Understanding Moisture Dynamics and Its Effect on Dielectric Response of Transformer Insulation

Yi Cui, *St. Member, IEEE*, Hui Ma, *Member, IEEE*, Tapan Saha, *Senior Member, IEEE*, Chandima Ekanayake, *Member, IEEE*

***Abstract*— Dielectric response measurement has recently been adopted by utilities for evaluating moisture content in cellulose insulation (paper and pressboard) of transformers. Moisture distribution is highly dependent on temperature. Since the temperature inside a transformer may change during the dielectric response measurement, the moisture in the transformer's cellulose and oil insulation can hardly attain an equilibrium state. Instead, moisture dynamics exist inside the transformer: (1) cellulose absorbs (desorbs) moisture from (to) oil with the changes in temperature; and (2) moisture migrates inside cellulose due to a moisture gradient. This paper investigates moisture dynamics and its effect on dielectric response of a transformer's cellulose insulation. It proposes a distributed parameter model to reveal the correlation between moisture distribution (under non-equilibrium conditions due to thermal transients) and dielectric response parameters (dielectric losses and permittivity) of cellulose insulation. It then estimates these parameters under moisture non-equilibrium conditions. The accelerated ageing and moisture diffusion experiments are conducted on a prototype transformer to verify the proposed model. The methodology developed in this paper can help the proper interpretation of dielectric response measurement of field transformers under thermal transients.**

***Index Terms*—Cellulose, dielectric response, insulation, moisture diffusion, moisture dynamics, oil, transformer.**

I. Introduction

Life expectancy of a power transformer is largely determined by the ageing condition of its cellulose insulation. Moisture is one of the most harmful agents for cellulose insulation. It can accelerate the cellulose ageing rate and reduce both dielectric and mechanical strength of cellulose insulation [1]. Therefore, it is of great interest for utilities to estimate moisture content in cellulose insulation of transformers.

Moisture content in cellulose can be directly measured by the Karl Fischer Titration (KFT) method. However, it requires collecting paper samples from a transformer's winding, which is difficult in practice. An alternative approach is through measuring the moisture content of an oil sample and then determining the moisture content in the cellulose from equilibrium charts [2-4]. This approach assumes an equilibrium state of moisture distribution in the transformer. However, it is hard to attain an equilibrium state in the transformer and any variation in temperature tends to change the moisture distribution in cellulose and oil [5]. This can lead to an inaccurate estimation of moisture in the cellulose [6].

Y. Cui, H. Ma, T. Saha and C. Ekanayake are with School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia (e-mail: y.cui3@uq.edu.au, huima@itee.uq.edu.au, saha@itee.uq.edu.au, chandima@uq.edu.au).

The utilities have widely adopted the dielectric response method for estimating moisture content in transformers' cellulose insulation. During dielectric response measurement, the transformer is removed from the grid and thus the temperature inside the transformer continuously drops. Consequently, during the course of the dielectric response measurement, moisture migrates between cellulose and oil. This will influence the interpretation of the results of dielectric response measurement and affect the accuracy of moisture estimation in the transformer's cellulose insulation. As an example, the authors made two dielectric measurements on one utility's transformer. During the first measurement a moisture content of 2.9 % at 30 °C top-oil temperature was recorded. The second measurement commenced immediately after, and recorded 3.6 % at 26.5 °C. Therefore, for an accurate estimation of moisture in cellulose insulation based on dielectric response measurement, it is necessary to investigate the correlations between moisture dynamics and dielectric response parameters (i.e. dielectric loss and permittivity) of a transformers' insulation.

This paper is aimed at understanding temperature dependent moisture dynamics and its effect on the dielectric response of the cellulose insulation of transformers. A distributed parameter model is proposed to explore correlations between moisture distribution under non-equilibrium conditions and dielectric response of cellulose insulation. By using this model, dielectric losses and permittivity of cellulose insulation are estimated when a transformer is under temperature variation and consequent moisture non-equilibrium. To verify the methodology developed in this paper, extensive ageing and moisture diffusion experiments are performed on a prototype transformer.

II. Moisture in Transformer's Insulation System

A. *Moisture Dynamics in Cellulose and Oil Insulation*

Due to moisture ingress from the environment and cellulose degradation, moisture is present in a transformer. During the normal operation of a transformer, most moisture is affiliated with its cellulose insulation. Water generally has low solubility in transformer oil. With an increase in temperature, the water solubility in oil can be significantly increased. On the other hand, free water can be formed if the moisture in oil exceeds the saturation level.

For an in-service transformer, it can absorb water from environment and its oil can contain some amount of water. The transformer's oil-cellulose insulation system is in an equilibrium state if the partial pressure of water in oil equals the partial pressure of water in cellulose. When the partial pressures in oil and cellulose become different, cellulose absorbs/desorbs water from/to oil to maintain the equilibrium. Moreover, moisture diffusion occurs inside cellulose insulation due to a moisture gradient.

B. Estimation of Moisture Contents in Cellulose Insulation

Over the past twenty years, extensive studies have been performed for estimating moisture content in cellulose insulation. Most of these studies are focused on moisture diffusion using Fick's second law [7] in one dimension as (1)

$$\frac{\partial W(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial W(x,t)}{\partial x} \right) \quad (1)$$

where $W(x,t)$ is the moisture content of cellulose at position x and time t. D denotes the diffusion coefficient and is usually not a constant but depends on both moisture concentration and temperature. By conducting laboratory experiments, researchers have derived diffusion coefficients for different types of cellulose (i.e. paper or pressboard, non-impregnated or impregnated, aged or non-aged, paper/pressboard with different thickness) under different local moisture concentration and temperatures [2-9]. However, certain variations may exist in these derived diffusion coefficients since the experiments were conducted with different setups and conditions. Such variations can pose difficulties for utilities on selecting the correct coefficient for a moisture content estimation in their transformers.

García *et al.* proposed a moisture-in-oil model for power transformer monitoring [8]. The model considered the equilibrium relations between oil and cellulose, the moisture dynamics before attaining the steady-state equilibrium and the increase of the amount of moisture due to cellulose ageing. However, it is not clear whether moisture in cellulose can be derived from this model.

Originally proposed by Piper and Fessler [9], the isothermal approach has also attracted the attention of some researchers [10]. This approach uses temperature and vapor pressure to derive the local moisture content in cellulose from the measurement of moisture-in-oil sensor. However, the sensor's location has a large influence on the moisture estimation. Given the complexity of a transformer's construction and different types of cellulose used at different layers and locations inside the transformer, a sufficient number of moisture-in-oil sensors need to be installed to provide an accurate estimation of moisture in the cellulose insulation of a transformer.

An alternative technique for estimating moisture content in cellulose is the dielectric response method. It measures several dielectric response parameters, which are influenced by temperature, moisture content and the ageing condition of the cellulose insulation in a transformer. By using a database built based on well-defined pressboard samples with different temperatures and moisture contents, it is possible to estimate the moisture content in cellulose insulation in a transformer. The next section will provide a brief review on dielectric response technique for moisture content estimation.

III. Dielectric Response of Transformer Insulation

A. Dielectric Response in Frequency Domain

When a dielectric material is imposed by an alternating electric field $\widehat{E} = E_m e^{i\omega t}$, the complex dielectric displacement in this material becomes (2)

$$\widehat{D}(\mathrm{t}) = \varepsilon_0 \varepsilon_\infty E_m e^{i\omega t} + \varepsilon_0 \int_{-\infty}^{t} f(\mathrm{t}-\mathrm{t}_0) E_m e^{i\omega t_0} dt_0 \quad (2)$$

where ε_0 denotes the permittivity of vacuum, ε_∞ denotes the high frequency relative permittivity of the material and *f(t)* is the response function of the material which monotonically decreases with time.

The Fourier transform of the response function $f(t)$ yields the complex susceptibility, $\widehat{\chi}(\omega)$

$$\widehat{f}(\omega) = \int_{0}^{\infty} f(t) e^{-i\omega t} dt = \widehat{\chi}(\omega) = \chi^{'}(\omega) - j\chi^{''}(\omega) \quad (3)$$

The real and the imaginary parts of the complex susceptibility are not independent from each other since they are both generated by the same response function $f(t)$. They can be regarded as the cosine and sine transforms of the response function respectively.

The total current density $\widehat{j}(\omega)$ in the dielectric material under $\widehat{E}(\omega)$ excitation can therefore be expressed as

$$\widehat{j}(\omega) = i\omega\varepsilon_0 [\underbrace{\varepsilon_\infty + \chi^{'}(\omega)}_{capacitive\ part} - \underbrace{i(\sigma_{dc}/\varepsilon_0\omega + \chi^{''}(\omega))}_{resistive\ part}]\widehat{E}(\omega) \quad (4)$$

where σ_{dc} denotes dc conductivity of the material. This expression shows that the current is composed of a resistive part and a capacitive part. The resistive part represents the energy losses in the material, which are dominated by two different mechanisms, one is due to dc conduction (movement of free charges) and the other is because of relaxation losses (re-orientation of bonded charges). The capacitive part is associated with the capacitance of the material.

In many situations, it is more convenient to use the complex permittivity instead of the complex susceptibility. It can be defined as follows

$$\widehat{j}(\omega) = i\omega\varepsilon_0 [\varepsilon^{'}(\omega) - i\varepsilon^{''}(\omega)]\widehat{E}(\omega) \quad (5)$$

where $\varepsilon^{'}(\omega) = \varepsilon_\infty + \chi^{'}(\omega)$ and $\varepsilon^{''}(\omega) = \sigma_{dc}/\varepsilon_0\omega + \chi^{''}(\omega)$.

The above equations show that the dc conductivity σ_{dc}, the high frequency component of the relative permittivity ε_∞, and the complex dielectric susceptibility $\widehat{\chi}(\omega)$, characterise the dielectric material in the frequency domain. It is possible to determine these parameters by measuring the magnitude and phase angle of the resultant currents when the material is subjected to an alternating voltage under different frequencies.

B. Dielectric Response Measurement for Moisture Estimation

For estimating moisture content in a transformer, the geometric information of the winding insulation of the transformer under investigation is needed. For a core type transformer the main insulation usually consists of a number of cylindrical shells of pressboard barriers, separated by axial spacers. A so-called *X-Y* model is widely used to represent such a structure [6]. By making use of a database and *X-Y* model, an algorithm can be implemented to find the best fit between the response of the model and the measured response of the transformer. This result can then be used for moisture estimation of a transformer's cellulose insulation.

The above moisture estimation assumes the transformer under test is kept at a constant temperature and attains moisture equilibrium. However, equilibrium is difficult to attain in the transformer during measurement. It is therefore necessary to investigate the correlation between temperature dependent moisture dynamics and the dielectric response of cellulose insulation. This will pave a way for properly evaluating moisture in cellulose insulation of the transformer onsite, which is under a temperature transient.

In the next section a distributed parameter model is proposed for studying the dielectric behavior of oil and cellulose insulation under non-equilibrium and non-uniform moisture distribution in a transformer.

IV. Distributed Parameter Dielectric Response Model

The proposed distributed model is shown in Fig. 1. In this model, the pressboard with thickness l is sliced into *N* layers ($i=1,2,...,N$). Assuming moisture in the transformer is in a non-equilibrium state, the moisture is not uniformly distributed along the thickness of the cellulose insulation. Consequently, each layer of pressboard has a different dielectric loss δ_i and permittivity ε_i.

The impedance $Z(\omega)$ of the whole piece of the pressboard in the frequency domain can be written as

$$Z(\omega)=1/G(\omega)=\sum_{i=1}^{N}Z_i(\omega)=\sum_{i=1}^{N}1/G_i(\omega) \qquad (6)$$

where N denotes the total number of sliced layers of the pressboard, $Z_i(\omega)$ and $G_i(\omega)$ are the impedance and admittance of the *i*-th layer of the pressboard respectively.

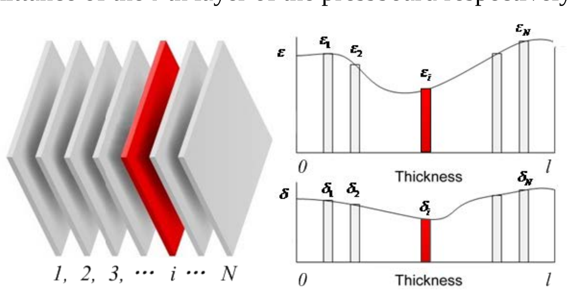


Fig. 1 Distributed model for modelling dielectric response of pressboard

In Fig. 1, each layer of pressboard can be represented by a parallel circuit consisting of a capacitor and a resistor. For the *i*-th layer of the pressboard, its admittance can be written as

$$G_i^*(\omega)=(\delta_i+j\omega\varepsilon_0\varepsilon_i^{'})S/\Delta x \qquad (7)$$

According to frequency domain dielectric spectroscopy theory [11], (6) can be rewritten as (8)

$$Z^*(\omega)=\sum_{i=1}^{N}\Delta x/S\left(\delta_i+j\omega\varepsilon_0\varepsilon_i^{'}\right) \qquad (8)$$

where S denotes the total area of the cylindrical pressboard, Δx is the thickness of each sliced layer of the pressboard, $\varepsilon_i^{'}$ denotes the real part of complex permittivity of the *i*-th layer of pressboard and δ_i represents the summation of conductive and polarization losses of the *i*-th layer of pressboard (the loss of the whole piece of pressboard is shown in (5)).

Assuming that the above pressboard can be sliced infinitely thin, (8) can be rewritten as (9)

$$Z^*(\omega)=\frac{1}{S}[\int_0^l\frac{\delta_x}{\delta_x^2+(\omega\varepsilon_0\varepsilon_x^{'})^2}dx-j\int_0^l\frac{\omega\varepsilon_0\varepsilon_x^{'}}{\delta_x^2+(\omega\varepsilon_0\varepsilon_x^{'})^2}dx)] \qquad (9)$$

In dielectric response measurement, the phases and magnitudes of the applied AC voltage and resultant current can be measured. Subsequently, the impedance $Z^*(\omega)$ of the pressboard can be obtained. Then the complex capacitance of the pressboard can be calculated by using (10)

$$Z^*(\omega)=1/G^*(\omega)=1/j\omega C^*(\omega)=1/j\omega C_0\varepsilon^*(\omega) \qquad (10)$$

Combining (7) and (10), the complex capacitance of the pressboard is expressed in (11)

$$C_i^*(\omega)=G_i^*(\omega)/j\omega=(\varepsilon_0\varepsilon_i^{'}-j\delta_i/\omega)S/\Delta x \qquad (11)$$

On the other hand, from (9) and (10) the complex capacitance of the pressboard can also be directly written as

$$C_i^*(\omega)=\varepsilon_i^*(\omega)C_0=\varepsilon_0 S\left(\varepsilon_x^{'}+j\varepsilon_x^{''}\right)/\Delta x \qquad (12)$$

By comparing (11) and (12), it can be expressed as

$$\varepsilon_x^{'}=\varepsilon_i^{'},\quad \delta_x=\delta_i=\varepsilon_0\omega\varepsilon_i^{''} \qquad (13)$$

Eq. (13) reveals that $\varepsilon_x^{'}$ in (8) equals the real part of permittivity $\varepsilon_i^{'}$ while δ_x in (8) can be calculated from the imaginary part of permittivity $\varepsilon_i^{''}$. Both the real and imaginary parts of permittivity of pressboard can be obtained from the results of dielectric frequency response measurements. The above distributed model will be used to investigate the moisture dynamics effect on dielectric response measurement in the following sections.

V. Experimental Setup

A. Prototype Transformer Configuration

A prototype transformer is used for experimental study in this paper. It is a single phase transformer rated at 5 kVA with 240 V secondary and 2.2 kV primary. Since the losses due to current flowing through the transformer's winding may not generate the required temperature, a heater was installed at the bottom of the transformer. This also helped to control the prototype transformer's temperature to simulate different thermal conditions for the accelerated ageing and moisture diffusion experiments. Fig. 2 shows the geometry of the insulation of the prototype transformer.

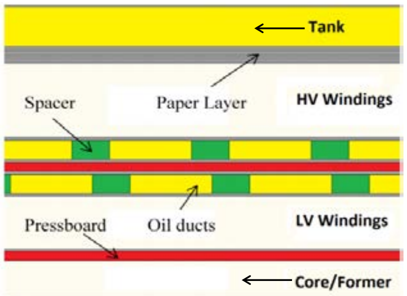


Fig. 2 Insulation geometry of the prototype transformer

In the prototype transformer, the cellulose insulation includes hybrid Diamond Dotted Paper (DDPP), Mouldable pressboard (MPB) and Spacers All Round (SAR) and they are immersed in transformer oil (Nynas Libra). The temperature class of the transformer's paper insulation is A. The ratio in *X*-*Y* model is calculated as $X = 38\%, Y = 16\%$, where X is the lumped sum of the thickness of all barriers in the duct divided by the duct width; Y is the total width of all spacers divided by the total length of the periphery of the duct [6].

B. Moisture Dynamics Experiments

After the commission of the prototype transformer, it was subjected to both electrical and thermal loading to attain a certain degree of ageing of its cellulose insulation (equivalent to 34 years of life consumption based on the degree of polymerization (DP) measurement of this transformer). Electrical loading was imposed by using a load bank with maximum power capacity of 6 kW. The prototype transformer was kept at 110 ºC (using the abovementioned heater) with 30A load current for an effective time period equal to 35 days (the transformer was kept at 50 ºC during the night and weekends).

After 35 days of accelerated electrical and thermal ageing of the prototype transformer, experiments were arranged to study the moisture dynamics and its effect on dielectric response of the cellulose insulation of the transformer. In the experiments, a sinusoidal temperature profile was imposed on the prototype transformer by using the above mentioned heater. The prototype transformer is sealed from the atmosphere. A moisture-in-oil sensor (Vaisala MMT 330 [12]) was installed in the prototype transformer. The sensor's tip was close to the cellulose insulation of the winding. By using this setup, the moisture at the interface between oil and cellulose insulation could be continuously monitored. Temperature was also measured by this sensor.

The moisture dynamics experiments were conducted in three steps:

(1) The transformer was kept at a constant temperature (55 °C) for one week to let it attain moisture equilibrium.

(2) The transformer was subjected to a sinusoidal temperature profile (Fig. 3) for one week. The period of one cycle sinusoidal temperature was 24 hours with the highest temperature of 80 °C and the lowest temperature of 30 °C.

(3) The transformer was kept at a constant temperature (55 °C) for another one week to let it attain moisture equilibrium. Dielectric response measurement was then performed.

Fig. 3 presents one complete cycle of moisture measurements under sinusoidal temperature. In the figure, the temperature (in green), moisture in oil (in red) and water activity (in blue, is defined as the ratio of the partial pressure of water in the material and the saturated vapor pressure of pure water at the same temperature [10]) were directly obtained from the above moisture-in-oil sensor.

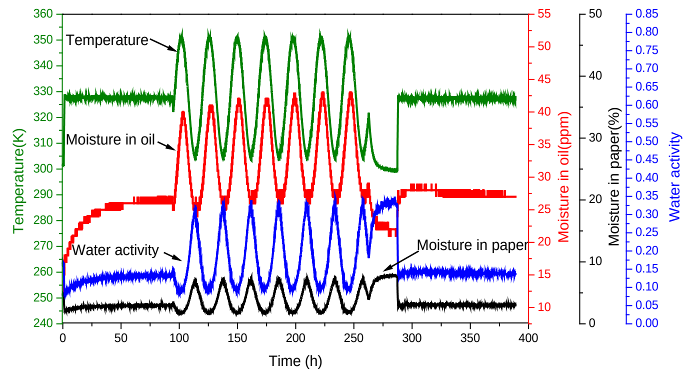


Fig. 3 Sinusoidal variation of temperature (green), water activity in oil (blue), moisture in oil (red, in ppm) and water content at the cellulose surface in contact with oil (black, in percentage) of the prototype transformer

The moisture concentration at the cellulose surface in contact with oil (in black in Fig. 3) was obtained using Fessler [9] equation as

$$W = 2.173 \times 10^{-7} \times P_v^{0.6685} \times e^{4275.6/T} \quad (14)$$

where W is the concentration of absorbed water as the ratio of the mass of water to the mass of dry cellulose, P_v is the vapour pressure of water in atm and T is the temperature in Kelvin.

VI. Modelling of Moisture Dynamics In Cellulose

This section investigates the above sinusoidal temperature driven moisture dynamics in cellulose. The time of moisture diffusion inside cellulose is much larger than that of moisture migration at the cellulose's surface contacting oil. Therefore, this section mainly focuses on moisture diffusion in cellulose.

This section firstly models moisture diffusion in un-aged pressboards. Then it investigates moisture diffusion in the prototype transformer based on the experiments in Section V.

A. Modelling Moisture Diffusion in Pressboard

It is assumed an un-aged dry pressboard (1 mm in thickness with less than 0.5% water content) has one side of its surface contacting with a large volume of oil, which contains a sufficient amount of water. When the pressboard is immersed into the oil, the partial pressure of water in oil is significantly larger than that in pressboard. Thus, the pressboard absorbs water from the oil when it is just immersed into the oil. The other side of the pressboard surface is sealed by an electrode for dielectric response measurement. The whole test cell is considered as a closed system. Under sinusoidal temperature variation, the moisture content at this side of the surface follows the curve in black shown in Fig. 3.

The initial values of moisture content and boundary condition of this pressboard is

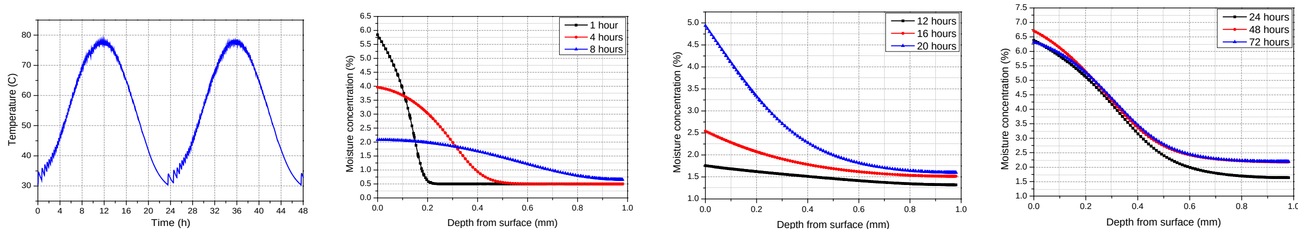
$$\begin{aligned} &W(x,t=0)=W_0, \quad W_0<0.5 \\ &W(x=0,t)=W_s, \quad \partial W(x=l,t)/\partial x=0 \end{aligned} \tag{15}$$

where W_0 is the moisture content in the whole bulk of un-aged pressboards and is assumed less than 0.5% initially. W_s is the concentration of moisture at the interface between pressboard and oil and it varies as sinusoidal shape (black curve in Fig. 3).

By solving Fick's second law (1) and (15), the moisture distribution along the thickness of the pressboard under sinusoidal temperature profile from the time instances t = 1 to 72 hours are obtained and depicted in Fig. 4.

hours sinusoidal temperature cycle. It can be seen from Fig. 4(d), the moisture distribution at the surface of the pressboard at the time instances t = 24, 48 and 72 hours are very close (the difference is less than 0.2%). The difference of moisture in the depth of the pressboard between t = 24, 48 and 72 hours is about 0.5%. Such a difference can be explained as follows.

After several cycles of diffusion, the pressboard becomes humid and water migration is mainly dominated by temperature. At low temperature (30 °C at time instances t = 24, 48, 72 hours) the slow water molecules' mobility and strong bond between cellulose molecules and water molecules imply that the moisture movement is not able to change its directions immediately when temperature changes. Therefore, a certain amount of moisture moves "back and forth" at a particular position of pressboard and a "standing wave" of moisture distribution can be formed.



(a) (b) (c) (d)

Fig. 4 Simulation results of moisture distribution in an un-aged pressboard (one dimension moisture diffusion) (a) temperature variation at different time instances (b)-(d) moisture distribution at different time instances (x=0 refers to the pressboard surface in contact with oil).

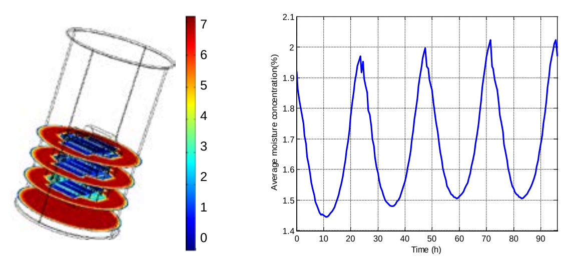
It is assumed that at t = 0 when the dry and un-aged pressboard sample was put into the oil tank, there exists a significant moisture gradient between the oil and the pressboard and at their interface vapor pressure of the oil is larger than that of the pressboard. Therefore, at t = 0 hour, the pressboard absorbs water from the oil and eventually water moves towards the depth of the pressboard. At the time instance t = 1 hour, there exists a large moisture gradient in the pressboard: moisture concentration at the pressboard surface is 5.7% and only 0.5% at other locations away from the surface (Fig. 4(b)). This moisture gradient dominates the water migration and water will continuously move into the pressboard along its thickness for some time though temperature starts to increase.

At the time instances t = 4 and 8 hours, the moisture moves further into the depth of the pressboard. The moisture at the pressboard surface is decreased from 4% to 2.1% while the moisture in most positions of the pressboard increased to above 1% from 0.5% (Fig. 4(b)). At the time instance t = 12 hours, the moisture at the surface of the pressboard almost attains uniformity of 1.75%. As can be observed from Fig. 4(a), at t = 12 hours the temperature starts to decrease from 80 °C. The water in the oil (close to the oil-pressboard interface) starts to move towards the pressboard. Therefore, at the time instances t = 16 and 20 hours, the moisture concentration at the pressboard surface (in contact with oil) increased. The moisture at the pressboard's surface is 2.5%, 5.0% for t= 16 and 20 hours respectively (Fig. 4(c)). The moisture at the pressboard surface reaches its peak of 6.4% at the time instance t = 24 hours. Also the moisture inside the pressboard is larger compared to previous time instances in this first temperature cycle (Figs. 4(b) and 4(c)).

The above moisture dynamics are repeated for the next 24

B. Modelling Moisture Diffusion in Prototype Transformer

Moisture distribution is not only a function of temperature and moisture gradients but also a function of mass and dimensions of the transformer's insulation system. Therefore, multi-physics modeling [13] is adopted to investigate moisture distribution in three dimensions (3D) of the prototype transformer as shown in Fig. 5. It considers the effects of electromagnetic, thermal, fluid flow and moisture migration physics on moisture dynamics in transformers. It especially takes into account the coupling and interactions of these physics as they collectively influence the moisture dynamics and moisture distribution inside the transformer. The details of multi-physics modeling will be provided in a future paper.



(a) (b)

Fig. 5 Moisture distribution of the prototype transformer (a) 3D moisture distribution (at time instance t = 72 hours); (b) average moisture concentration at different time instances. Transformer was under thermal transients as shown in Fig. 3.

Fig. 5(a) presents the moisture distribution in the prototype transformer at the time instance t = 72 hours. Based on the 3D moisture distribution results, the average moisture concentration of the whole bulk of cellulose insulation can be calculated as $W_{average} = \iiint_{\Omega} W(x,y,z)\,dV/V$, where V is the total bulk volume of the cellulose insulation and $W(x,y,z)$ is the moisture concentration at a particular location of the cellulose insulation. Fig. 5(b) presents the calculated average moisture concentration of the cellulose insulation at different time instances. It can be observed from Fig. 5(b) that moisture variations in sinusoidal shape are within the range from 1.45% - 2.0%. The overall moisture of the cellulose insulation of the prototype transformer is 1.7 % by taking the average of data in Fig. 5 (b). It has good agreement with the results from the Karl Fischer Titration method, which indicates 1.5% moisture content in a cellulose specimen collected from the prototype transformer.

Fig. 6 shows the moisture distribution in the prototype transformer's whole bulk cellulose insulation along its radial centreline under different time instances (temperature varies according to Fig. 3). In Fig. 6 the legend of the vertical axis is in ppm for moisture concentration in oil and it is in percentage for moisture concentration in cellulose insulation. From Fig. 6 it can be seen that the moisture is not uniformly distributed inside the cellulose insulation of the prototype transformer. A large proportion of the cellulose has a relatively low moisture level (less than 3%) while the moisture of the cellulose surface in contact with oil (x = 0 and 0.4 m) may reach up to 5% - 7%. The moisture distribution along the transformer height direction also exhibits gradients (Fig. 5(a)). This is due to the non-uniform thermal distribution along the height direction and the existence of a fluid flow field inside the prototype transformer.

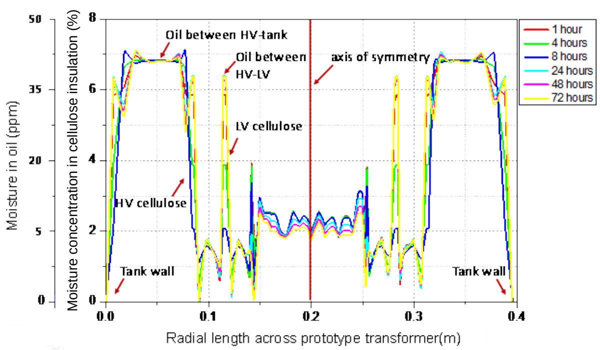


Fig. 6 Moisture distribution of the whole bulk cellulose insulation in the prototype transformer (d = 0.2 m denotes the symmetric line of the cellulose insulation). Temperature varies according to Fig. 3.

VII. Analysis of Moisture Dynamics' Effect on Dielectric Response of Cellulose Insulation

Based on the experiments and modeling results provided in Sections V and VI, this section applies the distributed parameter model proposed in Section IV to study the moisture dynamics' effect on dielectric response of cellulose insulation of the prototype transformer. The study is carried out in two steps:

(1) By using a database built upon the dielectric response measurements on the prototype transformer under constant temperature, the distributed model is applied to explore the correlations between the cellulose's position along its thickness and the cellulose's dielectric response parameters (loss and permittivity) under uniform moisture distribution conditions.

(2) Based on the analysis in step 1, the dielectric response of the cellulose insulation in the prototype transformer under moisture dynamics and temperature transient is estimated. The estimation is verified by the experiments under sinusoidal temperature profile. It needs to be mentioned that the analysis in step 1 does not include the influence of the temperature on the dielectric response. Therefore, the temperature corrections will be conducted (detailed in Section VII C).

A. Dielectric Loss of Cellulose Insulation vs. Moisture

After the prototype transformer attains moisture equilibrium and the moisture is uniformly distributed (Section V B, Step 3), dielectric frequency response measurement is performed from 1 kHz to 1 mHz. Fig. 7 presents both real and imaginary parts of permittivity of the cellulose insulation at 50°C with four different moisture contents, i.e. 1.08%, 1.37%, 1.61% and 3.23% in the prototype transformer. It can be seen from Fig. 7 that the imaginary part of permittivity is influenced by moisture concentration. At a particular frequency, the imaginary part of permittivity increases when more moisture resides in the cellulose insulation.

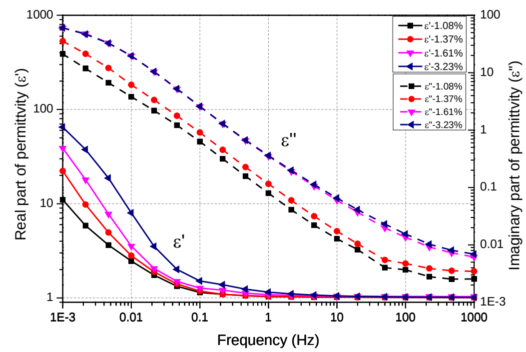


Fig. 7 Real (ε') and imaginary (ε") parts of permittivity of the prototype transformer insulation under uniform moisture distribution at T = 50 °C

The dielectric loss of cellulose insulation under each frequency with different moisture contents can be obtained from Fig. 7 and (13), which is shown in Fig. 8 (data points). Suppose the dielectric loss and the moisture can be modelled as

$$\delta = \alpha_1 e^{\beta_1 \cdot W} \tag{16}$$

where W denotes the moisture concentration in the cellulose insulation, α_1 and β_1 are parameters, which can be computed using the least squares method. Fig. 8 presents the modelled curves of dielectric loss with respect to moisture contents in the cellulose insulation under uniform moisture distribution at 50°C.

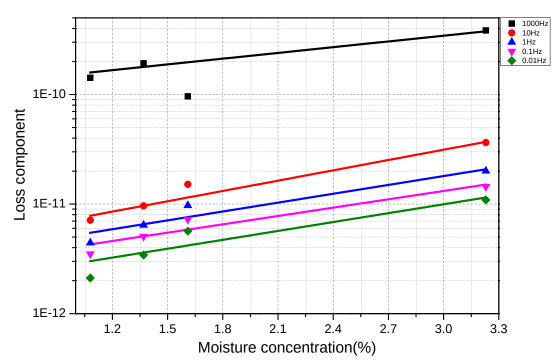


Fig. 8 Dependency between dielectric loss and moisture contents under uniform moisture distribution condition. T = 50 °C.

Once the relationship between dielectric loss and moisture content is obtained by using Fig. 6 and (16), the dielectric loss of the cellulose insulation at different diffusion positions (x axis in Fig. 6) at any specific time instance can be estimated. The estimated values at time instance t = 6 hours are shown in Fig. 9 (denoted as data points). Due to the axis symmetry, only half of the curve (x axis from 0 - 0.2 m) in Fig. 6 is presented.

Suppose that the dielectric loss and diffusion position of the cellulose has an exponential relationship

$$\delta = \alpha_2 e^{\beta_2 \cdot x} \tag{17}$$

where x denotes the position of cellulose insulation, α_2 and β_2 are parameters which can be computed using the least squares method. The modelled dielectric loss with respect to the position of cellulose at the time instance t = 6 hours is presented in Fig. 9 (denoted as curves, T = 50 °C). It should be mentioned that the curves in Fig. 9 are applied to non-equilibrium and non-uniform moisture distribution in the cellulose insulation.

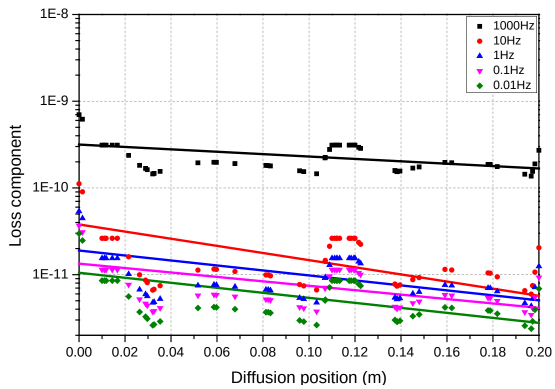


Fig. 9 Dependency between loss and the depth of cellulose insulation (at time instance t = 6 hours diffusion). Data points denote the values obtained from (16) and Fig. 6; Curves are obtained using (17).

B. *Permittivity of Cellulosic Insulation vs. Moisture*

The above approaches are also applied to investigate the correlation between the real part of permittivity of cellulose insulation and moisture content. Fig. 10 depicts the modelled curves of the real permittivity with respect to moisture concentrations under different frequencies at T = 50 °C. Fig. 11 depicts the modelled real permittivity with respect to the depth of cellulose insulation at T = 50 °C. In Fig. 11, the modelled real part of permittivity is for the time instance t = 6 hours.

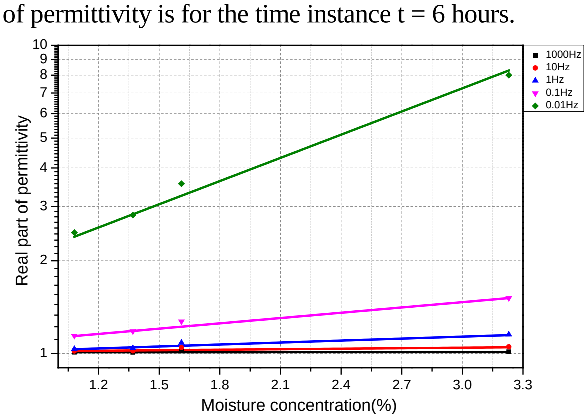


Fig. 10 Dependency between real part of permittivity and moisture contents under uniform distribution condition. T = 50 °C.

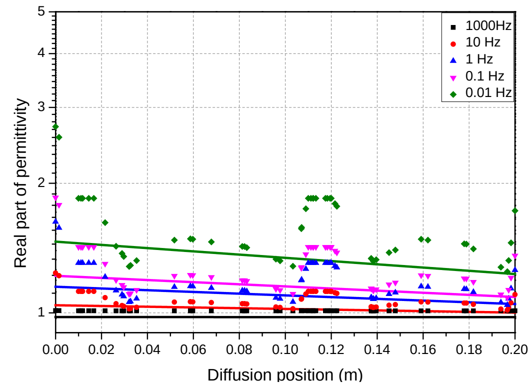


Fig. 11 Dependency between real part of permittivity and the depth of cellulose insulation (at time instance t = 6 hours).

C. *Validation of Distributed Parameter Model*

After obtaining the complex permittivity through the procedures described in Section VII A and VII B, dielectric response measurement is performed on the prototype transformer. The comparison between the measured and the estimated complex permittivities is then made. The comparison provides a validation for the proposed distributed parameter model.

The dielectric response measurement was repeated every hour for 24 hours while the sinusoidal temperature profile (the same as shown in Fig. 3) was imposed on the prototype transformer. During measurement, sinusoidal temperature variation can significantly influence the dielectric response of cellulose, especially for low frequencies because it takes a relatively longer time to take measurement at low frequencies.

The dependency between permittivity and temperature [11] can be expressed as (18)

$$\varepsilon'_T = \varepsilon_{r\infty} + \frac{\varepsilon_{rs} + \varepsilon_{r\infty}}{1+\omega^2\tau_h^{\,2}e^{2H/kT}}, \quad \varepsilon''_T = \frac{(\varepsilon_{rs} - \varepsilon_{r\infty})\omega\tau_h e^{H/kT}}{1+\omega^2\tau_h^{\,2}e^{2H/kT}} \tag{18}$$

where ε_{rs} is the dielectric constant at zero excitation frequency or dc value, $\varepsilon_{r\infty}$ is the dielectric constant at very high frequency, τ_h is a pre exponential factor, H is the activation energy, T is the absolute temperature and k is the Boltzmann constant.

As the dependency between dielectric response and diffusion positions in Section VI is obtained under a constant temperature of 50°C, necessary temperature corrections are needed to compensate the influence of the temperature on the complex permittivity in dielectric response modelling when sinusoidal temperature is applied. The temperature correction is presented in Fig. 12.

In Fig. 12, for each round of dielectric response measurements, the average temperature at a particular frequency is corrected by $T_{ave} = (1/P_i)\int_0^{P_i} T dt$, where P_i is the total measurement duration at the *i*-th frequency and T is the temperature at different time instances as depicted in Fig. 4 (a). By substituting T_{ave} into T of (18), the estimated real and imaginary part of permittivity at each frequency under sinusoidal temperature can be corrected. The estimated and measured real and imaginary parts of permittivity of cellulose insulation after temperature correction under non-equilibrium and non-uniform moisture distribution at different times are drawn in Fig. 13.

From Fig. 13 it can be observed there is a similar trend in the estimated and measured dielectric responses at different time instances. Some degree of discrepancy between the estimated and measured permittivities can be observed: (1) at low frequencies, which may be due to the modeling errors (can be observed in Fig. 9 and Fig. 11); and (2) at time instance t = 6 hours, which may be due to the lack of data for high moisture content in modeling (Fig. 8 and Fig. 10).

From Fig. 13 it can also be seen that there is a decreasing trend in both estimated and measured real permittivities at different time instances (i.e. different moisture distribution in the cellulose insulation). When the moisture concentration increases, the real permittivity also increases at each frequency. The imaginary permittivity increases throughout the whole frequency range when more moisture moves into cellulose insulation. However, the increase of the imaginary part of permittivity at low frequencies is more dominant.

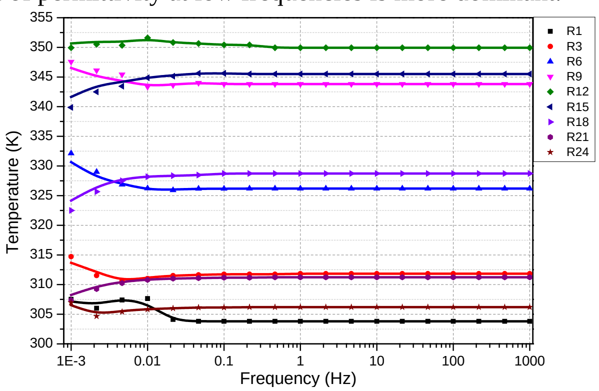


Fig. 12 Temperature correction (R_j denotes the j-th round of dielectric response measurement, data points denote the maximum temperature at each frequency, solid lines denote the corrected temperature at each frequency)

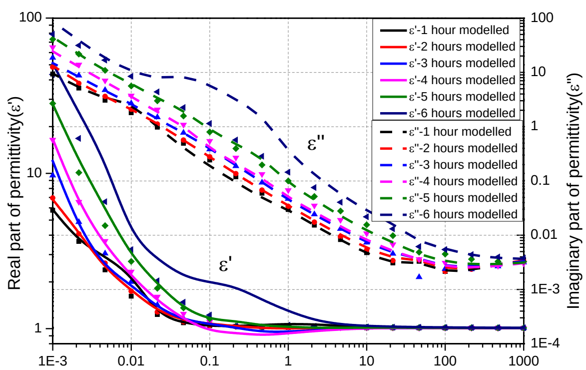


Fig. 13 Comparison between measured and estimated dielectric response (temperature varies according to Fig. 3, from T = 30°C to T = 80°C. Lines denote the modelled data and dots denote the measured data)

To improve the applicability of the proposed method a software tool is implemented, which can be used by practicing engineers as an alternative to current dielectric response measurement analysis software available with the commercial products. Fig. 14 illustrates the major components of this software tool, including:

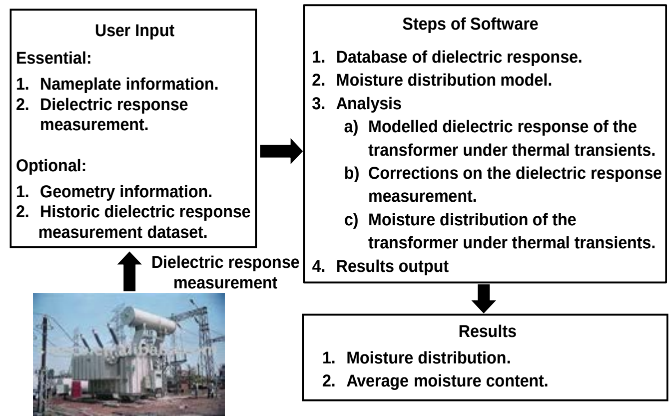


Fig. 14 Components of software tool for moisture estimation

(1) Database of dielectric response of transformers: This database consists of dielectric response measurement from various transformers of different manufacturers. Users can also expand the database by including dielectric response measurement results of their transformers. If the transformer of interest is not included in the database and the user doesn't have any historic measurement dataset of this transformer, the datasets of other transformers with similar rating, insulation geometry and age will be utilized by the software in its calculation.

(2) Moisture distribution model of transformers: The software tool consists of moisture distribution models of many transformers, which are developed from transformers' geometrical information of different manufacturers. For the transformer of which the geometry information is not available, the software will approximate its geometry by using the available information of the transformer (e.g. rating, core type, temperature rise, oil volume etc.). It is assumed that the transformer's insulation construction follows common engineering practice and meets certain criteria (standards). It is also assumed that the moisture dissolved in oil is measured (by either water-in-oil probes or DGA/oil test of the transformer). Based on the above approximated transformer geometry and the measured moisture in oil, the software will produce a moisture distribution model for the transformer of interest.

(3) Analysis: Users conduct dielectric response measurement on the transformer of interest and input the dielectric response data to the software. The software will automatically perform the following calculations:

(a) Combine the above database and moisture distribution model to compute the dielectric response of the transformer considering the effect of temperature variations.

(b) Apply the computed dielectric response in (a) to make corrections on the measured dielectric response of the transformer. Such correction can be done by adjusting the parameters (α and β in Equations 16 and 17) in the model until the error between computed and measured dielectric response is minimized.

(c) Compute the moisture distribution inside the transformer's cellulose insulation under thermal transients.

(4) Output: The software will provide the following information.

(a) Moisture distribution of transformer's cellulose insulation.

(b) Average moisture content in transformer's cellulose insulation.

With the advancement of sensor technology, more sensors can be installed at critical positions for continuously monitoring the temperature and moisture in transformer oil. By integrating the online sensor based monitoring, modeling approach, and dielectric response measurement, the reliability of estimation of moisture and its distribution in transformer insulation system can be improved by the proposed method described in this paper.

VIII. Conclusions

This paper developed a distributed parameter model to interpret the dielectric response of cellulose insulation of transformers under thermal and moisture transients. By using the methodologies proposed in this paper, the dielectric response of a transformers' cellulose insulation under thermal transients and moisture non-equilibrium condition can be estimated. It is expected that the proposed methodology can provide proper interpretation of dielectric response measurement and accurate moisture estimation for transformers at substations.

Acknowledgment

The authors gratefully acknowledge Australian Research Council, and industry partners Powerlink Queensland, Energex, Ergon Energy, and TransGrid for supporting this work.

References

[1] L. E. Lundgaard, W. Hansen, D. Linhjell and T. J. Painter, "Aging of oil-impregnated paper in power transformers," *IEEE Trans. Power Del.*, vol.19, pp. 230-239, 2004.

[2] Pahlavanpour, M. Martins and Eklund, "Study of moisture equilibrium in oil-paper system with temperature variation," in *Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials*, 2003,1124-1129.

[3] T. V. Oommen, "Moisture equilibrium charts for transformer insulation drying practice," *IEEE Transactions on Power Apparatus and Systems*, vol.103, pp. 3062-3067, 1984.

[4] 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, pp. 11-20, 1999.

[5] B. Buerschaper, O. Kleboth-Lugova and T. Leibfried, "The electrical strength of transformer oil in a transformerboard-oil system during moisture non-equilibrium," in *Proceedings of Annual Conference on Electrical Insulation and Dielectric Phenomena*, 2003,269-272.

[6] C. Ekanayake, S. M. Gubanski, A. Graczkowski and K. Walczak, "Frequency response of oil impregnated pressboard and paper samples for estimating moisture in transformer insulation," *IEEE Trans. Power Del.*, vol.21, pp. 1309-1317, 2006.

[7] A. F. Howe, "Diffusion of moisture through power-transformer insulation," *Proceedings of the Institution of Electrical Engineers*, vol.125, pp. 978-986, 1978.

[8] B. Garcia, J. C. Burgos, A. M. Alonso and J. Sanz, "A moisture-in-oil model for power transformer monitoring - Part I: Theoretical foundation," *IEEE Trans. Power Del.*, vol.20, pp. 1417-1422, 2005.

[9] W. A. Fessler, T. O. Rouse, W. J. McNutt and O. R. Compton, "A refined mathematical model for prediction of bubble evolution in transformers," *IEEE Trans. Power Del.*, vol.4, pp. 391-404, 1989.

[10] D. Martin, C. Perkasa and N. Lelekakis, "Measuring paper water content of transformers: a new approach using cellulose isotherms in nonequilibrium conditions," *IEEE Trans. Power Del.*, vol.28, pp. 1433-1439, 2013.

[11] A. K. Jonscher, Dielectric Relaxation in Solids, London: Chelsea Dielectrics Press, 1983.

[12] "MMT330 Moisture and Temperature Transmitter Series for Oil" available at http://www.vaisala.com/en/industrialmeasurements/products/moistureinoil/Pages/MMT330.aspx.

[13] M. A. Tsili, E. I. Amoiralis, A. G. Kladas and A. T. Souflaris, "Power transformer thermal analysis by using an advanced coupled 3D heat transfer and fluid flow FEM model," *Int. J. Therm. Sci.*, vol.53, pp. 188-201, 2012.

IX. Biographies

Yi Cui (S'12) received the B.Sc. (Engg.) and M.Sc (Engg.) in Electrical Engineering from Southwest Jiaotong University, China in 2009 and 2012 respectively. He is currently pursuing the Ph.D. degree in the School of Information Technology and Electrical Engineering, the University of Queensland, Australia. He is a member of IEEE since 2012. His research interests include condition assessment and fault diagnosis of power transformer.

Hui Ma (M'95) received his B.Eng and M.Eng degrees from Xi'an Jiaotong University, China in 1991 and 1994, M.Eng (by research) degree from Nanyang Technological University, Singapore in 1998, and PhD degree from the University of Adelaide, Adelaide, Australia in 2008. Currently Dr. Ma is a research fellow in the School of Information Technology and Electrical Engineering, the University of Queensland, Australia. Prior to joining the University of Queensland, Dr. Ma has many years research and development experience. From 1994 to 1995, he was a researcher in Xi'an JiaotongUniversity, China. From 1997 to 1999, he worked as a firmware development engineer in CET Technologies Pte. Ltd., Singapore. He was with Singapore Institute of Manufacturing Technology as a research engineer from 1999 to 2003. His research interests include industrial informatics, condition monitoring and diagnosis, power systems, wireless sensor networks, and sensor signal processing.

Tapan Kumar Saha (M'93, SM'97) was born in Bangladesh in 1959 and immigrated to Australia in 1989. He received his B.Sc Engineering (electrical and electronic) in 1982 from the Bangladesh University of Engineering & Technology, Dhaka, Bangladesh, M. Tech (electrical engineering) in1985 from the Indian Institute of Technology, New Delhi, India and PhD in 1994 from the University of Queensland, Brisbane, Australia. Tapan is currently Professor of Electrical Engineering in the School of Information Technology and Electrical Engineering, University of Queensland, Australia. Previously he has had visiting appointments for a semester at both the Royal Institute of Technology (KTH), Stockholm, Sweden and at the University of Newcastle (Australia). He is a Fellow of the Institution of Engineers, Australia. His research interests include condition monitoring of electrical plants, power systems and power quality.

Chandima Ekanayake (M'00) received his B.Sc.Eng.(Hons) in 1999 from University of Peradeniya Sri Lanka. He obtained his Tech. Lic. and PhD from Chalmers University of Technology Sweden in 2003 and 2006 respectively. Currently he is a lecturer in the School of Information Technology and Electrical Engineering, the University of Queensland (UQ), Brisbane, Australia. Before joining UQ he was with University of Peradeniya Sri Lanka as a Senior lecturer. During his PhD studies he was working for a European Union Project called REDIATOOL where he engaged in research related to Diagnostics of Transformer Insulation from dielectric response measurements. From 2001, he has been involving on condition monitoring of transformers installed at Ceylon Electricity Board, Sri Lanka. He was the Chair of IEEE Sri Lanka Section in year 2006 and 2007. His research interests are condition monitoring of power apparatus, alternatives for insulating oil, transient studies on power systems and energy related studies.