KIEE International Transactions on EA, Vol. 4-C, No. 3, pp. 81~90, 2004

Application of Dielectric Spectroscopy Measurements for Estimating Moisture Content in Power Transformers

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Abstract - Frequency Domain Spectroscopy (FDS) measurements were performed on pressboard samples containing different moisture contents and on insulation system of power transformers. The results were used for evaluating sensitivity of the so-called X-Y model, which is applied for estimating moisture content in transformer insulation using the results of FDS measurements. Based on the observations of this analysis a simplified model, called X model, was introduced in which the presence of spacers in transformer insulation has been neglected. Finally, reliability of the X model was assessed by comparing estimates of moisture contents based on FDS measurements on field installed power transformers with moisture contents obtained from chemical analyses of their oil samples.

Keywords: frequency dependent dielectric spectroscopy, moisture, oil conductivity, oil paper insulation, permittivity

1. Introduction

Degradation of insulation in power transformers, which mainly consists of oil and paper, is one of the main factors affecting transformer failures. Chemical analyses and electrical measurements are used for assessment of the insulation condition. The chemical analyses provide direct information on parameters such as water content and degree of polymerisation in paper as well as on water and sludge content in oil, acidity and quantity of different gasses dissolved in oil. However, most of the chemical analyses must be performed in laboratory conditions as well as for some of them paper samples are needed. Electrical measurements are on the other hand simpler and it is possible to perform them on site. Because of this simplicity, electrical tests are nowadays preferred for condition monitoring of transformer insulation rather than the chemical tests.

Traditional electrical tests such as measurements of insulation resistance (IR), polarisation index (PI) and loss factor (tand) provide limited information about the state of transformer insulation since they are single value parameters. To overcome this disadvantage, dielectric response measurements were introduced for the condition monitoring of transformer insulation, namely return voltage measurements (RVM), polarisation and depolarisation current measurements (PDC) and frequency domain spectroscopy measurements (FDS), especially for evaluation of water content in transformer pressboard [1].

Numerous investigations aiming to evaluate the applicability of dielectric response measurements were performed by different authors [2-8]. CIGRE Task Force 15.01.09 has concluded in its recent report [1] that despite of positive outcomes of these evaluations, further investigations are still necessary. Especially, a need for performing a large number of calibrating measurements of the moisture content based on both electrical measurements and chemical analyses of oil by Karl Fisher titration was pointed out.

Not only the measuring techniques but also a model allowing for interpretation of the results has been developed [5]. The model, called X Y model, is nowadays used for the diagnostics and it allows to interpret results of the measurements in terms of moisture content in the pressboard. However, the main disadvantage of this approach is a necessity for knowing details of the geometrical design of transformer insulation, which is rather often difficult to find for engineers at power companies.

Work presented in this paper is based on the FDS measurements and oil analyses from field installed power transformers in Sri Lanka and their comparisons with results of measurements on well-defined pressboard samples in laboratory. In parallel Karl Fisher titration was used to measure the moisture content in the oil and in the pressboard samples. Results of the measurements on the pressboard samples were utilised for performing sensitivity analyses of the X-Y model. As a result a simplified model, called X model has been proposed for estimating moisture content in transformer insulation in case when detail information about its geometry is lacking.

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Received December 11, 2003 ; Accepted April 28, 2004

2. Experimental Set-ups

2.1 Frequency Domain Spectroscopy (FDS) Measurements

All the measurements were performed using IDA 200 insulation diagnostic system. Its measuring range is from 0.1 mHz to 1 kHz at voltages up to 200 V_{peak} [9]. The FDS measurements on the impregnated samples in laboratory were performed to form a database on the correlation between the frequency dependent complex permittivity and moisture content of pressboard. The measurements were performed by means of a special test cell, as illustrated in Fig. 1, at a 50 V_{peak} ac voltage and at a room temperature (between 20 °C and 27 °C). The thickness and diameter of all the pressboard samples under the study were 2 mm and 159 mm, respectively. The diameter of the measuring electrode was 113 mm, which yielded a geometrical capacitance between the electrodes of 44.4 pF. An additional weight was placed on the top electrode to apply equal pressure on the pressboard samples during the measurements.

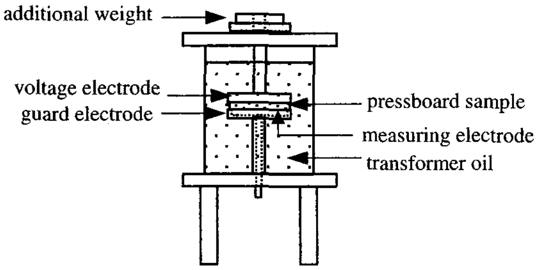

Fig. 1 Schematic diagram of the test cell

In the FDS measurement on transformer oil, a three terminal stainless steel cylindrical oil test cell was used. To avoid possible non-linear effects, the applied voltage was limited to 5 V_{peak}. Results of these measurements were used to calculate the conductivity of the oil. Since there are no relaxation processes in oil within the frequency window of interest, the conductivity of oil could be calculated according to:

$$\sigma(\omega)=\frac{C''(\omega)}{C_0}\varepsilon_0\omega \qquad (1)$$

where;

ω is the angular frequency

$\sigma(\omega)$ is the frequency dependent conductivity of oil,

$C''(\omega)$ is the imaginary part of complex capacitance,

C_0 is the geometrical capacitance of the cell.

For performing measurements in the field, all the terminals of HV and LV windings of the transformers were short-circuited separately. The grounded tank was connected to the guard terminal. The FDS measurements were done between HV and LV windings.

2.2 Karl Fisher Titration (KFT) Measurements

The moisture content in pressboard samples was measured using the coulometric KFT [10]. In this case, the indirect stripping oven technique was utilised. Here, a known weight (about 0.5 g) of pressboard sample was placed in the oven, which was heated to 140 °C. Moisture released from the pressboard was led away to the titration vessel by a dry N_2 gas flow. The procedure described in IEC 60814 was followed for determining the moisture content in the pressboard [10].

For calibrating the moisture content estimated from FDS measurements on the transformers, KFT analyses were performed on their oil samples. The direct coulometric KFT technique was utilised and the methodology described in IEEE 62-1995 was followed for interpreting the result [11].

3. Response of Pressboard Samples

Complex permittivities derived from the measured complex capacitance of the five different pressboard samples are presented in Fig. 2. These results are normalized at 27 °C by assuming an activation energy of 0.9 eV [5, 12].

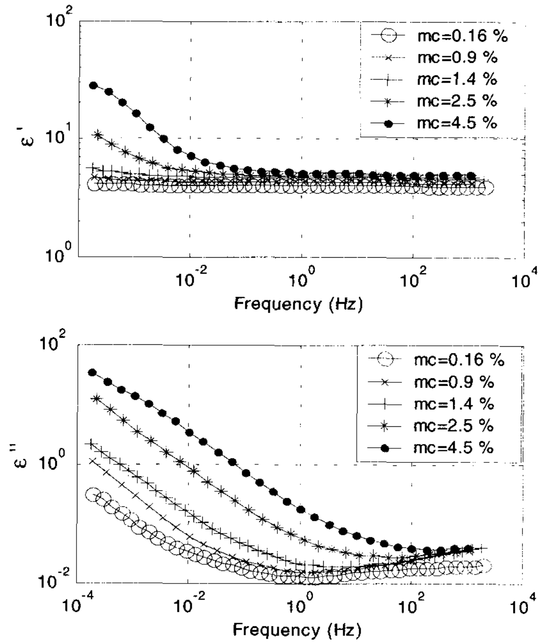

Fig. 2 Real and imaginary components of complex permittivity as a function of frequency at 27 °C for pressboard samples containing different amounts of moisture (mc)

As shown in Fig. 2, the real part of permittivity ε′ increases at low frequencies with increasing moisture content in the pressboard. The dielectric loss ε″ also substantially increases with increasing moisture content. At the same time, the variation of ε′ with moisture content at 1 kHz is relatively small. This behaviour was one of the basic observations used in the development of the simplified model.

4. Modelling of Transformer Insulation

The data obtained from the measurements of pressboard samples were used for modelling the dielectric response and for estimating the moisture content in the insulation of the transformers measured in the field. Linear variations of the logarithmic values of both the permittivity ε′ and the loss ε″ between two consecutive moisture contents were assumed for calculating the responses corresponding to moisture contents not included in the database.

4.1 X-Y Model

The main insulation of the transformers consists of cylindrical pressboard barriers in series with oil ducts and spacers (Fig. 3). By combining all oil ducts, barriers and spacers, this model of main insulation can be simplified [5], as shown in Fig. 4. The total complex capacitance of this model at temperature T can be described as,

$$\hat{C}(\omega,T)_{duct}=\left(\frac{Y}{\frac{1-X}{\hat{\varepsilon}_{spacer}(\omega,T)}+\frac{X}{\hat{\varepsilon}_{barrier}(\omega,T)}}+\frac{1-Y}{\frac{1-X}{\hat{\varepsilon}_{oil}(\omega,T)}+\frac{X}{\hat{\varepsilon}_{barrier}(\omega,T)}}\right)C_0 \qquad (2)$$

where,

$$X=\frac{\text{total thickness of the barriers}}{\text{width of the duct}}$$

$$Y=\frac{\text{total width of the spacers}}{\text{periphery of the duct}}$$

$$\hat{\varepsilon}_{spacer}(\omega,T)=\hat{\varepsilon}_{barrier}(\omega,T)=\hat{\varepsilon}_{pressboard}(\omega,T)$$

$$\hat{\varepsilon}_{oil}(\omega,T)=\varepsilon'_{oil}-j\frac{\sigma(T)}{\varepsilon_0\omega} \qquad (3)$$

In real power transformers, X and Y vary often between 0.2 – 0.5 and 0.15 – 0.25, respectively [5]. In order to simplify this X-Y model further, the influence of model parameters was studied.

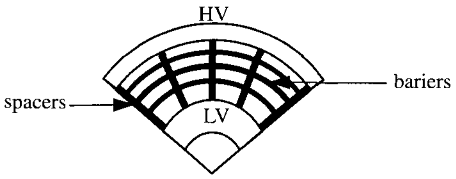

Fig. 3 Cross section of main insulation of a core type power transformer

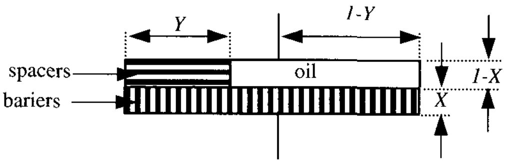

Fig. 4 Simplified insulation structure of a core type power transformer

4.2 Analyses of X-Y Model

4.2.1 Influence of oil conductivity σ

The conductivity of oil can vary broadly, both due to presence of contaminants and due to changing temperature. Fluctuation of conductivity due to temperature variations can be calculated by assuming an Arrhenius type of behaviour with properly set activation energy. It was therefore, necessary to analyse the influence of oil conductivity varying in a wide range. In this study, field measurements were performed at temperatures varying between 25 and 65 °C. Hence, oil conductivity of 0.05 pS/m at 25 °C (or 1.25 pS/m at 65 °C) was assumed as the lower limit of the conductivity range selected. The upper limit of the range was selected as 104 pS/m at 65 °C (or 4 10^2 pS/m at 25 °C), which was about 10 times higher than the acceptance limit of the conductivity of used oil [13].

Fig. 5 shows the influence of oil conductivity on FDS responses at 25 °C , when the amount of moisture content in pressboard and the amount of pressboard in the insulation system were kept at a minimum level, i.e. X = 0.2, Y = 0.15 and 0.2 % moisture content in pressboard. In the figure, the variations of permittivity and loss clearly indicate for Maxwell – Wagner behaviour of the system, which is mainly influenced by the conduction in the oil. One may observe that when oil conductivity is less than 4 10^2 pS/m, it has little influence on the permittivity ε′ of the system at frequencies above 100 Hz.

Fig. 6 shows the influence of oil conductivity at 65 °C, when the amount of moisture content in paper and the amount of pressboard in the insulation system are kept at a maximum level i.e. X = 0.5, Y = 0.25 and 5 % moisture content in pressboard. Due to the significant influence of low frequency dispersion in the paper, the influence of oil conductivity on the total permittivity of the system is weaker in comparison with the previous case. In addition, when the oil conductivity is less than 1 10^4 pS/m at 65 °C, it has little influence on the permittivity ε' of the system at frequencies above 100 Hz.

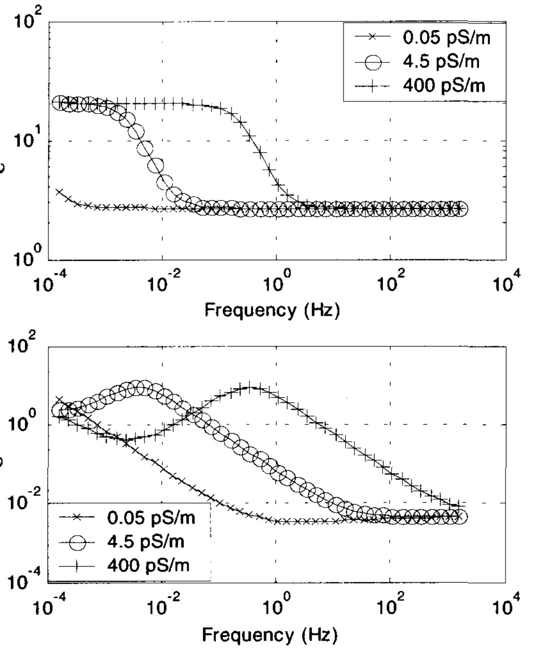

Fig. 5 Derived real and imaginary components of complex permittivity for the X-Y model for different values of oil conductivity at 25 °C, when X=0.2, Y=0.15 and moisture content=0.2%

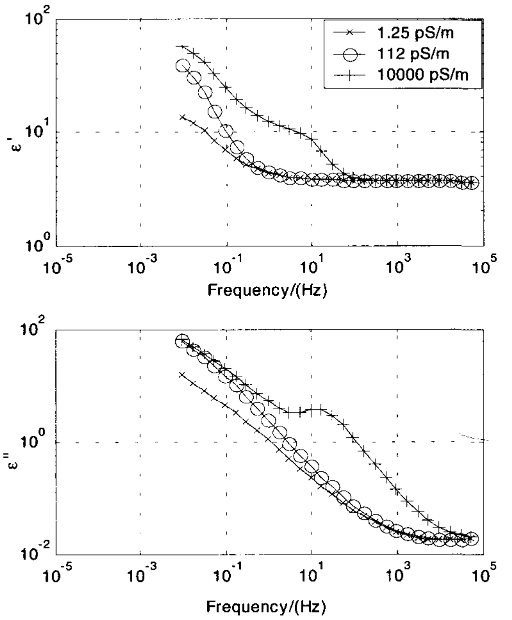

Fig. 6 Derived real and imaginary components of complex permittivity for the X-Y model for different values of oil conductivity at 65 °C, when X=0.5, Y=0.25 and moisture content=5%

The values of permittivity ε' of the X-Y system at 1 kHz under different conditions are presented in Table 1. One may notice that in both cases studied, the change of oil conductivity had little influence on the value of permittivity ε' at 1 kHz . The difference in ε' at 1 kHz between the two cases considered was mainly caused by the variation of other model parameters.

4.2.2 Influence of spacers

The maximum influence of spacers on the final dielectric response can be encountered when Y is equal to 0.25. Hence, the influence of spacers was examined by comparing the dielectric responses of the X – Y system with Y = 0.25 and Y = 0.The influence of spacers was studied under different conditions since the total response was dependent on the amount of barriers, moisture content, oil conductivity and temperature (Fig.s 7-10). The figures also show the residual curves representing the difference between two response curves corresponding to Y = 0.25 and Y = 0. Table 2 describes the way the spacers influence the total dielectric response under different conditions,

Table 1 ε' of X-Y system at 1 kHz under different conditions

Case No.	Conductivity σ (pS/m)	ε' at 1 kHz
Case 1	0.05	2.66
	4.5	2.66
	400	2.66
Case 2	1.25	3.67
	112	3.67
	10000	3.68

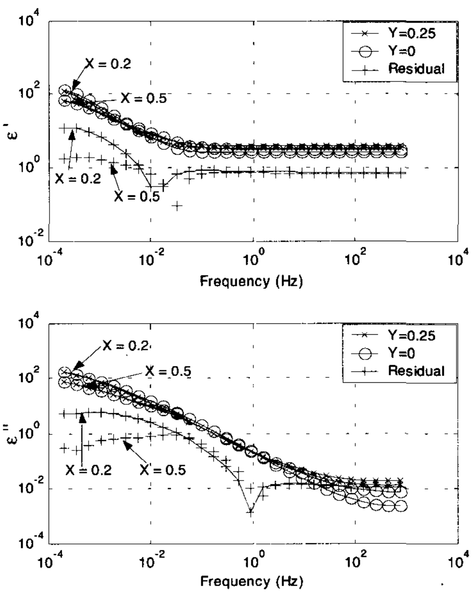

Fig. 7 Influence of spacers with different amounts of barriers

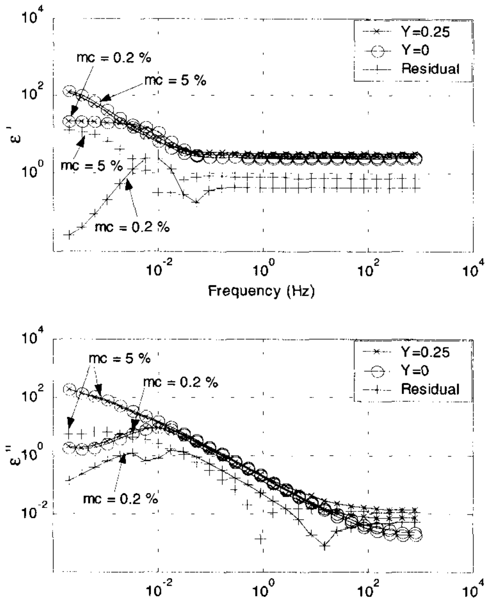

Fig. 8 Influence of spacers with different amounts of moisture content

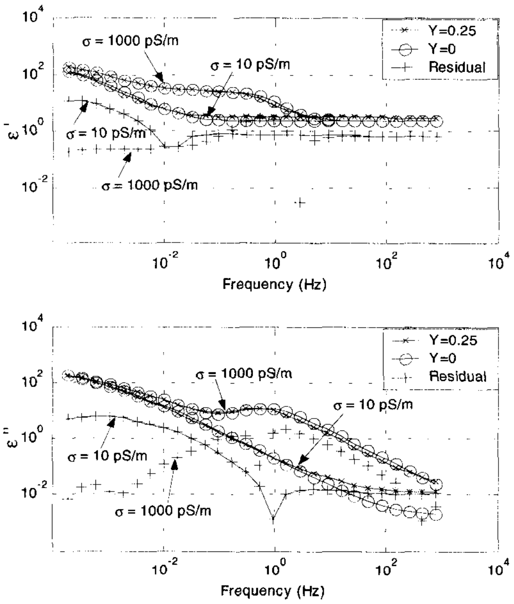

Fig. 9 Influence of spacers at different oil conductivity values

based on the results shown in Fig.s 7-10. As shown in all four figures, the effect of spacers on the shape of the final dielectric response curve is not particularly significant within the specified ranges of all the other parameters studied. This effect could be explained by fact that more conductive oil is always connected in parallel to the less conductive spacer in the model. One can clearly observe this effect in Fig. 9, where the dielectric responses with two different values of oil conductivity are plotted. When oil conductivity increases the residual decreases substantially.

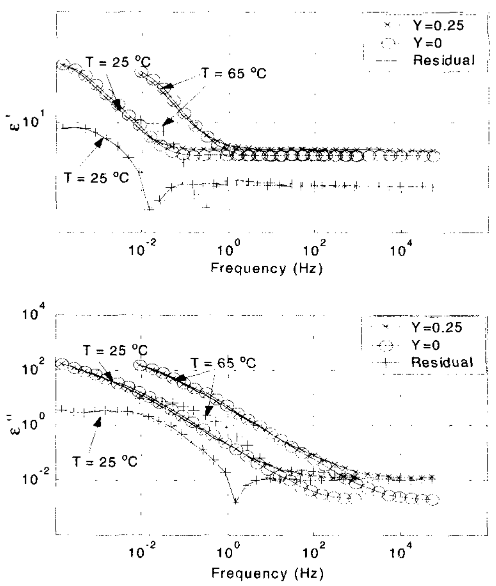

Fig. 10 Influence of spacers at different temperatures

In Table 2, the column corresponding to the mean relative error shows errors introduced by removing spacers from the model. The maximum mean error related to the real component of the permittivity is about 20 %. However, in the imaginary component, this error can be as high as 35 %. According to the results shown in Table 2, the maximum influence of spacers on the dielectric response of the model could be seen at higher temperatures with relative low content of barriers and low oil conductivities.

Table 2 Influence of spacers under different conditions

Fig. No.	Variable parameter		Values of other parameters mc-% ; σ-pS/m ; T-°C	Mean relative error (in %)		Permittivity (ε') at 1 kHz		
	Name	Value		ε′	ε′′	Y= 0.25	Y=0	Error (%)
7	X	0.2 0.5	mc – 5 $\sigma_{(25\,°C)}$ – 10 T – 25	14 9	20 19	3.1 3.6	2.5 3	19 17
8	mc (%)	0.2 5	X – 0.2 $\sigma_{(25\,°C)}$ – 10 T – 25	12 19	33 30	2.8 3.1	2.4 2.5	14 19
9	$\sigma_{(25\,°C)}$ (pS/m)	10 10^3	X – 0.2 mc – 5 T – 25	19 10	30 15	3.1 3.1	2.5 2.5	19 19
10	T (°C)	25 65	X – 0.2 mc – 5 $\sigma_{(25\,°C)}$ – 10	19 20	30 35	3.1 3.2	2.5 2.5	19 22

4.2.2 Variation of permittivity at 1 kHz (ε′1kHz)

As already presented in Table 1, oil conductivity has little influence on permittivity ε′ at 1 kHz. Furthermore, the last right hand column of Table 2 shows the estimated error of permittivity ε′ at 1 kHz when the spacers are removed. One can see that this error was always not higher than 22 %. The other two parameters, which affect ε′ at 1 kHz, are moisture content in paper and the amount of barriers in the model. Fig. 11 shows the influence of these two parameters within the region of interest of each parameter. When X = 0.5, the dielectric response of the barriers has the greatest influence on the total response. This gives a maximum variation of ε' at 1 kHz ($\Delta\varepsilon'$ at 1 kHz) with moisture content, the value of which is 0.22 as shown in Table 3. Therefore, we assume for further analysis that ε' at 1 kHz does not vary with moisture content for a given X and it is equal to the mean value of ε' at 1 kHz, as shown in Fig. 11. Then the introduced maximum error should be around 4 %, as indicated in Table 3.

The variation of the mean ε' at 1 kHz with X is shown in Fig. 12. The points obtained from the calculation are well fitted by a quadratic curve described by the following expression, in which

$$y = X^2 + 0.94X + 2.2 \qquad (4)$$

This expression provides an easy way for calculating the mean ε' at 1 kHz for a given X.

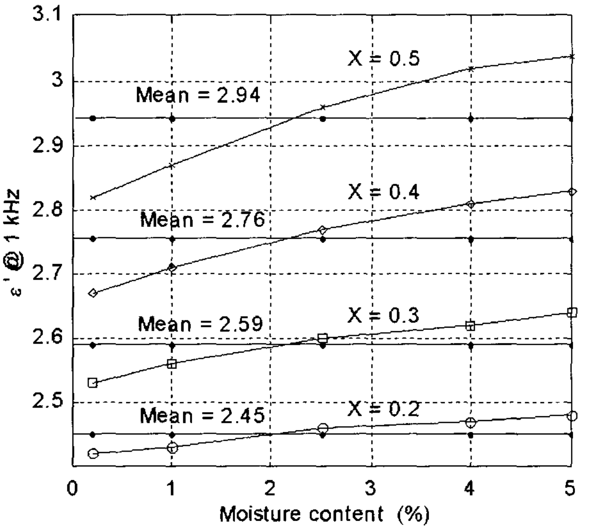

Fig. 11 Variation of ε' at 1 kHz with moisture content in paper and amount of barriers when Y=0

Table 3 Mean ε' at 1 kHz for different X and possible maximum percentage error if constant ε' at 1 kHz (mean) value is assumed at each X

X	$\Delta\varepsilon'_{1\,\text{kHz}}$	Mean $\varepsilon'_{1\,\text{kHz}}$	Maximum error (%)
0.2	0.06	2.45	1.2
0.3	0.11	2.59	2.4
0.4	0.16	2.76	3.4
0.5	0.22	2.94	4.3

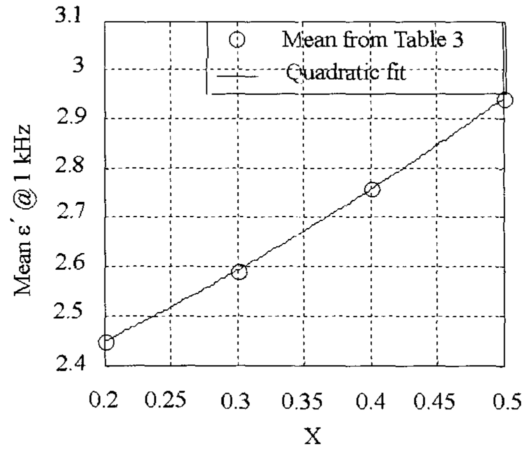

Fig. 12 Variation of mean ε' at 1 kHz with varying amount of barriers

The analysis performed reveals that the influence of spacers on the total dielectric response of the X-Y model is relatively low and permittivity ε' at 1 kHz is mainly determined by the amount of barriers. Therefore, when the construction details of transformer insulation is not known one may simplify the X-Y model to a X model, while keeping the resulting errors of analysis within reasonable limits.

4.2.3 X Model

The dielectric response of X model, illustrated in Fig. 13, can be represented as

$$\hat{\varepsilon}_{\text{x model}}(\omega,T)=\frac{1}{\dfrac{1-X}{2.2-\dfrac{j\sigma_{\text{oil}}(T)}{\varepsilon_0\omega}}+\dfrac{X}{\hat{\varepsilon}_{\text{barrier}}}} \qquad (5)$$

The response is characterised by the conductivity and permittivity of oil, the moisture content in paper, the amount of barriers and the temperature. Out of these parameters, the moisture content in paper and the amount of barriers are the only two unknowns, if one could measure the conductivity of the oil separately.

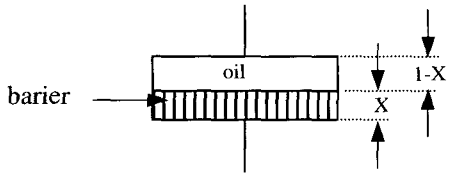

Fig. 13 Further simplified X model of the transformer insulation

In the modelling technique proposed, first barrier content is assumed and then the geometrical capacitance of the transformer is calculated,

$$C_0 = \frac{C'_{1kHz,measured}}{\varepsilon'_{1kHz}} \qquad (6)$$

This provides a path for transforming the measured complex capacitance into complex permittivity. Subsequently, the error between the modelled and the measured values of the complex permittivity responses is minimised by changing the amount of moisture content in paper. This error minimisation is performed by means of an optimization routine developed in MATLAB software. The same procedure is followed for different X values until a lowest possible error is obtained.

5. Application of X Model

Below, four examples are presented in which X model was utilised for estimating moisture content in transformers belonging to Ceylon Electricity Board in Sri Lanka.

First, results of measurements on a 18 MVA 12/132 kV single-phase transformer (T1) are presented. The transformer was installed in 1965 in one of the existing hydropower stations. Fig. 14 shows the frequency variations of the complex capacitances of this transformer. The transformer temperature during the measurements was stable and around 30 °C. These results were used for estimating the moisture content in paper insulation by comparing them with curves derived from X model. The Fig. 14 illustrates also the comparison of modelled and the measured results with the best fitting. The conductivity of oil was 190 pS/m at 30 °C. The moisture content and the amount of barriers were estimated as 4.2 % and 31 %, respectively. The estimated geometrical capacitance was equal to 1 nF (ref. Table 4).

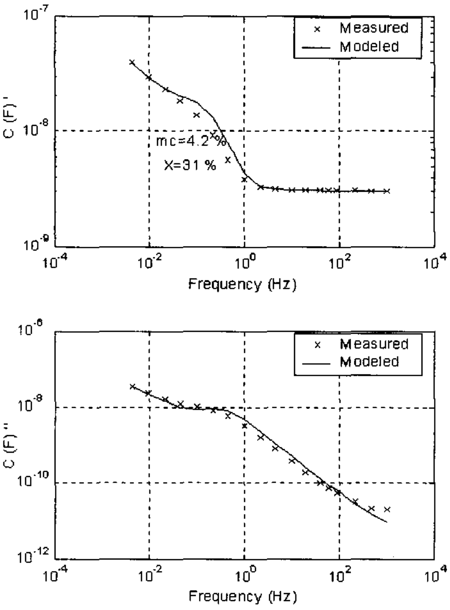

Fig. 14 Comparison of modelled and measured capacitance and loss of the single-phase power transformer T1 at 30 °C

During the operation of this unit oil samples were taken for further analyses. Temperature of the oil during the sampling was 47 °C. KFT analysis of the oil yielded the moisture content of 86 ppm. The corresponding moisture content in paper, derived with help of the methodology described in IEEE 62 – 1995, was 3.5 % (ref. Table 4). Results of the oil analyses reveal that the moisture content estimated from the FDS results was relatively close to the value obtained from the chemical analysis. However, due to lack of information on construction details of this unit, the accuracy of the other estimated parameters could not be verified.

Fig. 15 presents the frequency dependent complex capacitance of a 27 MVA 12.5/132 kV three-phase transformer (T2), which has been operating since 1990. Although this is a fairly new transformer, its insulation resistance has been drastically reduced throughout recent years. Furthermore, the records about this transformer contain information that its oil seals were of inferior quality and oil was leaking through the seals. Therefore, one possible reason for the gradual reduction of the transformer's insulation resistance could be moisture ingress through the poor oil seals. One could therefore expect an increased content of moisture in the transformer insulation. Fig. 15 shows also the best fit between the measured and the model curves of the complex permittivity. The measured conductivity of the oil was 9 pS/m at 27 °C. The estimated moisture content was 3.5 %. The estimated geometrical capacitance was equal to 1.6 nF.

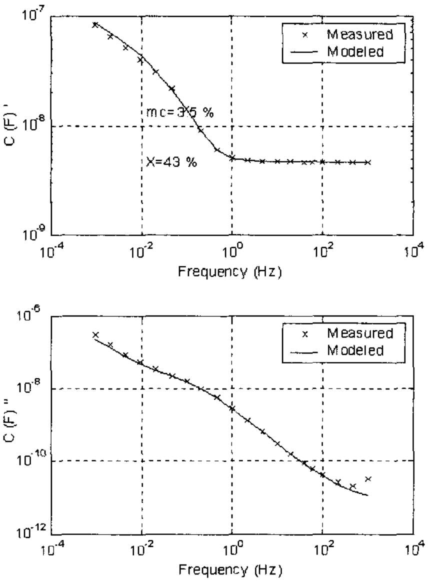

Fig. 15 Comparison of modelled and measured capacitance and loss of the three-phase power transformer T2 at 55 °C

The oil sample was taken from this transformer at about 50 °C and the measured moisture content was 66 ppm. This corresponds to 2 % moisture content in paper [11]. The results of oil analyses show that the estimated moisture content from oil analyses was about 34 % lower than the moisture content estimated from X model. These results confirm that the moisture content in this transformer was increased, although it has been in operation for less than ten years. Therefore, it was recommended after performing the analyses that immediate action must be taken to repair the damaged oil seals and, if possible, to perform vacuum purification of oil.

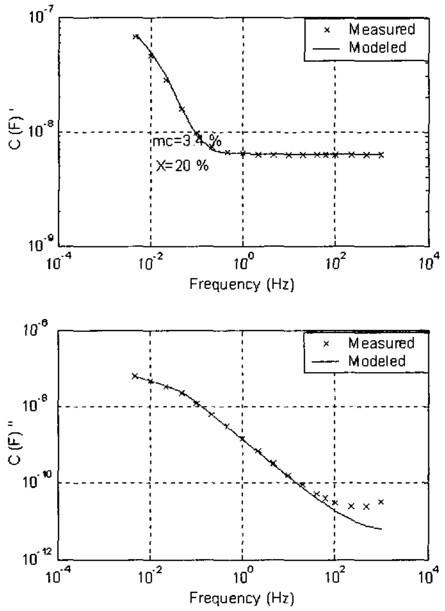

Fig. 16 Comparison of modelled and measured capacitance and loss of the three-phase power transformer T3 at 30 °C

The other three-phase power transformer considered for the analyses is a 31.5 MVA, 132/33 kVA step down power transformer (T3). This transformer has been in operation since 1986. There were no reported major breakdowns or problems related to this transformer. However, during these analyses it was found that moisture content in the transformer is higher than the acceptance limit of 2 % as defined by IEEE 62 - 1995 [11]. Fig. 16 presents the measured and the modelled capacitance and loss for this transformer. The estimated parameters from X model and the oil analyses are shown in the Table 4.

The applicability of the proposed X model was also checked on distribution transformers. Here, an example is shown for a distribution transformer rated 100 kVA, 20/0.4 kV (T4), which was built in 1979. According to information obtained from the manufacturer, it contained a foiled low voltage winding and enamel coated high voltage winding. The main insulation was formed of pressboard barriers and glued masonite spacers. Before the measurements this distribution transformer was heated and kept at 70 °C for two weeks, which hopefully allowed for balancing the water content in the oil and the paper, before oil samples were taken from the hot transformer (at 70 °C) for further analyses.

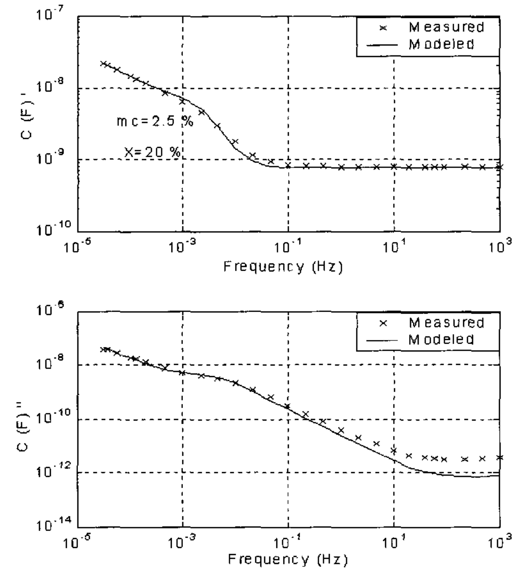

Fig. 17 Comparison of modelled and measured permittivity and loss of the distribution transformer T4 at 20 °C

Table 4 Results of oil analyses and estimated parameters from X model for different transformers

Trans-former	Oil analyses					Model parameters			
	Sampled temp (°C)	Conductivity measurement		Moisture content		Measurement temp. (°C)	mc (%)	X (%)	C_0 (nF)
		σ (pS/m)	Temp (°C)	Oil (ppm)	pb (%)				
T1	47	190	30	86	3.5	30	4.2	31	1
T2	50	9	27	66	2	55	3.5	43	1.6
T3	48	34	33	72	2.7	30	3.4	20	2.6
T4	70	4	20	90	2	20	2.4	20	0.3

pb - moisture content in pressboard estimated from IEEE 62 – 1995 ; mc – moisture content estimated from X model ; X – estimated barrier content ; C_0 – estimated geometrical capacitance

The results of the FDS measurements on this transformer are illustrated in Fig. 17. In addition, curves derived from X model are shown in the same figure. Conductivity of the oil measured at 20 °C was 4 pS/m. The estimated moisture content and the barrier content obtained from X model were 2.4 % and 20 %, respectively. The calculated geometrical capacitance was equal to 0.3 nF. The estimated moisture content from the oil analysis was 2 % (ref. Table 4).

As shown in the Table 4 in three cases (T1, T3 and T4) estimated moisture content from X model was fairly close to the value estimated from IEEE 62 – 1995 standard, where the maximum difference was 0.7 % of moisture content. However, for T2 estimated moisture content from X model is 1.5 % more than the corresponding quantity obtained from oil analyses. As shown in the Table 4 FDS measurement on this unit was performed at an elevated temperature, just after it was isolated from the system. In this unit it was hard to expect the moisture equilibrium between pressboard and oil to be established since it was operating only for a few hours at the corresponding temperature.

6. Conclusions

Use of so called X-Y model for estimating moisture content in transformer insulation requires access to detailed information about design of transformer insulation for evaluating the content of barriers and spacers. The sensitivity analyses of the X-Y model revealed that influences of moisture content, oil conductivity and amount of spacers on the dielectric permittivity of the transformer insulation system at high frequencies were relatively low. In addition, it was recognized that the influence of spacers on the total dielectric response in the X-Y model was also low.

A simplified X model was introduced by neglecting the effect of the spacers in the transformer insulation. The FDS measurements with the proposed model and oil analyses provide fairly close results. However, for improving the quality of the modelling, a comparison of model results with KFT analyses in a much larger population of power transformers is still needed.

Acknowledgement

Authors greatly appreciate the support of Ceylon Electricity Board for providing facilities to make measurements on their field-installed transformers. Measurements on the pressboard samples were performed at the high voltage laboratory of ETH, Zurich. Special thanks go to Prof. Klause Fröhlich and Mr. Wolfgang Hribernik for providing facilities for these measurements. The financial support given by Sida/SAREC Sweden is greatly appreciated.

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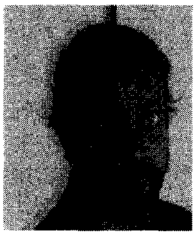

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