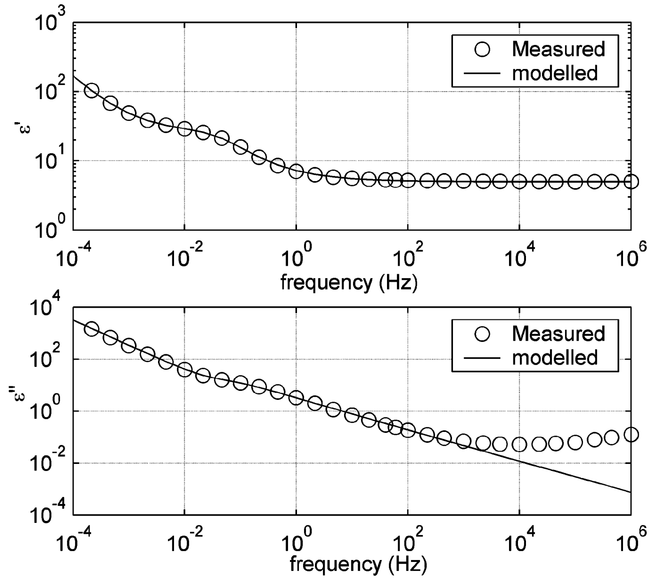

Fig. 14. Measured and modeled curves of permittivity and loss of pressboard sample with 4% moisture intake at 50 °C.

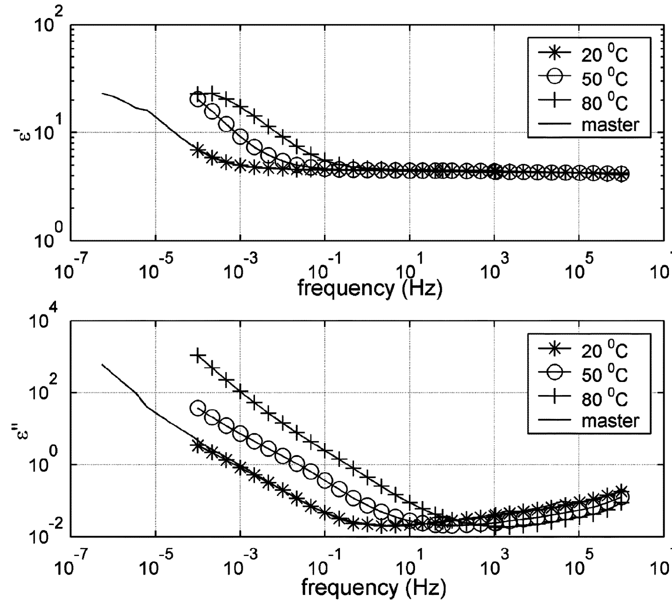

Fig. 15. Measured dielectric responses and a derived master curve (solid line) at 20 °C for a sample with 1% moisture content.

TABLE III
DC CONDUCTIVITIES OF DIFFERENT PRESSBOARD SAMPLES AT DIFFERENT TEMPERATURES

Moisture content	dc conductivity (pS/m)		
	@ 20 °C	@ 50 °C	@ 80 °C
1.0 %	0.01	0.4	8.5
2.0 %	0.09	2.9	64.2
2.9 %	0.20	5.2	72.1
4.0 %	0.67	13.9	240.6

The estimated dc conductivity of the sample with 4% moisture intake was at 50 °C equal to 13.9 pS/m. The same analysesperformed on the other samples showed that dc conductivity increased with moisture content and temperature. The calculated dc conductivities are shown in Table III. The strongest change of conductivity due to change of moisture content is observed when the temperature is at 20 °C. At this temperature, the conductivity of impregnated pressboard having 4% of moisture is 67 times higher than that of impregnated pressboard having 1% of moisture. On the other hand the change of conductivity due to change of temperature is as high as 850 times, which is observed in the sample having the lowest moisture content. These results show that dc conductivity is more sensitive to the temperature than the moisture content.

3) Influence of Temperature: Dielectric response of impregnated pressboard is highly temperature dependent. However, for most of the materials, including impregnated pressboard, the spectral shape of the response does not change with temperature, at least over a temperature range in which the structure of the material does not alter. This allows for normalizing time or frequency dependent spectra for different temperatures by shifting the corresponding spectra until they coincide into a single curve, having wider time/frequency range, called a master curve [13]. For some materials, a shift of the spectral function due to a

TABLE IV
CALCULATED ACTIVATION ENERGIES FOR DIFFERENT PRESSBOARD SAMPLES

Moisture content (%)	1	2	2.9	4
Activation energy (eV)	0.8	0.9	1.1	1.0

change in absolute temperature from T1 to T2 can be expressed with an Arrhenius factor (activation energy). The master curve technique is applicable for both real and imaginary components of the frequency dependent complex permittivity [13].

The measured responses at three temperature levels of all the impregnated pressboard samples were utilized for obtaining their master curves. Fig. 15 presents the measured responses and the derived master curve at 20 °C of the sample with 1% moisture content. The corresponding activation energies for all the considered moisture contents are listed in Table IV.

According to the results shown in the table, there is an incremental tendency in the activation energy with increasing moisture content. The reason for this could be explained as an increasing plasticizing effect of water on cellulose fibers.

4) Response of Aged Impregnated Pressboard: Similar dielectric measurements were performed on the aged impregnated pressboard samples having lowest and highest moisture intakes and their dielectric responses were compared with responses of corresponding unaged samples. Fig. 16 presents comparison of frequency responses at three temperature levels. Fig. 16(a) shows that the process of aging makes a significant increment and change in spectral shape in both the real and the imaginary parts of the complex permittivity when the frequency is between 0.1 mHz and 100 Hz. However, it is not clear yet if these changes are caused by reducing DP or by ageing by-products, such as acids formed during the aging. Furthermore, when the aging is less pronounced, as in the case of dry aged sample [Fig. 16(b)], the difference in the dielectric response is comparably low, especially at lower temperatures. One may notice in this figure that

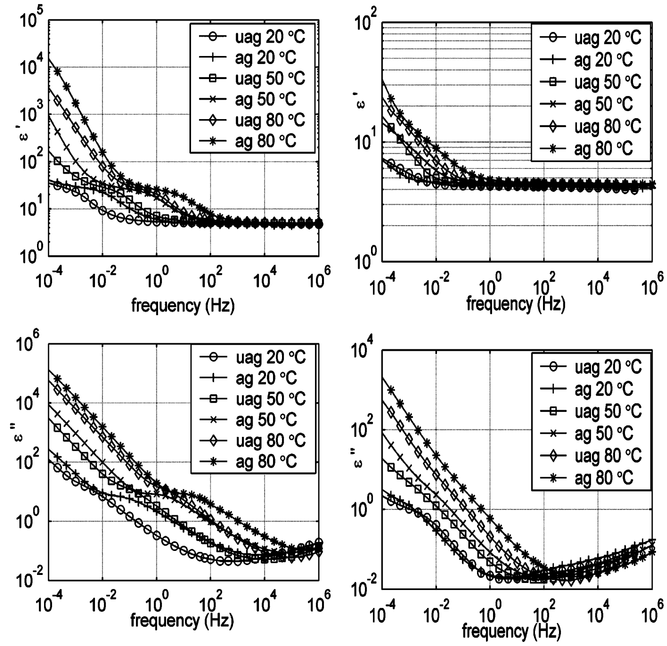

Fig. 16. Comparison of the frequency response of aged and unaged impregnated pressboard having (a) highest moisture intake and (b) lowest moisture intake at different temperatures.

TABLE V
CALCULATED DC CONDUCTIVITIES OF AGED PRESSBOARD SAMPLES (WITHIN BRACKETS—RATIO OF CONDUCTIVITY WITH RESPECT TO CORRESPONDING VALUES FOR NEW SAMPLES)

Moisture intake of the aged sample	dc conductivity pS/m		
	@ 20 °C	@ 50 °C	@ 80 °C
0.6 %	0.09 (*)	0.6 (3.5)	10.7 (4.3)
4 %	5.3 (6.7)	61.2 (3.5)	1216 (5.5)

*dc Conductivity of Corresponding New Sample was Extremely Low, it was Not Possible to Calculate dc Conductivity With Sufficient Accuracy.

permittivity and loss of the aged sample show a little decrement when the temperature is 20 °C. The difference in the spectral shape of the less aged and new samples is insignificant. Dielectric responses of the aged samples were also modeled using (3) and (4). Calculated dc conductivities and their ratios with dc conductivities of corresponding new samples are presented in Table V. As indicated in the table dc conductivity of pressboard was considerably increased with ageing. One possible reason for this could be the acids formed during the aging.

5) Frequency Response of Impregnated Paper: The same measuring setup used for measurements on impregnated pressboard was utilized for measurements on impregnated paper. Surface of the paper samples were smooth and therefore, measured response could be treated as the pure response of oil impregnated paper ($A = 0$, $B = 0$). Fig. 17 shows that the frequency response of impregnated paper and pressboard are similar. The permittivity of pressboard is about 40% higher than that of paper. Such increased permittivity is expected since pressboard has a denser structure. The difference in loss is not uniform throughout the frequency span investigated. In low frequencies (0.1 mHz–10 mHz), the loss in impregnated paper is slightly higher than the loss of impregnated pressboard

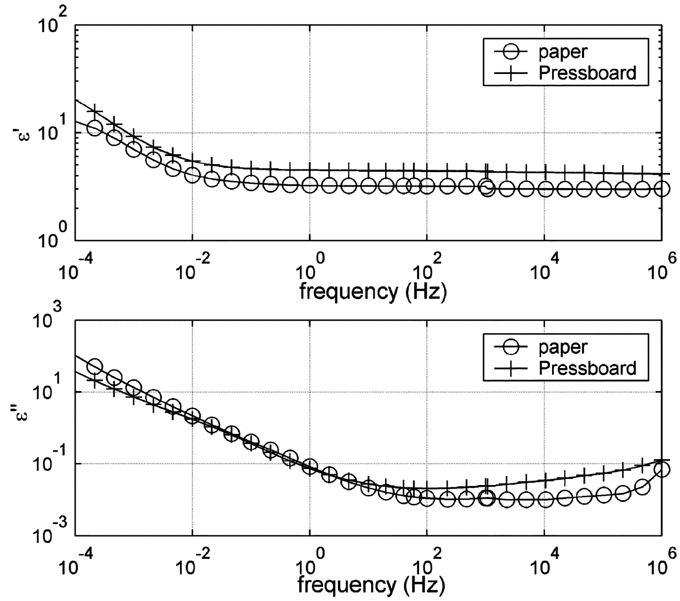

Fig. 17. Frequency response of impregnated paper and impregnated pressboard having 1% moisture intake at 50 °C.

whereas at high frequencies (1 Hz–1 MHz), this relation is opposite. The sudden increase of losses in impregnated paper seen at the highest frequencies ($\sim$ 1 MHz) is most probably a result of the measuring artifact.

V. CONCLUSIONS

The measurements performed in this study allowed for deriving master curves of the dielectric responses of impregnated pressboard and paper for different moisture contents in a broad frequency range (i.e., between 10^{-6} Hz–10^{8} Hz, 14 orders of magnitude). The presence of moisture mainly influences the low-frequency part of the response. Temperature, moisture content, and ageing have a similar influence on the dc conductivity of impregnated pressboard. Similar behavior is observed in both impregnated paper and pressboard although there exists a small difference, mainly caused by the differences in material density. It has also been shown that responses of different samples having similar moisture content exhibited minor deviations. Therefore, it is important to use in modeling, the average data from several samples.

It has been shown that for avoiding the influence of nonlinear behavior of oil-paper insulation systems, dielectric measurements should be performed at as low voltage level as possible. A model based on linear dielectric behavior, was used to examine the influence of additional oil layers between the electrode and the impregnated pressboard samples. It has been shown that the presence of thin oil gaps of low conduction did not influence strongly the determined responses. On the other hand, if the gap size was comparable to the sample thickness, extracting the response of pressboard from the measured data was very difficult.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Czerwonak transformer factory in Poland. Sample preparation was done in the High Voltage Division of Poznan University

of Technology, Poznan, Poland. Dielectric measurements and KFT analyses were performed in the high voltage laboratory of Chalmers University of Technology, Gothenburg, Sweden.

REFERENCES

[1] J. Fabre and A. Pichon, "Deteriorating processes and product of paper in oil. Application to transformers," in *CIGRE*, Paris, France, 1960, Paper 137.

[2] C. Ekanayake, "Application of dielectric spectroscopy for estimating moisture content in power transformers," Dept. Elect. Power Eng., Chalmers Univ. Technol., Gothenburg, Sweden, Tech. Rep. 465 L for Tech. Lic. Degree, 2003.

[3] Y. Du, M. Zahn, B. C. Lesieutre, A. V. Mamishev, and S. R. Lindgren, "Moisture equilibrium in transformer paper-oil systems," *IEEE Electr. Insul. Mag.*, vol. 15, no. 1, pp. 11–20, Jan./Feb. 1999.

[4] V. D. Houhanessian, "Measurement and analysis of dielectric response in oil-paper insulation systems," Ph.D. dissertation, Swiss Federal Inst. Technol., Zurich, Switzerland, 1998.

[5] U. Gafvert, L. Adeen, M. Tapper, P. Ghasemi, and B. Jonsson, "Dielectric spectroscopy in time and frequency domain applied to diagnostics of power transformers," in *Proc. 6th Int. Conf. Properties and Applications of Dielectric Materials*, 2000, pp. 825–830.

[6] G. Csepes, I. Hamos, R. Brooks, and V. Karius, "Practical foundations of the RVM (recovery voltage method) for oil/paper insulation diagnosis," in *Proc. Electrical Insulation and Dielectric Phenomena Conf. Annu. Rep. (Cat. no. 98CH36257)*, vol. 1, 1998, pp. 345–355.

[7] "Dielectric response methods for diagnostics of power transformers," CIGRE, Rep. TF 15.01.09, 2001.

[8] U. Gafvert, G. Frimpong, and J. Fuhr, "Modeling of dielectric measurements on power transformers," in *Proc.1998 CIGRE*, vol. 5, pp. 8–8.

[9] "Dielectric loss in thin film of insulating liquids," *J. Inst. Elect. Eng. (London)*, vol. 88, no. 23, pp. 33–54, 1941.

[10] A. A. Zaky and R. Hawley, *Conduction and Breakdown in Mineral Oil*, 1st ed. London, U.K.: Peregrinus, 1973.

[11] M. Sonaka, V. Hlavac, and R. Boyle, *Image Processing, Analysis and Machine Vision*, 2nd ed. Pacific Grove, CA: Brooks/Cole, 1999.

[12] A. Dernfalk, "Diagnostic methods for composite insulators with biological growth," Ph.D. dissertation, Chalmers Univ. Technol., Gothenburg, Sweden, 2004.

[13] A. K. Jonscher, *Dielectric Relaxation in Solids*, 2nd ed. London, U.K.: Chelsea Dielectrics, 1996.

[14] A. Helgeson, "Analysis of dielectric response measurement methods and dielectric properties of resin-rich insulation during processing," Ph.D. dissertation, Kungle Tekniska Högskolan, Stockholm, Sweden, 2000.

Chandima Ekanayake (S'01) was born in Matale, Sri Lanka, in 1973. He received the B.Sc. degree in electrical and electronic engineering from University of Peradeniya, Sri Lanka, in 1999 and the Tech. Lic. degree in 2003 from Chalmers University of Technology (CTH), Gothenburg, Sweden, where he is currently pursuing the Ph.D. degree.

His current research work is on diagnostics of power transformer insulation by dielectric response.

Stanislaw M. Gubanski (M'89–SM'90–F'01) received the M.Sc. degree in high-voltage engineering and the Ph.D. degree in material science from the Technical University of Wroclaw, Wroclaw, Poland, in 1974 and 1976, respectively.

Currently, he is a Professor in the Department of Electric Power Engineering, Chalmers University of Technology, Gothenburg, Sweden. He was a Researcher with the University College of North Wales, Bangor, U.K., from 1976 to 1977 and a Senior Lecturer with the Technical University of Wroclaw from 1977 to 1988. From 1989 to 1996, he was an Associate Professor in the Department of Electric Power Engineering, Royal Institute of Technology, Stockholm, Sweden.

Dr. Gubanski is a Chair of the IEEE DEIS Nominations Committee. He is also a convener of the CIGRE Task Force D1.01.09 Dielectric Response Methods for Diagnostics of Power Transformers.

Andrzej Graczkowski was born in Poznan, Poland, in 1973. He received the M.Sc. and Ph.D. degrees in high voltage engineering from Poznan University of Technology, Poznan, in 1998 and 2002, respectively.

Currrently, he is a Lecturer and Researcher with Poznan University of Technology. His research interests include space charge measurements, electric-field distribution in HVdc cables, and transformer diagnostics based on dielectric spectroscopy.

Krzysztof Walczak was born in Poznan, Poland, in 1973. He received the Ph.D. degree in diagnostics of vacuum breakers in 2001.

Currently, he is a Lecturer and Researcher with Poznan University Technology, where he has been since 2000. His research interests include high-voltage measurements, overvoltage protection, and high-voltage insulation for power apparatus.