Deriving an Equivalent Circuit of Transformers Insulation for Understanding the Dielectric Response Measurements

Tapan K. Saha, *Senior Member, IEEE*, Prithwiraj Purkait, *Member, IEEE*, and Frank Müller, *Student Member, IEEE*

***Abstract*—Preventive diagnosis and maintenance of transformers have become more and more popular in recent times in order to improve the reliability of electric power systems. Dielectric testing techniques such as return voltage measurement (RVM) and polarization-depolarization current (PDC) measurement are being investigated as potential tools for condition assessment of transformer insulation. A better understanding and analysis of the dielectric test results are only possible with a clear understanding of the physical behavior of the insulation system in response to moisture and aging. A circuit model, which describes the dielectric behavior of the transformer's main insulation system, has been parameterized in this paper. The values of the parameters of the model have been identified from the dielectric tests. A correlation has been developed between the physical condition of the insulation and the equivalent model parameters that enable a clear and transparent interpretation of the dielectric test results.**

***Index Terms*—Depolarization current, dielectric response, equivalent circuit, modeling, polarization current, return voltage, transformer insulation.**

I. Introduction

THE CONDITION of oil/paper insulation system in a power transformer is deteriorated by the electrical, thermal, and environmental stresses during its operation. The physical and chemical deterioration processes (aging and moistening) induced by these stresses alter the molecular microstructure of dielectrics and thereby influence the conduction and polarization processes. recovery voltage measurements (RVMs) [1]–[5] and polarization-depolarization current (PDC) [5]–[10] measurements are examples of dielectric response measurements that have been used in recent times for the diagnosis of power transformers insulation condition. A greater part of the experts are, however, still circumspect about the implementation of dielectric tests for assessment of the insulation condition with certainty. One of the reasons for that has been the fact that the results of such testing cannot be interpreted confidently because the exact relationship between the measured dielectric parameters and the fundamental dielectric processes of insulations is not yet clearly understood.

The two fundamental dielectric processes–conduction and polarization arise in dielectric due to the presence of an electric field. Both processes are related to the microstructure of the insulation material. The change of structure is caused by the deterioration and moistening of insulation. The development, application and interpretation of the dielectric test methods require the full and exact knowledge of the relationship between the basic dielectric processes and the dielectric parameters measured. The simulation of the dielectric processes gives the possibility to explain some exact relationships that may help to interpret the test results correctly.

An effort has been made in this paper to understand the dielectric response of oil/paper insulation as related to its fundamental structure and its behavior to an external electric field. A model of the insulation structure of transformers based on the principles of linear dielectric response has been derived. The model presented here allows quantitative analysis of the dielectric response of the composite oil/paper insulation system of a power transformer. The model takes into account the geometry of the transformer and the influence of the properties of the constituent materials (oil and paper). Examples are provided in this paper to demonstrate the effectiveness of this tool to analyze results from field measurements on transformers.

II. Insulation Model for Dielectric Response

Over the last few years, several researchers [3]–[15] have proposed a number of equivalent circuits for modeling the transformer oil/paper insulation system for a better understanding of the dielectric response. In essence, all of the models proposed so far have been derived from an extended Debye approach based on a simple RC model.

Gafvert *et al.* [16], [17] described the development and analysis of an insulation model for studying the polarization processes from the basic equations of dielectric physics.

Houhanessian *et al.* [6], [7], [9], [13] described the derivation of an equivalent circuit from relaxation current (PDC) measurements. Many of the above researchers have also derived the RV spectra from the equivalent insulation model. The modeling processes as discussed so far in the above literature [11]–[17] were heavily dependent upon the correct knowledge about the design, geometry, and arrangement of insulation within the transformer. Such information may not be available easily from the utility

Manuscript received January 14, 2003; revised April 12, 2003. Paper no. TPWRD-00015-2003.

T. K. Saha is with the School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, Qld 4072, Australia (e-mail: saha@itee.uq.edu.au).

P. Purkait is with the Electrical Engineering Department, HIT, Haldia, India (e-mail: praj@ieee.org).

F. Müller was with High Voltage Test Laboratories, University of Applied Sciences, Schweinfurt, Germany. He is now with IBC Solar AG, Bad Staffelstein, Germany.

Digital Object Identifier 10.1109/TPWRD.2004.835436

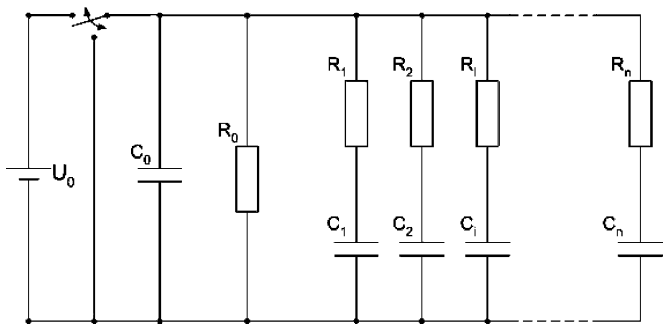

Fig. 1. Equivalent circuit to model a linear dielectric.

companies—making the proposed modeling task difficult. The simplified model discussed in this paper considers the insulation system as a "black box" and attempts to identify the individual effect of paper and oil condition on the model parameters without requiring any prior knowledge about their relative arrangements.

A. Basic Theory Behind the Model

In the presence of an electric field, a polarization current is developed due to the tendency of dipoles to align in the direction of the field. When the field is removed, the dipoles relax and return to the original state [11], [14]. In a polymer dielectric, every polar group can have a different configuration of neighboring molecules. Thus, the response time of the groups after the application of an electric field may differ from one to another [11]. These processes can be modeled by a parallel arrangement of branches each containing a series connection of resistor and capacitor as shown in the circuit of Fig. 1 [3], [4], [6], [10]–[14]. These dipoles, represented as R_i-C_i, are randomly distributed, and have associated time constants given by $\tau_i = R_i C_i$. Apart from the polarization current, conduction current flows in the insulation in the presence of an electric field. The conduction current in the insulation is due to the insulation resistance R_0 as shown in Fig. 1. C_0 represents the geometric capacitance of the insulation system [6].

B. Identification of the Model Parameters

For this model, most of the circuit parameters have been derived from measured polarization and depolarization currents (i_p and i_d). The capacitance C_0 is determined by conventional capacitance measurement techniques at power frequency [6]. The insulation resistance R_0 is calculated from the difference between polarization and depolarization currents at larger values of time [13]. The depolarization current is comprised of summation of various relaxation mechanisms that appear at different locations within the transformer insulation [5]. Various parts of the insulation have their unique relaxation characteristics depending upon the aging and moisture condition [5], [10], [11]. The paper and pressboard insulation have a different time constant of polarization as compared to the time constant of oil. The relaxation currents can thus be modeled as the sum of exponentials of the various relaxation mechanisms. The individual elements R_i-C_i with the corresponding time constants $\tau_i = R_i \cdot C_i$ can then be determined by fitting the depolarization current with the following equation:

$$i_d = \sum_{i=1}^{n} \left(A_i \cdot e^{(-t/\tau_i)} \right) \tag{1}$$

where

$$A_i = U_0 \cdot \frac{\left(1 - e^{(-t_p/\tau_i)}\right)}{R_i}. \tag{2}$$

The first task in the modeling work is to identify the τ_i and A_i corresponding to different branches. The process starts with the largest time constant branch. The depolarization current at longer times can be assumed to be due only to the largest time constant branch, with the influences of the rest of the smaller time constant branches dying down well before that time. Hence, the final part of the depolarization current is used to find out the values of τ_i and A_i corresponding to the largest time constant branch using an exponential curve-fitting technique. Once the exponential component with the largest time constant is identified, it is then subtracted from the original depolarization current to go to the next level. In this level, like before, the final part of the resultant current curve is influenced by the second largest time constant only, with the next smaller time-constant branches practically going to zero well before that time. Following the same exponential curve-fitting procedure, the values of τ_i and A_i corresponding to the second largest time-constant branch are found out. Proceeding in the same way—all of the other time-constant branches are identified. Once the values of τ_i and A_i corresponding to different time-constant branches are found, the values of R_i and C_i can be easily separated and the equivalent model can be constructed.

The number of branches in most practical modeling purposes varies from six to ten depending upon the nature of the depolarization current. The range of the values of the individual time constants, resistances R_i and C_i, are found to be dependent upon the oil and paper conditions. The values of R_i and C_i corresponding to the smaller time-constant branches are found to be more related to the condition of the oil—whereas the condition of the paper insulation is found to be responsible for affecting the higher time-constant branches.

Fig. 2 shows a sample plot a depolarization current from a 45-MVA transformer with the corresponding exponential function components that have been used to model the insulation. The simulated depolarization current is also plotted in Fig. 2, which shows a reasonably good agreement with the measured current. Table I contains the calculated values of the A_i, R_i, C_i, and τ_i-s corresponding to different branches of the simulated model of the transformer. The parameter values are rounded up for easy readability. Since the magnitude and nature of depolarization current is related to the geometry and the condition of the insulation, the values of these R_i-C_i parameters obtained through curve fitting on the depolarization current are expected to take the effects of both geometry and condition of the insulation into account.

The difference between the polarization and depolarization currents is the time-dependent dc current [18]. The initial portion of this current is influenced by the high mobility of the charge carriers in the liquid dielectric (oil). However, after few

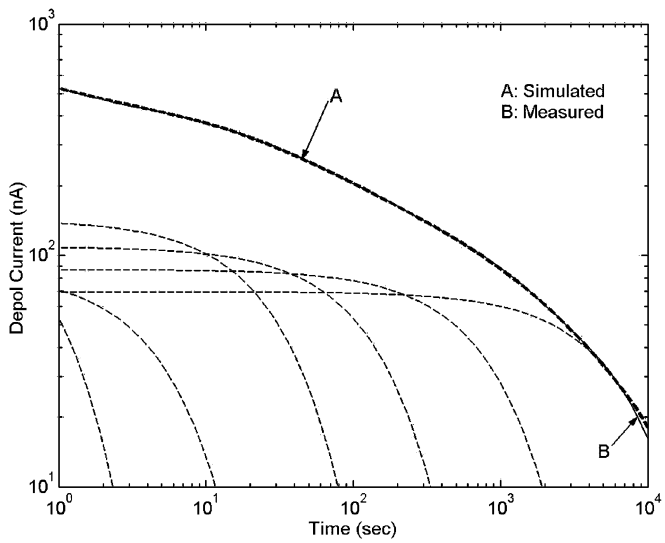

Fig. 2. Measured and simulated depolarization current with the constituent exponential components.

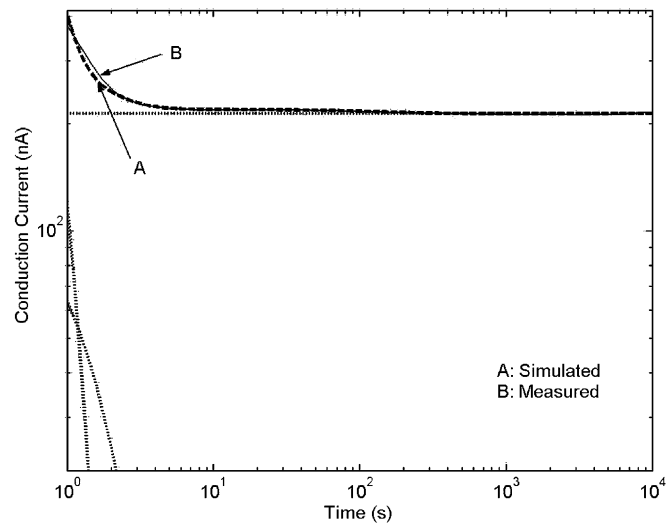

Fig. 3. Nature of the variation of conduction current.

TABLE I
EQUIVALENT CIRCUIT PARAMETER VALUES FOR A 45-MVA TRANSFORMER

Branch	A_i (amp)	τ_i (sec)	R_i (GΩ)	C_i (nF)
1	7.0×10^{-8}	6800	7.0	950
2	8.5×10^{-8}	880	6.0	150
3	1.0×10^{-7}	140	4.5	30
4	1.5×10^{-7}	30	3.5	8.5
5	8.5×10^{-8}	5.5	6.0	0.9
6	2.0×10^{-7}	0.8	2.5	0.3

tens of seconds, this transient part dies down and the conduction current due to the insulation resistance R_0 only flows. The value of R_0 is then obtained from the long time-constant values of this conduction current. For accurate modeling of the polarization current, however, the initial transient part also needs to be fitted by more than one exponential function representing the decay of this time-dependent dc component of current at smaller times.

Fig. 3 is a sample plot for the time-dependent dc current (difference between polarization and depolarization currents) as a function of time. The exponential functions used for modeling the initial decaying nature are also shown in the same figure. It is also seen in Fig. 3 that the initial decaying part dies down fast and the difference current practically remain constant for the rest of the time.

The value of R_0 obtained from the above plot is 2.5 GΩ for the same 45-MVA transformer. The value of the capacitance C_0 measured at 50 Hz by an AC bridge is 10.2 nF.

C. Calculating Return Voltage From the Equivalent Model

During the charging up process with the time t_p, the capacitor C_0 is charged to its full capacity almost instantaneously, whereas the other branch capacitors C_i are charged up to different levels according to their associated time constants. After the predefined charging time, the voltage source is disconnected and the dielectric is short-circuited. The depolarization process starts with the immediate discharge of C_0; the other capacitors C_i are slowly discharged depending upon, once again, their associated time constants. For measurement of the RV, the discharge process is interrupted in-between (at time t_d) and a high impedance voltmeter is connected across the terminals of the dielectric. During the incomplete depolarization process, each branch capacitor discharges up to different levels. After connecting the voltmeter, the charge distribution inside the dielectric attains a new equilibrium state and in the process brings the return voltage. The relation between the return voltage U_{ri} and the voltage U_{ci} in the capacitor C_i for any particular cycle with charging time t_p is given by (3)

$$\frac{U_{ri}(s)}{U_{Ci}(s)} = \frac{s^n N_{n,i} + s^{n-1} N_{n-1,i} + \cdots + N_0}{s^{n+1} D_{n+1} + s^n D_n + s^{n-1} D_{n-1} + \cdots + D_0} \quad i = 1, 2, \ldots, n. \tag{3}$$

The zeros (z) and poles (p) of the transfer function given by (3) can be obtained by solving the numerator polynomial and denominator polynomial, respectively. The coefficients (N and D) of these polynomials are obtained from circuit solution of the equivalent model as combinations of the R-s and C-s. The return voltage due to the capacitor C_i in time domain is then obtained by computing the inverse Laplace Transform from (3). The total recovery voltage due to all of the branch capacitors is obtained simply as the summation of their individual contributions.

These steps are repeated for various charging times in increasing order to obtain the so-called RV-spectra—which is nothing but a plot between the peak voltages of each RV cycle versus the corresponding charging times. The general equation for the peak voltage of the RV cycle with t_p charging time is given in (4).

$$\begin{aligned} U_{r\max}(t_p) = {} & U_0 A_{\max 1}(t_m)\left(1 - \exp\left[\frac{-t_p}{R_1 C_1}\right]\right) \\ & \cdot \exp\left[\frac{-t_p}{2R_1 C_1}\right] + \cdots\cdots + U_0 A_{\max n}(t_m) \\ & \cdot \left(1 - \exp\left[\frac{-t_p}{R_n C_n}\right]\right) \cdot \exp\left[\frac{-t_p}{2R_n C_n}\right] \end{aligned} \tag{4}$$

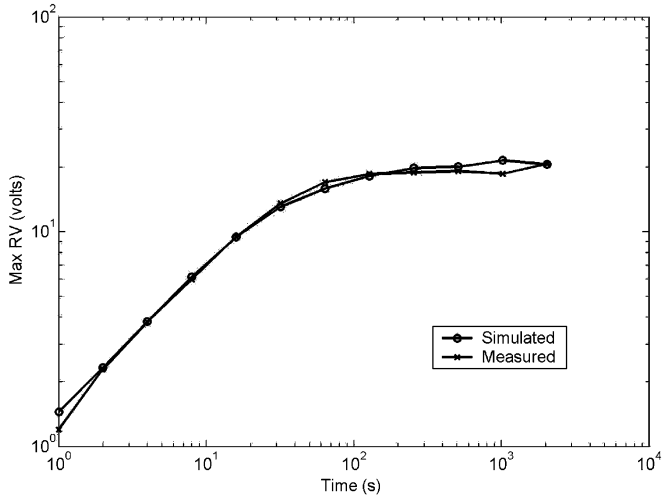

Fig. 4. Measured and simulated RV spectra.

where t_m is the time to reach the peak of the corresponding return voltage curve

$$A_{\max i}(t_m) = A_{i,1}e^{t_m p_1} + \cdots + A_{i,n+1}e^{t_m p_{n+1}} \quad (5)$$

$$A_{i,j} = \frac{b_i \prod_l (p_j - z_{i,l})}{p_j \prod_{k \neq j} (p_j - p_k)} \quad (6)$$

$$b_i = \frac{N_{n,i}}{D_{n+1}}$$

$$j,k = 1,\ldots,n+1 \quad \text{and} \quad i,l = 1,\ldots,n. \quad (7)$$

The detailed procedure for obtaining the return voltage from the insulation model has been discussed by Jota *et al.* in [14]. Fig. 4 shows the RV spectra obtained from measurement as well as simulation for a 45-MVA transformer in relation to Fig. 2 with parameters obtained as shown in Table I.

III. Dependence of the Model Parameters on Condition of Insulation

It has been pointed out by [9] and other researchers that the condition of the paper and pressboard influences mainly the shape of the polarization and depolarization currents at long time range. In contrast, the initial time dependence of these currents is very sensitive to the condition of the oil. In the present paper, the physical behavior of the model parameters including R_i-C_i of the different branches and their associated time constants, the value of the geometric capacitance C_0 and the insulation resistance R_0, have been investigated with variations of oil and paper conditions.

A. Variation of R_i and C_i

The values of the parallel branch resistors and capacitors R_i and C_i (i.e., the polarization parameters and their associated time constants) are related to the condition of the oil and paper insulation [5], [10], [11]. As shown in Figs. 5 and 6, the variation in the values of R_i and C_i for the smaller time constants (less than 10 s in the case shown, that is, the branches 5 and 6 in Table I) shifts the initial values of polarization and depolarization currents. Since the initial parts of these relaxation currents are related to the oil condition [16], it can be interpreted that

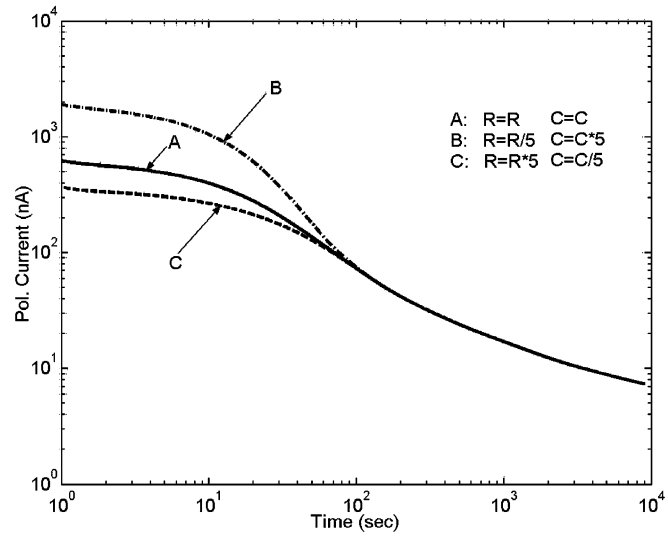

Fig. 5. Dependence of the polarization current on the values of R_i and C_i for the smaller time-constant branches of the insulation model.

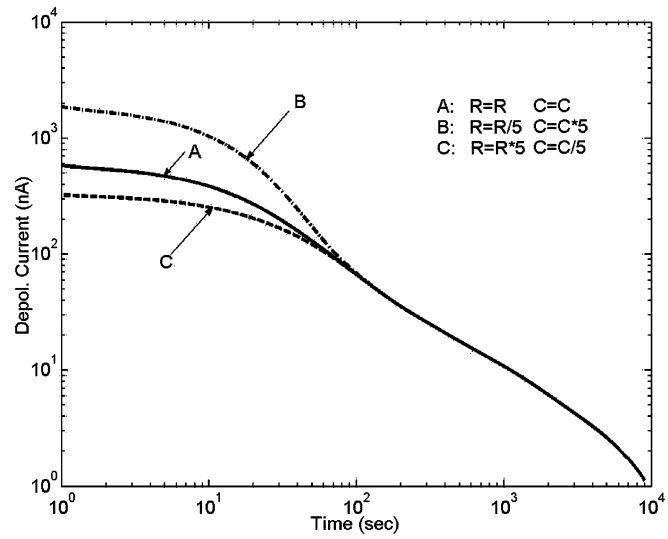

Fig. 6. Dependence of the depolarization current on the values of R_i and C_i for the smaller time-constant branches of the insulation model.

the values of R_i and C_i for the smaller time-constant branches are governed by the condition of the oil. A better condition of oil tends to increase the value of R_i-s and decreases the value of C_i-s for the smaller time-constant branches and thereby reduce the magnitude of initial portion of polarization and depolarization currents. On the other hand, aged and moist oil will increase the initial magnitudes of polarization and depolarization currents as a result of decrease in R_i-s and increase in C_i-s for the smaller time-constant branches.

Fig. 7 is the plot of the simulated RV spectra obtained for the three different pairs of R_i-C_i for the smaller time-constant branches as mentioned above. The CIGRE Task Force 15.01.09 published a comprehensive report [19]—in which it has been reported that there may be another subsidiary peak of the RV spectra away from the dominant time constant. In such a case, the dominant time constant corresponds to the oil peak and any subdominant maximum would stem from polarization phenomena in the solid insulation.

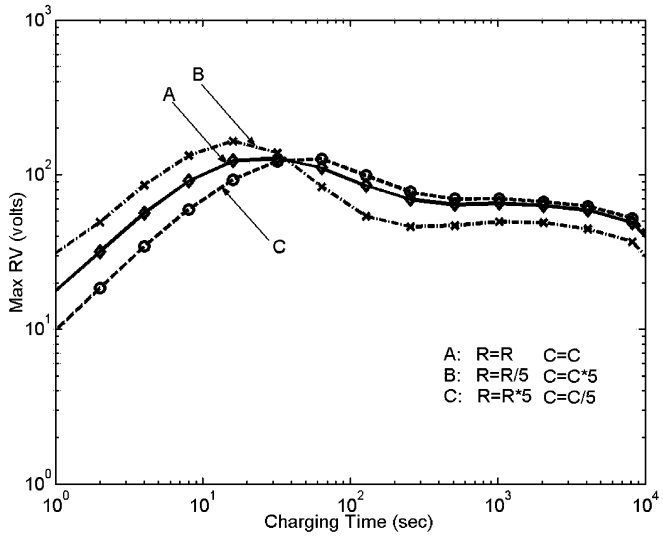

Fig. 7. Dependence of the RV spectra on the values of R_i and C_i for the smaller time-constant branches of the insulation model.

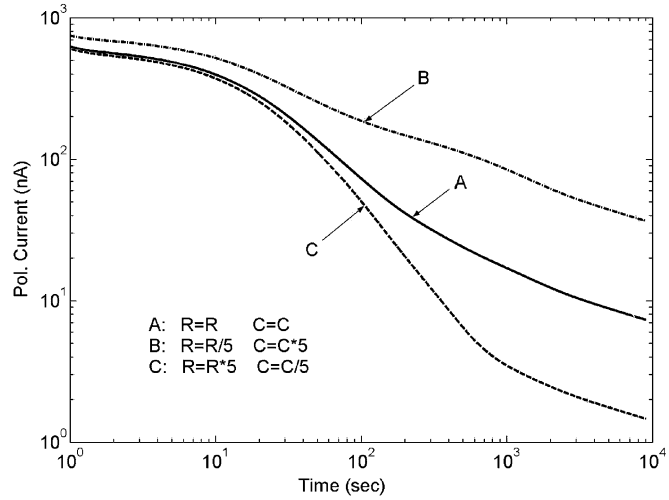

Fig. 8. Dependence of the polarization current on the values of R_i and C_i for the larger time-constant branches of the insulation model.

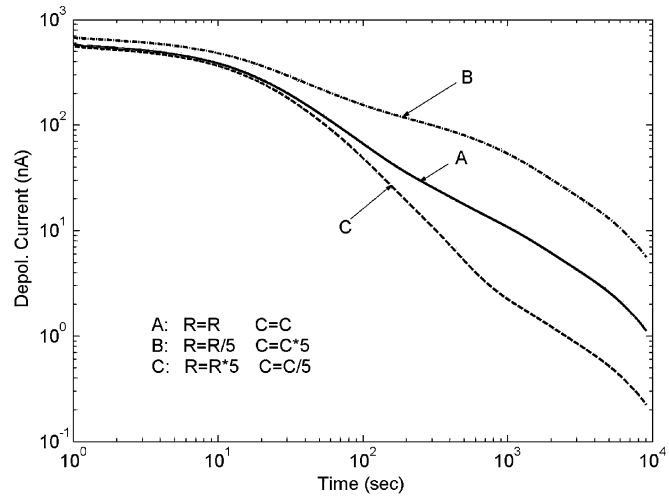

Fig. 9. Dependence of the depolarization current on the values of R_i and C_i for the larger time-constant branches of the insulation model.

As can be seen in Fig. 7, the variations in the R_i and C_i values of the smaller time-constant branches shift the dominant central time constants of the RV spectra without affecting the position of the subsidiary peaks which occur at much higher times. Thus, RV spectra with higher R_i and smaller C_i (better insulation condition) are found to have higher values of dominant central time constants (first peak) as compared to the RV spectra with lower R_i and higher C_i. This supports the observation that the values of R_i and C_i for the smaller time-constant branches correspond to the condition of the oil, which affects the initial portion of the polarization and depolarization current and only the first dominant peak of the RV spectra. This is a significant finding, which will help to interpret RV results.

On the other hand, the final long-term magnitudes of the relaxation currents are found to depend only on the values of R_i-s and C_i-s of the larger time-constant (around 1000 s or more) branches. Figs. 8 and 9 are plots showing variations of polarization and depolarization currents due to change of R_i-s and C_i-s for the larger time-constant branches (branches 1 and 2 in Table I).

It is thus found that the final parts of the relaxation currents are governed by the larger time-constant branches, values of which are dependent on the condition of the paper insulation [16]. A better condition of the paper tends to increase the value of R_i and decrease the value of C_i for the larger time-constant branches thereby reducing the relaxation current magnitudes at larger values of time. Aged and moist paper on the other hand, decrease the value of R_i and increase the value of C_i for the larger time-constant branches resulting in reduction of the relaxation current magnitudes at longer times.

It is observed that the effects of changing the values of R_i and C_i for larger time-constant branches are not that significant on the dominant central time constants (first peak) of the RV spectra. The subsidiary peaks (second peak) of the RV spectra, however, are found to vary significantly. This once again supports the observation that the R_i and C_i values for the larger time-constant branches of the insulation model correspond to the condition of the paper and they affect the final portion of the polarization and depolarization currents and the subsidiary peaks of the RV spectra. This major finding will alleviate some confusion over the interpretation of RV results.

Fig. 10 is the simulated RV spectra plotted for the three different pairs of R_i-C_i for the larger time-constant branches.

Changing the values of R_i and C_i for the intermediate time-constant branches (branches 3 and 4 in Table I) affect the shape of the polarization and depolarization currents in the intermediate region of time, around the 10–1000-s range. In this region, the "interfacial" effects of oil and paper are predominant [9]. The plots for polarization current depolarization current and RV spectra are shown in Figs. 11–13 respectively.

It was pointed out by the authors of [9] that the dominant central time constant (first peak) of the RV spectra is largely influenced by this "interfacial polarization" between the oil ducts and paper/pressboard. It is observed in Fig. 13 that both the dominant and the subsidiary peaks of the RV spectra are being affected by the changes in R_i and C_i values of the intermediate time-constant branches. These intermediate R_i and C_i branches can thus assume to be attributed to the "interfacial polarization" phenomena in the composite dielectric.

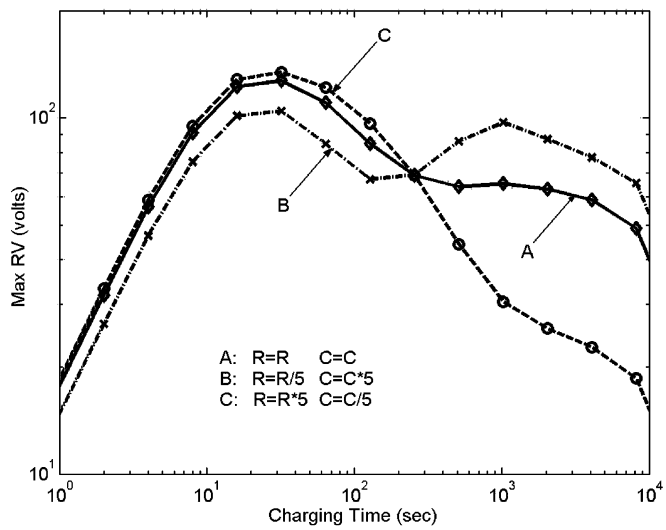

Fig. 10. Dependence of the RV spectra on the values of R_i and C_i for the larger time-constant branches of the insulation model.

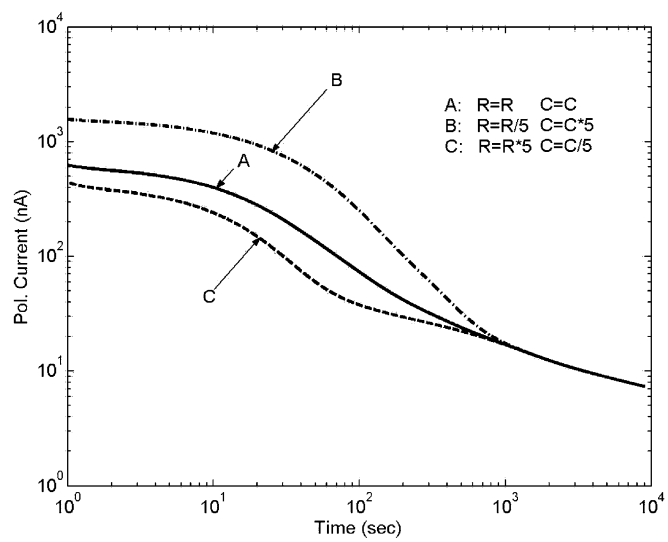

Fig. 11. Dependence of the polarization current on the values of R_i and C_i for the intermediate time-constant branches of the insulation model.

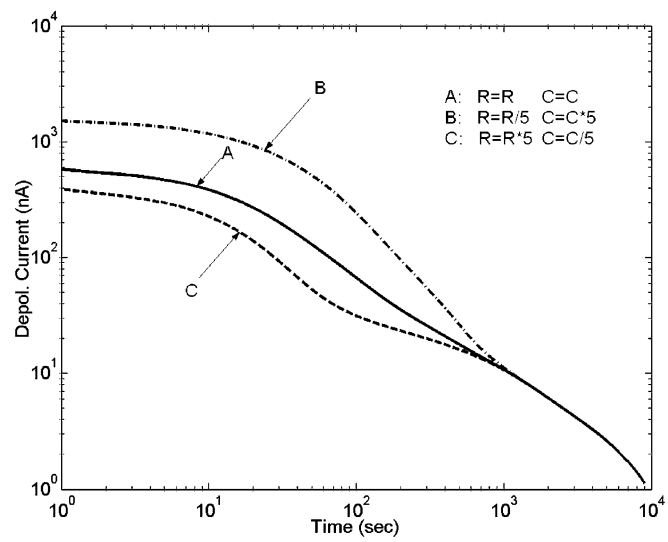

Fig. 12. Dependence of the depolarization current on the values of R_i and C_i for the intermediate time-constant branches of the insulation model.

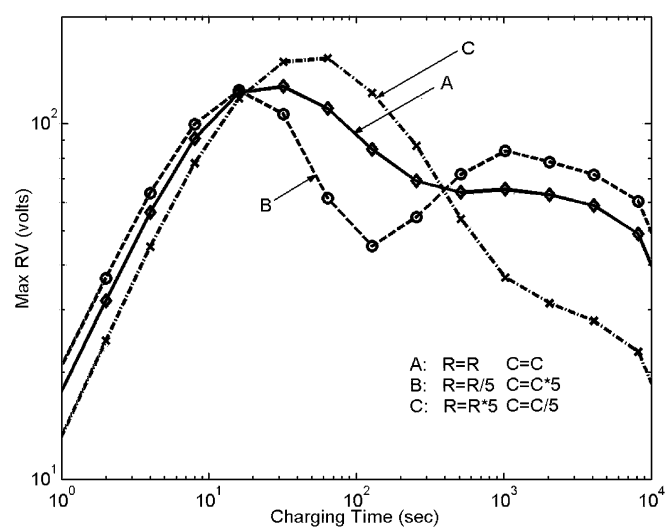

Fig. 13. Dependence of the RV spectra on the values of R_i and C_i for the intermediate time-constant branches of the insulation model.

B. Variation of R_0 and C_0

The insulation resistance R_0 provides information about the overall status of the insulation. A higher value of R_0 indicates better condition of insulation whereas lower R_0 corresponds to aged and moist insulation. Figs. 14 and 15 show the variation of polarization and depolarization currents and RV spectra respectively corresponds to two different values of the insulation resistance R_0. Higher values of R_0 tend to reduce the polarization current magnitudes but the shift of the first dominant peak of the RV spectra is found to be too insignificant. There is, however, a noticeable shift in the subsidiary peak of the RV spectra with the change of the value of R_0.

The dependence of the simulated RV spectra on the value of geometric capacitance C_0 of the insulation model is shown in Fig. 16. The value of this capacitor is dependent on the geometry of the insulation arrangements inside the transformer. Hence, as expected, changing C_0 alters the magnitude of the RV spectra along with shifting the central time constants [19]. The variation of the geometric capacitance C_0 thus has a significant impact on the RV spectra. In (1) and (2), however, depolarization current is first normalized with the geometric capacitance and then curve fitted to obtain the values of R_i-C_i. That is the reason the impact of C_0 on depolarization current (2) is not visible. In practice, the polarization and depolarization currents depend on geometry and size of the insulation system.

IV. Analysis of Field Test Results

With these background observations about the dependence of the equivalent model parameters on the condition of the oil and paper insulation, an attempt has been made in this section to analyze the results of dielectric testing on a field transformer. The transformer was undergoing an oil-reclamation process and the tests were performed both before and after the oil-reclamation to study the effect of the reclamation process on the dielectric response. According to the information available from the utility,

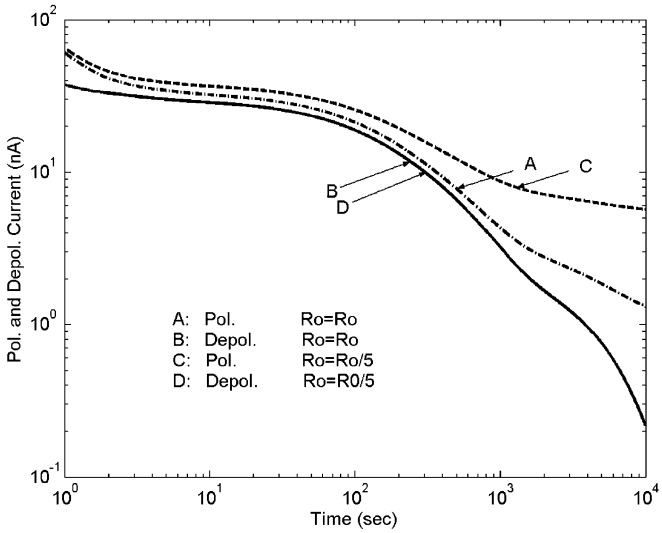

Fig. 14. Dependence of the polarization and depolarization currents on the value of the insulation resistance R_0.

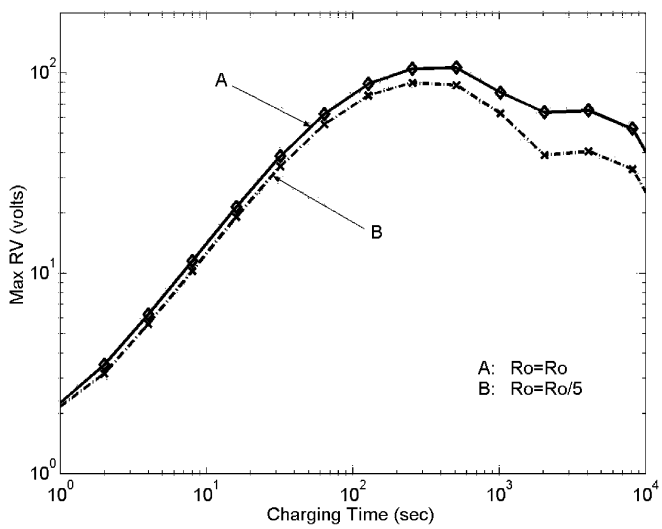

Fig. 15. Dependence of the RV spectra on the value of the insulation resistance R_0.

the oil-reclamation process basically consisted of recycling, filtering, and drying the oil through vacuum and at high temperature. The dry and filtered oil was pumped back to the tank and the whole process was continued in a close cycle. In such a close cycle oil reclamation process, it is expected that some moisture and other degradation byproducts will be driven off the oil. At the same time when dry oil is circulated through the transformer, some moisture will also migrate out of the paper toward the relatively dry oil. Thus, in such an oil-reclamation process, the oil moisture content and other aging byproducts are expected to go down along with some improvement in the paper moisture condition as well. The oil moisture content values both before and after oil reclamation, measured by Karl Fischer Titration method are presented in Table II. Table II also contains the paper moisture content values determined using the equilibrium chart [20] from the measured oil moisture content values at the corresponding oil sampling temperatures.

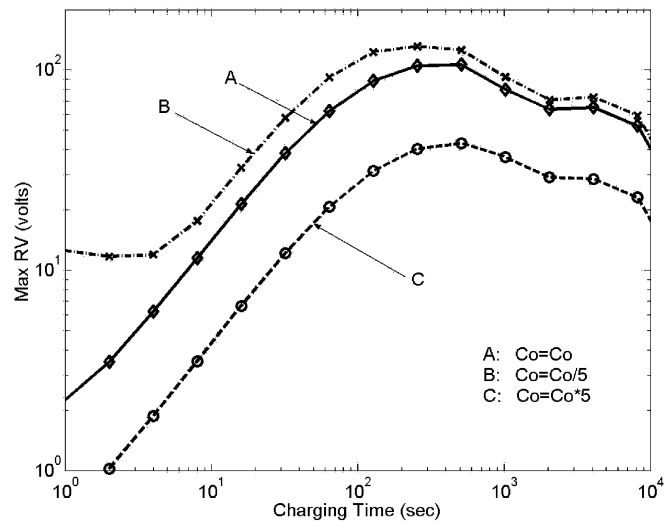

Fig. 16. Dependence of the RV spectra on the value of the geometric capacitance C_0.

TABLE II
OIL AND PAPER MOISTURE CONTENT BEFORE AND AFTER OIL RECLAMATION

Transformer		Before Oil Reclamation	After Oil Reclamation
Moisture Content	Oil (ppm)	28	10
	Paper (%)	5	3.5
Oil Sampling Temp. (^{0}C)		23	25

As seen in Table II, the estimated paper moisture drops to a value of 3.5% after oil reclamation from the initial value of 5% before the oil reclamation. It, however, remains a fact that the accuracy of the equilibrium chart [20] is questionable at the lower ranges of oil and paper moisture content values. Even then, it is not beyond expectation that during such an oil-reclamation process, some moisture has migrated out of the paper insulation toward the relatively dry oil. Figs. 17 and 18 are the plots for the polarization and depolarization currents and simulated RV spectra for the transformer both before and after the oil-reclamation process. Table III summarizes the values of the equivalent circuit parameters for the transformer.

As can be seen from Fig. 17, the polarization and depolarization currents during the initial period are much lower after oil reclamation as compared to those before the oil-reclamation process. The long term values of the currents are, however, not very different—indicating the fact that oil-reclamation alone cannot improve the paper condition appreciably, even if the oil condition improves to a certain extent.

As seen in Fig. 18, the first dominant peak of the RV spectra shifts toward a higher time—indicating an overall improvement in the condition of the oil after the oil-reclamation. However, the subsidiary peaks of the two RV spectra are only slightly different. As mentioned in [19], these subsidiary peaks are related to polarization of the paper insulation. This once again supports the observation that after the oil-reclamation though the oil condition improves, the paper condition is not improved significantly.

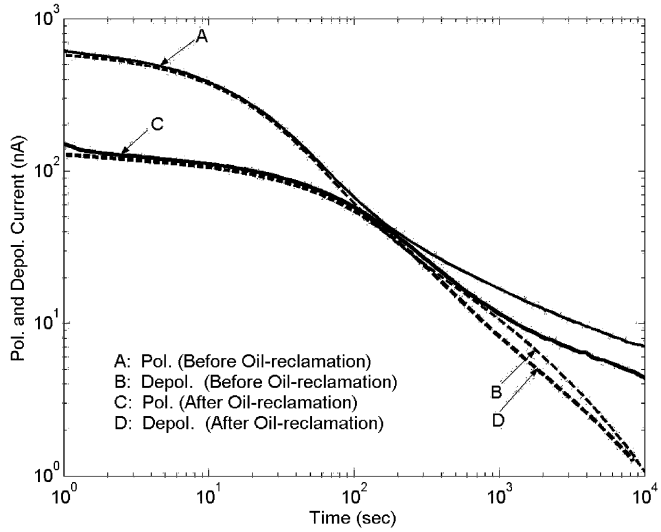

Fig. 17. Polarization and depolarization before and after oil reclamation.

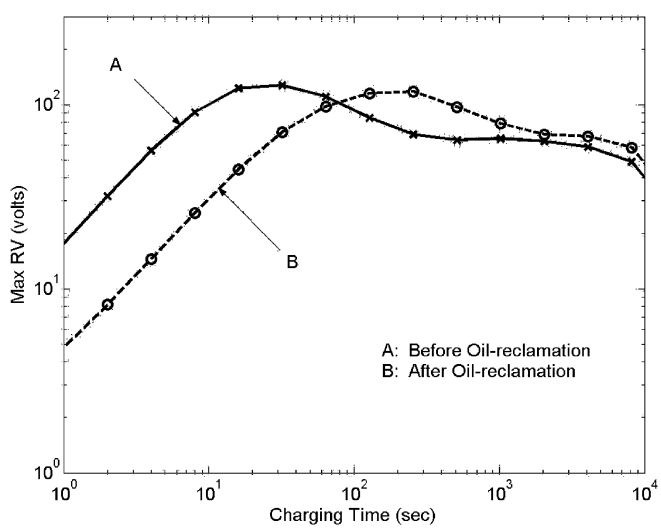

Fig. 18. RV spectra before and after oil reclamation.

TABLE III
EQUIVALENT CIRCUIT PARAMETER VALUES BEFORE AND AFTER OIL RECLAMATION

Branch	Before oil-reclamation		After oil-reclamation	
	R_i (GΩ)	C_i (nF)	R_i (GΩ)	C_i (nF)
1	58.0	83.0	70.0	68.0
2	29.0	26.5	30.0	22.0
3	11.5	14.5	9.0	18.0
4	2.5	17.0	13.0	3.5
5	1.5	9.5	34.0	0.1
6	2.5	0.15	21.0	0.02
R_0 (GΩ)	81.0		140.0	
C_0 (nF)	3.34		3.3	

R_i-C_i values are calculated for this transformer from before and after oil reclamation results and are shown in Table III. As seen from Table II, the oil moisture content has substantially improved after the oil reclamation process. It can be seen from the values of R_i-C_i in Table III, that the improvement in the quality of the oil after the oil-reclamation process has been reflected in the values of R_i and C_i for the lower time-constant branches. Branches 4, 5, and 6 have higher values of R_i and lower values of C_i after the oil-reclamation process when compared to the corresponding values before the oil reclamation process. Since the geometry of the insulation system is essentially the same before and after the oil reclamation, this variation in the equivalent model R_i-C_i parameter values for the smaller time-constant branches can solely be related to the change in condition of the oil. On the other hand, the difference between the R_i and C_i values for the larger time constant branches (branches 1 and 2 in Table III) corresponding to before and after oil-reclamation are not too different from each other—indicating the fact that the oil-reclamation does not improve the paper condition appreciably. However, a comparatively small improvement in the paper moisture content (from 5% to 3.5%) has been reflected as a slight increase in the values of R_i and a decrease in the values of C_i for the higher time-constant branches 1 and 2. The insulation resistance R_0 is found to have higher value after the oil-reclamation—once again indicating an overall improvement of the condition of the insulation along with drying up of the paper to a certain extent. The value of C_0, however, as mentioned before, almost remains the same—since it is more dependent on the geometry of the insulation than its condition. It thus seems possible to assess the condition of the insulation as a whole from the insulation resistance R_0 and also oil and paper condition separately by having a close study of the values of the R_i and C_i parameters of the branches corresponding to different time constants.

The experimental results presented in the above Section IV involve test data on a single transformer both before and after oil reclamation. Thus, the geometry of the insulation structure essentially remained the same in both the cases of before and after oil reclamation. The results thus presented clearly indicate the dependence of the equivalent model parameters on the condition of the oil and paper, with the geometry remaining invariant. However, in order that this approach be applied to different transformers with different insulation geometry and size—it is essential that the polarization and depolarization currents be made independent of geometry before applying the curve-fitting procedure to find out the values of R_i-C_i of the different polarization branches. This can be achieved by dividing the polarization and depolarization currents by the geometric capacitance of the transformer before starting the curve-fitting procedure. This will ensure that all of the currents are normalized to the same scale of geometry and that the values of R_i and C_i thus obtained will be dependent only on the condition of the oil and paper.

V. CONCLUSION

A model of the transformer's main insulation system, which describes its dielectric behavior, has been presented in this paper. The values of the parameters of the equivalent model have been obtained from PDC measurements. Once the model has been parameterized, dielectric responses such as the polarization, depolarization currents, and the return voltage can be simulated. A good agreement has been found between the measured PDC and RV spectra and the corresponding simulated curves, demonstrating a higher accuracy of the model.

So far, the interpretations of the dielectric response measurements are often convicted of being too simplistic—without

addressing the physical behavior of the insulation. The approach adopted in this paper promises to overcome most of the controversies in the interpretation by correlating the dielectric responses to the basic components of the insulation model. The variations of the PDC and the RV spectra of the values of the equivalent model parameters have been investigated. In this way, the dielectric behavior of a complex insulation system has been explained from the properties of the basic model. The oil and paper conditions are found to affect the parameters of the equivalent model in a definite and distinct way—thereby enabling correct and transparent interpretation of the dielectric diagnosis results.

REFERENCES

[1] T. K. Saha, M. Darveniza, D. J. T. Hill, and T. T. Le, "Electrical and chemical diagnosis of transformer insulation, part A: Aged transformer samples," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1547–1554, Oct. 1997.

[2] T. K. Saha, M. Darveniza, and Z. T. Yao, "Field experience with interfacial polarization spectra measurements for assessing insulation condition in transformers," in *Proc. 11th Int. Symp. High Voltage Engineering*, vol. 5, London, U.K., 1999, pp. 140–143.

[3] G. M. Urbani and R. S. Brooks, "Using the recovery voltage method to evaluate aging in oil-paper insulation," in *Proc. IEEE Int. Conf. Conduction and Breakdown in Solid Dielectrics*, Vasteras, Sweden, 1998, pp. 93–97.

[4] A. Bognar, L. Kalacsai, G. Csepes, E. Nemeth, and J. Schmidt, "Diagnostic tests of high voltage oil-paper insulation systems (in particular transformer Insulation) using DC dielectrometrics," in *Proc. CIGRE*, Paris, France, 1990, Paper no. 15/33-08.

[5] A. A. Paithankar and C. T. Pinto, "Transformer insulation diagnosis: Recovery voltage measurement and DC absorption test," in *Proc. Electrical Insulation Electrical Manufacturing Coil Winding Conf.*, 2001, pp. 597–600.

[6] V. der Houhanessian and W. S. Zaengl, "Application of relaxation current measurements to on-site diagnosis of power transformers," in *Proc. IEEE Annu. Rep. Conf. Electrical Insulation and Dielectric Phenomena*, 1997, pp. 45–51.

[7] ——, "On-Site diagnosis of power transformers by means of relaxation current measurements," in *Proc. IEEE Int. Symp. Electrical Insulation*, 1998, pp. 28–34.

[8] T. Leibfried and A. J. Kachler, "Insulation diagnostics on power transformers using the polarization and depolarization current (PDC) analysis," in *Proc. IEEE Int. Symp. Electrical Insulation*, 2002, pp. 170–173.

[9] M. Hässig, R. Bräunlich, R. Gysi, J.-J. Alff, V. der Houhanessian, and W. S. Zaengel, "On-site applications of advanced diagnosis methods for quality assessment of insulation of power transformers," in *Proc. IEEE Annu. Rep. Conf. Electrical Insulation and Dielectric Phenomena*, 2001, pp. 441–447.

[10] T. Leibfried and A. J. Küchler, "Insulation diagnostics on power transformers using the polarization and depolarization current (PDC) analysis," in *Proc. IEEE Int. Symp. Electrical Insulation*, 2002, pp. 170–173.

[11] G. Mohamed and E. Németh, "Computer simulation of dielectric processes," in *Proc. 7th. Int. Symp. High Voltage Engineering*, Dresden, Germany, 1991, pp. 309–312.

[12] E. Németh and T. Horváth, "Fundamentals of the simulation of dielectric processes of insulations," in *Proc. 8th. Int. Symp. High Voltage Engineering*, Yokohama, Japan, 1993, pp. 177–180.

[13] V. der Houhanessian and W. S. Zaengl, "Time domain measurements of dielectric response in oil-paper insulation systems," in *Proc. IEEE Int. Symp. Electrical Insulation*, Montreal, QC, Canada, 1996, pp. 47–52.

[14] P. R. S. Jota, S. M. Islam, and F. G. Jota, "Modeling the polarization in composite oil/paper insulation systems," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 2, pp. 145–151, 1999.

[15] A. Küchler and T. Bedel, "Dielectric diagnosis of water content in transformer insulation systems," *Eur. Trans. Electr. Power*, vol. 11, no. 1, pp. 65–68, 2001.

[16] G. Frimpong, U. Gafvert, and J. Fuhr, "Measurement and modeling of dielectric response of composite oil/paper insulation," in *Proc. 5th Int. Conf. Properties and Applications of Dielectric Materials*, vol. 1, 1997, pp. 86–89.

[17] U. Gafvert, G. Frimpong, and J. Fuhr, "Modeling of dielectric measurements on power transforms," in *Proc. CIGRE*, Paris, France, 1998, Paper no. 15/103.

[18] A. K. Jonscher, *Dielectric Relaxation in Solids*: Chelsea Dielectric Press, 1983.

[19] "Dielectric Response Methods for Diagnosis of Power Transformers," in *Electra no. 202*, 2002, CIGRE Task Force 15.01.09.

[20] T. V. Oomen, "Moisture equilibrium in paper oil insulation systems," in *Proc. 16th Electrical/Electronics Insulation Conf.*, Chicago, IL, 1983, pp. 162–166.

Tapan K. Saha (SM'97) was born in Bangladesh and emigrated to Australia in 1989.

Currently, he is an Associate Professor in the School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, Australia. Before joining the University of Queensland, he taught at the Bangladesh University of Engineering and Technology, Dhaka, for three-and-a–half years and then at James Cook University, Townsville, Australia, for two-and-a–half years. His research interests include power systems, power quality, and condition monitoring of electrical plants.

Dr. Saha is a Fellow of the Institution of Engineers, Australia.

Prithwiraj Purkait (M'99) was born in Kolkata, India, in 1973. He received the B.E.E., M.E.E., and Ph.D. degrees from Jadavpur University, Kolkata, in 1996, 1999, and 2002, respectively.

Currently, he is a Lecturer in the Department of Electronics and Instrumentation Engineering at Haldia Institute of Technology, Haldia, India. He is also involved in postdoctoral research at the University of Queensland, Brisbane, Australia. He was also a Design Engineer with M/s Crompton Greaves Ltd., Mumbai, India, for one year. His current research includes transformer insulation condition assessment techniques and advanced signal processing applications in high-voltage engineering.

Frank Müller (S'02) was born in Werneck, Germany, in 1975. He received the Diploma degree in electrical engineering from the University of Applied Sciences, FH Würzburg-Schweinfurt, Germany. He did his thesis work at the School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, Australia, as a Deutscher Akademischer Austauschdienst—German Academic Exchange Service (DAAD) Fellowship Holder.

He specializes in power systems engineering.