Analysis and Modeling of Dielectric Responses of Power Transformer Insulation

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Abstract—This paper reports the modeling on dielectric response for power transformer condition assessment. A model (a numerical tool) is implemented by C++ code based on dielectric theory. The model can calculate return voltage and polarization/depolarization currents. It can also calculate the maximum return voltage to generate spectrum data. Through the modeling, the parameters which contribute to the dielectric response in the real measurement can be seen much more clearly. A good numerical model is indispensable to remove the uncertainty and to accurately interpret the measurement results. The model can help us quantitatively analyze the measurement results from dielectric responses of oil paper insulation.

Index Terms—Modeling, condition monitoring, dielectric response measurements, polarization current, return voltage, transformer insulation.

I. INTRODUCTION

Utilities desire to know the accurate condition of their equipment, including aged and new power transformers. Condition monitoring techniques need to provide clear and correct information about the condition of the equipment to satisfy this requirement. The quality of the electrical insulation is a key element for reliable operation of a power transformer. The electrical insulation materials of a power transformer are mineral oil and cellulose paper. During its operation, the oil/paper insulation can be aged due to thermal, oxidative and hydrolytic degradation. The service ageing can be monitored by chemical techniques, such as dissolved gas analysis (DGA). The ageing also can be assessed by electrical diagnostic techniques, such as dielectric response measurements. Dielectric response measurements are non-destructive and relatively new diagnostic techniques used to assess the condition of oil/cellulose insulated equipment, such as power transformers. The methods of dielectric response measurements in the time domain are polarization/depolarization current measurement and return voltage (RV) measurement.

In recent time return voltage measurement has gained significant attention by utility engineers. However, accurate interpretation of RV still remains a difficult task. Due to the uncertainty in the results obtained from return voltage measurement, modeling of the RV is essential which can help us to quantitatively analyze the RV. A mathematical model of return voltage can give us great help in the interpretation of RVM test results. Through the model for return voltage the actual parameters involved or contributing to the results can be easily seen. These parameters are: DC conductivity (σ), permittivity (εr), response function (f(t)), geometrical capacitance (C0), etc. A good numerical model is indispensable to accurately interpret the measurement results and thus helps to correlate with physical properties of insulation. Gafvert et al. [1] [2] have done some significant work in this area.

Our model, a numerical tool is based on the dielectric response—polarization/depolarization current measurement. From the current measurement, we can determine the response function. With the response function, we can model (calculate) the return voltages and the RV spectrum.

We have designed comprehensive C++ software to implement the model. At this stage the model can estimate return voltage (with selected charging/discharging time). It can also find out the maximum return voltage to generate spectrum data.

II. BACKGROUND KNOWLEDGE

This section provides the background knowledge of the dielectric response measurement (in the time domain). Fig. 1 shows a simplified diagram of dielectric response measurement (time domain) for a power transformer. Transformer HV and LV terminals are connected together to form a two terminal test object. In the diagram, polarization current measurement is performed with s1 closed, s2 and s3 open. For the depolarization current measurement, s2 is closed, s1 and s3 open. For the return voltage measurement, s3 closed and s1, s2 open.

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The polarization currents measurement is performed by applying a step excitation voltage ($V_c$) on the dielectric materials and depolarization current is measured with power supply removed as shown in Fig. 2.

Fig. 3 shows measured polarization currents from some moisture-conditioned samples we prepared in our laboratory. It can be seen that the amplitude of long term DC polarization current is very sensitive to the moisture content in paper insulation. This demonstrates that polarization current measurement is capable of assessing the paper insulation moisture level [3].

Return voltage measurement is shown in Fig. 4. In RV measurement, a transformer is charged initially for 0.5 second, then in every next cycle the charging time is doubled, up to 1024 seconds. The charging to discharging time ratio is always kept as 2. Charging and discharging current and return voltage data are recorded for every test cycle. Summarize the maximum return voltage and the central time constant from each test cycle, a return voltage spectrum can be formed. The return voltage spectrum can give an indication to the insulation condition. Some typical return voltage spectra are given in Fig. 5. The operation times of these transformers are as follows: T4 (3.15 MVA) was 3 years, T5 (5 MVA) was 38 years, and T6 (5 MVA) was 33 years. Take the T4’s spectrum (the right hand side one in Fig. 5) as an example, the peak in the spectrum can provide indication of the insulation condition. The spectrum also provides the range of the response in the time domain [4] [5] [6] [7].
III. MODELING

This section describes the theory and practice of the modeling. The modeling includes three parts: Modeling of polarization and depolarization currents, modeling response function $f(t)$, and modeling return voltage, where the return voltage modeling is the most complex part.

A. Modeling Polarization and Depolarization Current

The polarization and depolarization current can be modeled with the following two equations [2].

$$i_{pol}(t) = C_0 V_c \frac{\sigma}{\varepsilon_0} + C_0 V_c f(t)$$  \hspace{1cm} (1)

$$i_{depol}(t) = -C_0 V_c f(t) + C_0 V_c f(t + t_{pol})$$  \hspace{1cm} (2)

where:
- $i_{pol}$ is the polarization current,
- $i_{depol}$ is the depolarization current,
- $C_0$ is the geometrical capacitance of the test object,
- $V_c$ is the step voltage (charging voltage),
- $\sigma$ is the DC conductivity of the dielectric material,
- $\varepsilon_0$ is the vacuum permittivity,
- $f(t)$ is the response function of the dielectric material,
- $t_{pol}$ is the length of the polarization period.

On the right hand side of (1), the first term relates to the intrinsic conductivity of the test object and the second term represents the polarization processes during the time of charging voltage application [8]. If we know $f(t)$, $C_0$ and $\sigma$, the currents can be modeled with the above two equations.

B. Modeling the Response Function $f(t)$

When the polarization time is sufficiently long, $f(t+t_{pol}) \approx 0$, from (2) the response function $f(t)$ is equal to

$$f(t) = \frac{-i_{depol}(t)}{C_0 V_c}$$  \hspace{1cm} (3)

The $f(t)$ is calculated from the depolarization current. If we want to model the currents (and the return voltage), we need to model the $f(t)$ from (3) into parametric form, in which the response function can be expressed as follows:

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m}$$  \hspace{1cm} (4)

The equation comes from the Curie-von Schweidler law: $i(t) = At^n$, a “universal” law which states the depolarization currents of a wide range of dielectric materials [9].

Using the KaleidaGraph software curve fitting function (which is based on the Levenberg-Marquardt algorithm), and the $f(t)$ calculated from (3), we can find the parameters of $f(t)$ for (4). TABLE I provides some $f(t)$ parameters.

<table>
<thead>
<tr>
<th>Test Object</th>
<th>A</th>
<th>$t_0$</th>
<th>n</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>100kva Transformer</td>
<td>0.1469</td>
<td>1710.9</td>
<td>0.2823</td>
<td>1.4657</td>
</tr>
<tr>
<td>2% H$_2$O Sample</td>
<td>0.01883</td>
<td>800.16</td>
<td>0.39136</td>
<td>1.439</td>
</tr>
<tr>
<td>3% H$_2$O Sample</td>
<td>0.02544</td>
<td>459.51</td>
<td>0.44221</td>
<td>1.8595</td>
</tr>
</tbody>
</table>

The capacitance $C$ of the test object can be obtained by using a LCR meter and then dividing by the relative permittivity $\varepsilon_r$, we can obtain $C_0$, $C_0=C/\varepsilon_r$.

The DC conductivity $\sigma$ of the test object can be obtained by adding equation (1) and (2) together, assume $f(t+t_{pol}) \approx 0$. An approximation of the DC conductivity of cellulose paper can be made from polarization and depolarization currents, using the following relation:

$$\sigma \approx \frac{\varepsilon_0}{V_c C_0} [i_{pol}(t_m) + i_{depol}(t_m)]$$  \hspace{1cm} (5)

where:
- $C_0$ is geometrical capacitance, $C_0 = C/\varepsilon_r$, ($C$ obtained from measurement, $\varepsilon_r$ is relative permittivity, in the range of 3~5),
- $t_m$ represents the largest value of time, for which the currents have been measured.

Once we find the $f(t)$’s parameters and obtain the geometrical capacitance of the test object as well as find out the dc conductivity of the test object, we can model (calculate) return voltage curves. $\sigma$ can be directly related to moisture and ageing. So by estimating the conductivity, we can also estimate the condition of insulation. The main questions of separation of moisture and ageing still remains unanswered. We have some work in progress to investigate this phenomenon [3].

C. Modeling the Return Voltage

The modeling of the return voltage starts with the current equation. The current density is the sum of conduction and displacement currents [10] [11].

$$i(t) = \sigma E(t) + \frac{dD}{dt}$$  \hspace{1cm} (6)

where:
- $\sigma$ is the DC conductivity of the dielectric material,
- $E(t)$ is an external electric field,
- $D(t)$ is electric displacement (or dielectric induction).
The dielectric induction is
\[ D(t) = \varepsilon_0 \varepsilon_r E(t) + P(t) \]  
where:
\( \varepsilon_0 \) is the relative permittivity,
\( P(t) \) is polarization.

The polarization is given by the convolution integral
\[ P(t) = \varepsilon_0 \int_0^t f(t-\tau) E(\tau) d\tau \]  
If we substitute (7) and (8) into (6), then the electric current becomes
\[ i(t) = \sigma E(t) + \varepsilon_0 \varepsilon_r \frac{dE}{dt} + \varepsilon_0 \frac{d}{dt} \left\{ \varepsilon_0 f(t-\tau) \cdot E(\tau) d\tau \right\} \]  
If we use Leibnitz’s rule for differentiation of integrals
\[ \frac{d}{d\alpha} \int_0^{\phi_1(\alpha)} F(x,\alpha) dx = \int_0^{\phi_1(\alpha)} \frac{\partial F}{\partial \alpha} dx - F(\phi_1,\alpha) \frac{d\phi_1}{d\alpha} + F(\phi_2,\alpha) \frac{d\phi_2}{d\alpha} \]  
then equation (9) can be modified to (10)
\[ i(t) = \sigma E(t) + \varepsilon_0 \varepsilon_r \frac{dE}{dt} + \varepsilon_0 f(0) E(t) + \varepsilon_0 \frac{d}{dt} \left\{ \varepsilon_0 f(t-\tau) \cdot E(\tau) d\tau \right\} \]  
Referring to Fig 4, during the return voltage measurement (of each cycle) a charging voltage (which generates the external field) is applied to a dielectric test object for times \( 0 < t < t_1 \). When \( t > t_1 \), charging voltage \( V_c=0 \), external field \( E=0 \), and discharging takes place during \( t_1 < t < t_2 \). When \( t> t_2 \), discharging path is removed, therefore the test object in Fig. 1 is in open circuit condition, that is \( i(t)=0 \), for \( t>t_2 \).

The \( 0-t_2 \) region of the integral in (10) may be treated as follows (refer to Fig. 4)
\[ \int_0^{t_1} \frac{f(t-\tau)}{dt} E(\tau) d\tau = \int_0^{t_1} \frac{f(t-\tau)}{dt} E(t) d\tau = E_0 \int_0^{t_1} \frac{f(t-\tau)}{dt} d\tau = E_0 [f(t-t_1) - f(t)] \]  
With the above result and the open circuit condition \( i(t)=0 \) for \( t\geq t_2 \), (10) becomes (12)
\[ \sigma E(t) + \varepsilon_0 \varepsilon_r \frac{dE}{dt} + \varepsilon_0 f(0) E(t) + \varepsilon_0 \varepsilon_0 f(t-t_1) - f(t)] + \varepsilon_0 \frac{d}{dt} \left\{ \varepsilon_0 f(t-\tau) \cdot E(\tau) d\tau \right\} = 0 \]  
Use \( E_0 = V_c/d \) (where \( V_0 = V_c = V_{\text{charging}} \)) and \( E = E_t = V_c/d \) to convert equation (12) to (13) for return voltage calculation.
\[ \sigma V(t) + \varepsilon_0 \varepsilon_r \frac{dV}{dt} + \varepsilon_0 f(0) V(t) + \varepsilon_0 V_0 [f(t-t_1) - f(t)] + \varepsilon_0 \frac{d}{dt} \left\{ \varepsilon_0 f(t-\tau) \cdot V(\tau) d\tau \right\} = 0 \]  
Integrate equation (13) between \( t \) and \( t_{i+1} \), where \( t_{i+1} > t > t_2 \) giving,
\[ \sigma \int_{t_{i+1}}^{t} V(t) dt + \varepsilon_0 \varepsilon_r \int_{t_{i+1}}^{t} \frac{dV}{dt} dt + \varepsilon_0 f(0) \int_{t_{i+1}}^{t} V(t) dt + \varepsilon_0 V_0 \int_{t_{i+1}}^{t} [f(t-t_1) - f(t)] dt + \varepsilon_0 \frac{d}{dt} \left\{ \varepsilon_0 f(t-\tau) \cdot V(\tau) d\tau \right\} dt = 0 \]  
where \( V \) in (14) is return voltage.

The DC conductivity \( \sigma \) in the return voltage modeling should be the composite conductivity which considers the oil and paper layers. The oil conductivity can also be calculated with (5) by replacing the \( t_m \) to \( t_0 \). Where the \( i_{\text{pol}}(t_b) \) and \( i_{\text{depol}}(t_b) \) are the initial values in polarization and depolarization currents. The conductance of the composite material can be calculate as follows [1]:
\[ G_{\text{composite}} = \frac{G_{\text{oil}} \ast G_{\text{paper}}}{G_{\text{paper}} + G_{\text{oil}}} \]  
Which means the composite conductivity can be calculated as (16).
\[ \sigma_{\text{composite}} = \frac{\sigma_{\text{oil}} \ast \sigma_{\text{paper}}}{\sigma_{\text{paper}} + \sigma_{\text{oil}}} \]  
The relative permittivity \( \varepsilon_r \) also needs to be considered for the composite system when a value is chosen.

The calculated and measured return voltage curves from a 100KVA transformer are given in Fig. 6.
Comprehensive C++ software has been designed to implement the model. The user-friendly interface of the software is shown in Fig. 7. At this stage the model can calculate return voltage (with selected charging time, as many cycles as we want), and polarization & depolarization current. It can also determine the maximum return voltage and the corresponding central time constant to generate spectrum data. Once the models are fully implemented, thorough understanding of RV spectra would be possible for different moisture and ageing condition. To support this modeling accelerated ageing experiments of different moisture and ageing condition are vital. The models also need to be validated by field transformer measurements and must be correlated with other diagnostic methods. This work is in progress and finding will be reported in future paper.

Fig. 7. The User Interface of the Model

IV. CONCLUSION

An attempt has been made to model dielectric response of transformer insulation. The modeling work shows promising result and this is still in progress. The dielectric modeling results will be correlated to chemical results to predict the condition of transformer. The task of RV results interpretation will be much more easier with this tool. The model will help us quantitatively analyze the results from dielectric response measurement. Through the modeling of the dielectric response, the parameters which significantly contribute to the response can be seen much more clearly. This greater clarity will allow us to predict more accurately the condition of the oil paper insulation in power transformer.

V. REFERENCES


VI. BIOGRAPHIES

Zheng Tong Yao received his BEE from the Department of Electrical and Computer System Engineering, James Cook University, Australia in 1995. From 1996 to 1998, he worked as an Electrical and Electronic Engineer at The University of Queensland (UQ), Australia. In 1999, Tong gained his Master Degree (by research) in the field of Computer Science and Electrical Engineering from UQ. From 1999, Tong is pursuing his PhD in the School of Information Technology and Electrical Engineering, UQ. He is a Member of IEEE.

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