SIMULATION OF DIELECTRIC FREQUENCY RESPONSE OF TRANSFORMER INSULATION SYSTEM

George Chen[1*] and Yu Guo[2]
[1]The Tony Davies of High Voltage Laboratory, University of Southampton, UK
[2]Xiangtan Electric Power Company, Hunan, China
*Email: <gc@ecs.soton.ac.ukr>

Abstract: Frequency domain spectroscopy has been widely used to monitor the condition of insulation system in power transformers. For a core type of transformer, a simplified X-Y model of a duct has been developed which allows one to examine the contribution from oil, barrier and spacer to the overall dielectric measurement. In the present paper, we have constructed a 3D model of the duct to investigate the effects of degree of polymerization, temperature and geometry on the results such as dissipation factor and complex permittivity. The results are compared with the X-Y model so the accuracy of the simplified model can be evaluated. It reveals that the major differences between X-Y and 3D models lie in the lower frequency region and the difference is varied with the effects of degree of polymerisation, temperature and geometry of the insulation. As the dielectric response in the low frequency region is often used to estimate the moisture, the simplified X-Y model may result in potential error in estimation of moisture content in the oil-paper insulation system.

1 INTRODUCTION

Assessment of insulation condition of electrical apparatus such as transformers, cables and rotating machines has received more attention due to their crucial roles in the power system [1]. Among them, the power transformers are the most critical and costly equipment used in the system and the failures of transformers can lead to an interruption of power supply as well as revenue loss both to the electricity utilities and to the customers [2]. The insulation system of power transformers consists of oil and paper/pressboard. Generally, insulation failures of power transformers are predominantly caused by the degradation affected by primary factors such as moisture, heat and oxygen [2]. Moisture in oil paper insulations can lead to three dangerous effects: it decreases the dielectric withstand strength [3], significantly accelerates ageing processes of cellulose [3] and causes the emission of bubbles at high temperature [4]. Therefore, knowledge about the actual moisture content provides essential information about the condition of the insulation.

Traditional electrical measurements such as insulation resistance (IR), polarization index (PI) and oil quality tests have no definite relationship with moisture content [2]. However, by assuming the transformer stays at a fixed temperature for sufficiently long time, the equilibrium in distribution of moisture between oil and paper/pressboard can be achieved [4]. Thus, the moisture content in impregnated paper can be estimated from the so called equilibrium curves [5]. However, the equilibrium state is practically rather rare for a transformer in operation [3] as the moisture distributes unequally both in the oil and in the pressboard; hence, it is of the highest importance to carry a quantitative study on the moisture concentrations within each component [6]. As a result, dielectric diagnostic methods were developed like Recovery Voltage Measurement (RVM), Polarization and Depolarization Current method (PDC) and Frequency Domain Spectroscopy (FDS) which deduce moisture in paper and pressboard from dielectric properties [4].

In this paper, the FDS of a core type of transformer has been modelled in both 3D and 2D using COMSOL. The results were compared with the simplified X-Y model and the influence of changes in parameters, i.e. degree of polymerization, temperature and geometry, has been investigated.

2 MODEL DESCRIPTION

The modelling and interpretation of the oil-paper insulation in a power transformer using the dielectric response methods take both materials properties, and the design of the transformers into consideration [7, 8]. In the present paper, a core type transformer as shown in Figure 1 [9] is considered and its main duct insulation consists of multiple cylindrical oil ducts separated by the pressboard barriers and then they are separated and supported by axial spacers [7, 10]. For modelling purposes, the transformer duct is lumped together to an “insulation module” and the combined oil/paper/pressboard insulation can be assumed as series/parallel plate capacitors [10]. The insulation structure is then characterized by a so-called *X-Y* model, where *X* represents the ratio of the total thickness of all the barriers in the duct to the radial width of the duct and *Y*, the ratio of the total width of all the spacers to the total length of the periphery of the duct [7].

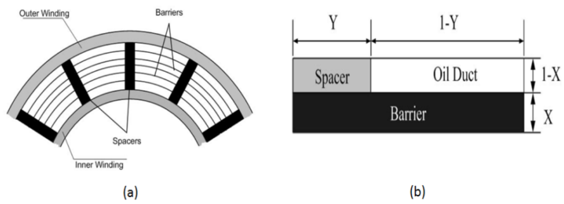

Figure 1: (a) Insulation structure between LV and HV windings. (b) Transformer insulation *X-Y* model [9].

Therefore, utilize the library of data on material properties and the geometry of the modelled insulation system, the PDC, RVM and FDS responses can be obtained. The calculations in the time domain (PDC and RVM methods) are based on the known response function *f(t)*, and they are temperature and humidity dependent while in the frequency domain (FDS technique), the composite dielectric relative permittivity of the insulation duct ε_{duct}, will be calculated as [7, 8, 11]

$$\varepsilon(\omega,T)_{duct} = \frac{Y}{\frac{1-X}{\varepsilon_{spacer}}+\frac{X}{\varepsilon_{barrier}}} + \frac{1-Y}{\frac{1-X}{\varepsilon_{oil}}+\frac{X}{\varepsilon_{barrier}}} \quad (1)$$

In equation (1), the relative permittivity of the oil, spacers and barriers are also complex quantities dependent on frequency, temperature and humidity [7]. Moreover, the calculation in time domain is the similar but involves with the convolution integrals. As a result, it will be more complicated numerically [8].

2.1 3D *Model*

The dimensions of the transformers have been given in Table 1. The dimensions of transformer T1 are referred to the paper [12] and the dimensions of the other two transformers are changed due to the investigation on the effect of parameters *X* and *Y* corresponding to the 2D *X-Y* model. The insulation of three transformers has two layers of oil gaps.

Table 1: Geometrical data of the 3D model of three transformers.

	T1	T2	T3
Total Spacers	40	40	40
Spacers width (mm)	25	25	40
Radius HV-Coil (mm)	754	786	754
Radius LV-Coil (mm)	684	684	684
Coil Height (mm)	1615	1615	1615
Total Pressboard (mm)	42	42	42
Total Oil duct (mm)	28	60	28

Furthermore, the electrical potential was applied on the HV winding with a sinusoidal voltage *20*sin(2*pi*freq*t)* where the *freq* was defined as the frequency in the Variables of model definitions, and then the LV winding was grounded. After that, the model was meshed as physics-controlled with extra-coarse condition due to the consideration about the time-consuming during the modelling while at lower frequencies below 1 Hz coarser mesh condition was applied. It is noteworthy that the mesh quality has influence on the results, but the difference is relatively small, hence, it is acceptable to mesh coarsely. The accomplished 3D model of the transformer T1 was given in Figure 2. Now we can set the time-dependent physics to run in one period dependent at a chosen frequency with 100 steps, and then run the model and choose the line integration on the interface of grounding and barriers of insulation. After that, evaluate the x-component or y-component current density and record the maximum current density which will be used to calculate the relative complex permittivity of the whole insulation system.

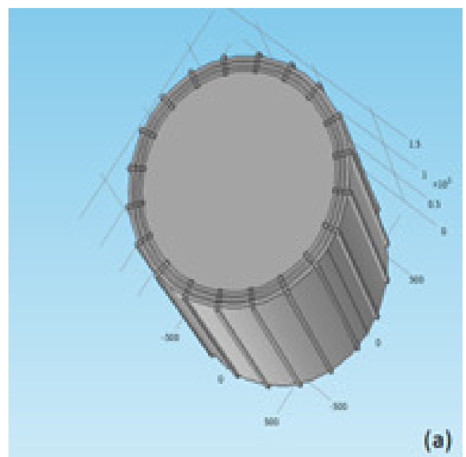

Figure 2: 3D model of T1 built in *COMSOL*

Table 2: Geometrical data of the 2D *X-Y* model of three transformers.

	T1	T2	T3
Spacers width (mm)	500	500	800
Spacers height (mm)	28	60	28
Barriers width (mm)	4430	4430	4430
Barriers height (mm)	42	42	42
Oil gap width (mm)	3930	3930	3630
Oil gap height (mm)	28	60	28

2.2 2D *X-Y* Modeling

The dimensions of the 2D model are equal to that of the 3D model except the coil height of the transformers is ignored. So the steps are similar to that of the 3D modelling, however, at the final step, evaluate the z-component current density and record the maximum current density which will be used to calculate the relative complex permittivity of the whole insulation system.

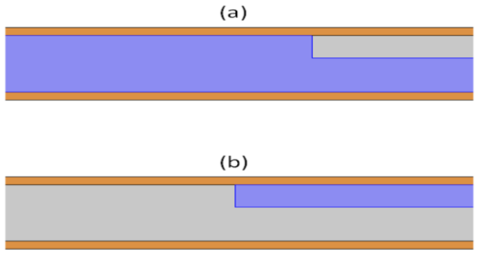

Figure 3: 2D Model (a) Paper material (b) Oil material.

3 RESULTS AND DISCUSSION

The influence of moisture, ageing time and testing temperature on the FDS results of oil-paper insulation has been widely reported [13]. It is generally recognised that the effects of ageing time are related to the reduction in degree of polymerization (DP) of cellulose itself. The new pressboard has higher DP value while the aged cellulose has a lower value. The quantitative analysis of the FDS results is given based on the data from two paper samples with different DP (DP=1180 and DP=600) [13].

The accuracy of the 2D model results can be investigated by comparing it with the calculated results. The equation (1) can be defined as the complex permittivity of the whole insulation system represented by the 2D *X-Y* model where the complex permittivity of pressboard and oil, and *X*, *Y* parameters are what we concerned. From Table 2, the following X and Y can be calculated.

$$X = \frac{42}{42+28} = 0.6;\ Y = \frac{500}{2\times\pi\times(584+\frac{42}{2})} = 0.113$$

As the transformer oil is non-polar liquid, its dielectric losses under low electric fields are mainly due to the conduction ionic impurities [3]. The frequency response of oil may be defined as [14]:

$$\varepsilon_{oil}(\omega, T) = 2.2 - j\frac{\sigma(T)}{\varepsilon_0 \omega} \qquad (2)$$

The dielectric response of the insulation using RVM, PDC and FDS techniques are all highly dependent of the temperature. This is due to the exponentially increase of both the oil and paper conductivity with rising temperature and then the conductivity can be expressed by [15, 16]:

$$\sigma(T) \approx A \cdot e^{(-E_{ac}/kT)} \qquad (3)$$

where T is the absolute temperature in Kelvin, A is a constant related to the mobility of ions in the insulation, k is Boltzman constant and E_{ac} is the activation energy [16]. The activation energy E_{ac} of the hypothetical oil sample was assumed to be 0.483 eV, and the constant A is 1.95×10^{-5} S/m [14]. Moreover, as the data of complex permittivity of pressboard was measured at a temperature of 110°C with DP=1180 and DP=600, the modelling in this section was assumed to be at a temperature of 110°C as well. Thus, from equation (3), a conductivity of 8.64 pS/m can be obtained for the oil. And then the relative complex permittivity of oil can be rewritten as:

$$\varepsilon_{oil}(\omega, 110^{\circ}C) = 2.2 - j\frac{\sigma(110^{\circ}C)}{\varepsilon_0 \omega} = 2.2 - j0.155/freq \qquad (4)$$

where *freq* represents the frequency.

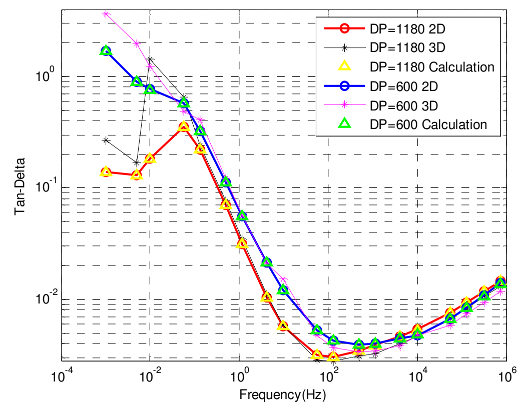

Figure 4: Dissipation factor (tanδ) with different degree of polymerization (DP).

Figure 4 illustrates the dissipation factor from 2D and 3D model. For comparison, the calculation based on equation (1) with two different ageing pressboard samples at varied frequency has also been included. It can be seen that the difference between the 2D model and calculated results either with DP=1180 pressboard or DP=600 pressboard is remarkably small (+/- 3 percent). As compared with the results from 3D model, in the middle frequency range, all three approaches are very similar. In the low frequency range, the simplified X-Y model underestimate tanδ while in the high frequency range it overestimates tanδ. The difference in tanδ reduces when DP decreases. Overall, it can be observed that the results obtained from the simplified X-Y model are credible. It is clear from both calculated and 3D simulated results that the minimum of tanδ shifts towards the higher frequency when DP decreases. The minimum dissipation factor has been associated with the moisture content [6, 17]:

$$\text{m.c.} = 15.297 + 2.53267 \times \ln(\tan\delta_{min}) \qquad (5)$$

Table 3 shows the minimum value of the dissipation factors in both 2D and 3D model and their corresponding frequencies of two different aged oil impregnated pressboard whose DP is 1180 and 600 respectively. The last column in Table 3 represents the results of the moisture contents calculated from equation (5).

Table 3: Minimum dissipation factors and calculated moisture contents of the oil-paper insulation.

DP		Minimum $\tan\delta$	f (Hz)	Moisture Contents (%)
1180	2D	0.00304	133	0.618
	3D	0.002824	133	0.431
600	2D	0.003906	486	1.253
	3D	0.003361	486	0.872

It can be seen that the ageing of the materials clearly affects the moisture contents which were modelled in the FDS method. Both the calculated moisture contents in 2D and 3D model increased approximately by 100% with the reduced DP. But the increment of moisture content in 2D model is higher than that in 3D model. Thus, the diversity between 2D and 3D model also influences the correct estimation of the moisture content in the insulation where this effect is more significant with the more aged (DP=600) insulation.

3.1 EFFECTS OF TEMPERATURE

Temperature shows significant influence on the FDS results. Here the insulation system at T=30°C and T=70°C has been modelled. The paper conductivity was taken from [13] and from equation (3), the oil conductivity is 0.175 pS/m and 1.521 pS/m can be obtained at T=30 °C and T=70 °C respectively, assuming the activation energy remains at 0.483 eV. Therefore, from equation (2), the complex permittivity of the oil can be derived as:

$$\varepsilon_{oil}(\omega, 30°C) = 2.2 - j\frac{\sigma(30°C)}{\varepsilon_0\omega} = 2.2 - j0.003/freq \qquad (6)$$

$$\varepsilon_{oil}(\omega, 70°C) = 2.2 - j\frac{\sigma(70°C)}{\varepsilon_0\omega} = 2.2 - j0.027/freq \qquad (7)$$

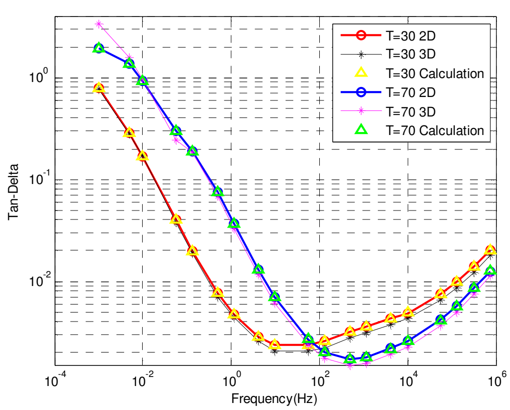

Figure 5: Dissipation factor (tanδ) at different temperature.

Figure 5 illustrates that the temperature has tremendous effects on the dissipation factor. When temperature increases the curve moves towards the right. On the other hand, the minimum of tanδ decreases with the temperature. The difference in tanδ values between the simplified X-Y model and 3D model increases with temperature. Overall, the simplified approach gives a good accurate account of tanδ of the insulation system.

3.2 EFFECTS OF PARAMETER *X*

The influence of the barriers (parameter *X* in *X-Y* model) on tanδ of the insulation system obtained from 3D model to 2D model has been studied. The dimensions of T2 have been used to compare with the results from T1. Moreover, the complex permittivity of the pressboard was referred to the paper with DP=600 from [13]. From Table 2, the total oil gap increases from 28 mm to 60 mm while the width of spacers remains unchanged, therefore,

$$X = \frac{42}{42+60} = 0.412; \; Y = \frac{500}{2\times\pi\times(684+\frac{42}{2})} = 0.113$$

Hence, the transformer T2 has a lower parameter *X* (X=0.412) compared to T1 (X=0.6).

In Figure 6, it can be observed that the minimum tanδ is independent of parameter X. Similar to the previous observation, the difference in the dissipation factor mainly occurs in the lower and higher frequency regions. When increasing X, tanδ decreases in low frequency region and increases in high frequency region. The minimum tanδ value and its corresponding frequency, together with the calculated moisture content are summarised in Table 4.

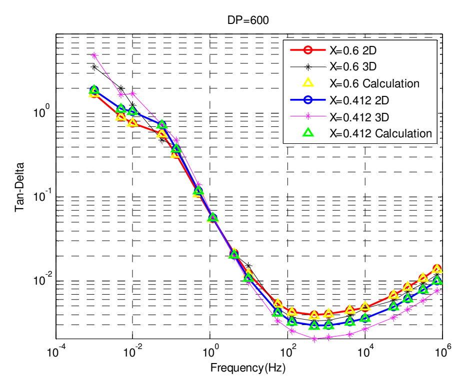

Figure 6: Effects of barriers on Dissipation factor (tanδ) when Y=0.113.

Table 4: Minimum dissipation factors and calculated moisture contents of the oil-paper insulation.

Parameter *X*		Minimum $\tan\delta$	f (Hz)	Moisture Contents (%)
0.6	2D	0.003906	486	1.253
	3D	0.003361	486	0.872
0.412	2D	0.002921	486	0.517
	3D	0.002065	486	~0

It is noteworthy that the moisture content of 3D model in T2 was close to zero as $\tan\delta_{min}$ is smaller than 0.0024. It can be seen that the oil gap clearly affects the estimation of the moisture contents which were modelled in FDS method. Although the calculation of the moisture content is not available in 3D model of T2, the substantial reduction of the minimum dissipation factor indicates that the simplification from 3D to 2D model will result in error in the estimation of the moisture content in oil-paper insulation systems.

3.3 EFFECTS OF PARAMETER *Y*

Similar study has also been carried out to examine the influences of the spacers (parameter *Y* in the *X-Y* model) on tanδ of the insulation system. This time the dimensions of T3 have been used for both 2D and 3D model. Based on the parameters given in Table 3, the total spacers width increases from 500 mm to 800 mm while the oil gap remains unchanged, therefore,

$$X = \frac{42}{42+28} = 0.6;\ Y = \frac{800}{2\times\pi\times(684+\frac{42}{2})} = 0.181$$

This means that the transformer T3 has a higher parameter *Y* (Y=0.181) compared to T1 (Y=0.113).

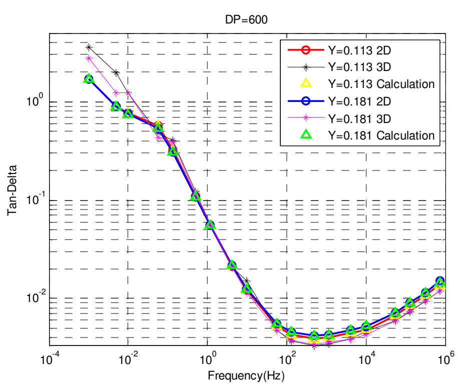

Figure 7: Effects of spacers on Dissipation factor (tanδ) when X=0.6.

Figure 7 shows the results concerning the effect of Y on tanδ. Similarly, Y has no impact on the position of tanδ minimum but influences its value. This will affect the moisture calculation as show in Table 5.

Table 5: Minimum dissipation factors and calculated moisture contents of the oil-paper insulation.

Parameter *Y*		Minimum $\tan\delta$	f (Hz)	Moisture Contents (%)
0.113	2D	0.003906	486	1.253
	3D	0.003361	486	0.872
0.181	2D	0.00421	486	1.443
	3D	0.003367	486	0.877

4 CONCLUSIONS

In this paper, the Frequency Domain Spectroscopy (FDS) has been used to investigate the accuracy of the simplification from 3D model to *X-Y* model carried out by *COMSOL Multiphysics Software* where the later model has been widely used nowadays for estimating the moisture content in the oil-impregnated paper insulation of power transformers. Moreover, the effects of degree of polymerization (DP) which related to ageing condition, the influence of temperature and geometry includes oil gaps and spacers have been modelled. The following conclusions can be drawn.

Overall, the simplified X-Y model provides a good approximation on the cylindrical core type insulation as far as FDS response is concerned. Simulation from 2D model is consistent with the simplified X-Y model, validating the simulation process. There are two major differences in tanδ when comparing 3D model and the simplified X-Y model. The first is frequency characteristic occurred in lower frequency and higher frequency regions. In the former tanδ is underestimated while in the latter tanδ is overestimated. The second is the minimum value of tanδ becomes lower. This means that the moisture calculated from the simplified X-Y model may be higher than the actual moisture content in the system. The difference between the two models depends on parameters such as DP of pressboard, temperature and geometrical parameters X and Y.

It has been found that the DP of pressboard has an obvious effect on tanδ. When DP decreases (aging), tanδ value increases and its frequency curve shifts towards right. Temperature shows a significant impact on tanδ,. When temperature increases the curve moves towards the right and the minimum of tanδ decreases with the temperature. Geometrical parameters X and Y affect tanδ value but not the frequency characteristics.

5 REFERENCES

[1] N. A. M. Jamail, M. A. M. Piah, N. A. Muhamad, “Comparative Study on Conductivity Using Polarization and Depolarization Current (PDC) Test for HV Insulation,” *IEEE International Conference on Electrical Engineering and Informatics,* Bandung, Indonesia, 2011, pp. 1-6.

[2] G. K. Supramaniam, Z.F. Hussien, T.M. Aizam, “Application of Frequency Domain Spectroscopy (FDS) in Assessing Dryness and Ageing State of Transformer Insulation Systems,” *IEEE 2nd International Power and Energy Conference,* 2008, pp. 55-61.

[3] C. Ekanayake, S. M. Gubanski, A. Graczkowski, K. Walczak, “Frequency Response of Oil Impregnated Pressboard and Paper Samples for Estimating Moisture in

Transformer Insulation," *IEEE Transactions on Power Delivery,* vol. 21, no. 3, 2006, pp. 1309-1317.

[4] M. Koch, M. Krüger, "A Fast and Reliable Dielectric Diagnostic Method to Determine Moisture in Power Transformers," in *International Conference on Condition Monitoring and Diagnosis,* Beijing, China, 2008, pp. 467-470.

[5] Y. Du, M. Zahn, B.C. Lesieutre, A.V. Mamishev, "Moisture Equilibrium in Transformer Paper-Oil Systems," *IEEE Electrical Insulation Magazine,* vol. 15, no. 1, 1999, pp. 11-20.

[6] W. S. Zaengl, "Applications of Dielectric Spectroscopy in Time and Frequency Domain for HV Power Equipment," *IEEE Electrical Insulation Magazine,* vol. 19, no. 6, 2003, pp. 9-22.

[7] S. M. Gubanski, P. Boss, G. Gsepes, V. Der Houhanessian, J. Filippini, P. Guuinic, U. Gäfvert, V. Karius, J. Lapworth, G. Urbani, P. Werelius, W. Zaengl, "Dielectric Response Methods for Diagnostics of Power Transformers," *IEEE Electrical Insulation Magazine,* vol. 19, no. 3, 2003, pp. 12-18.

[8] U. Gäfvert, L. Adeen, M. Tapper, P. Ghasemi, B. Jönsson, "Dielectric Spectroscopy in Time and Frequency Domain Applied to Diagnostics of Power Transformers," in *Proc. 6th Intern. Conf. on Properties and Applications of Dielectric Materials* (ICPADM), Xian, China, 2000, pp. 825-830.

[9] M. K. Pradhan, J. H. Yew, T. K. Saha, "Influence of the Geometrical Parameters of Power Transformer Insulation on the Frequency Domain Spectroscopy Measurement," *IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century,* 2008, pp. 1-8.

[10] C. F. Ten, M. A. R. M. Fernando, Z. D. Wang, "Dielectric Properties Measurements of Transformer Oil, Paper and Pressboard with the Effect of Moisture and Ageing," *IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena,* 2007, pp. 727-730.

[11] U. Gäfvert, "Influence of Geometric Structure and Material Properties on Dielectric Frequency Response of Composite Oil Cellulose Insulation," *in Proceedings of International Symposium on Electrical Insulating Materials,* Kitakyushu, Japan, 2005, pp. 73-76.

[12] M. Jaya, T. Leibfried, "Dielectric Modelling and Diagnosis of the Oil-Paper-Insulation System in Power Transformers," [On-line]: https://www.ieh.kit.edu/rd_download/jaya_paper326.pdf

[13] Ruijin Liao, Jian Hao, G. Chen, Lijun Yang, "Quantitative Analysis of Ageing Condition of Oil-paper Insulation by Frequency Domain Spectroscopy," *IEEE Transactions on Dielectric and Electrical Insulation*, vol. 19, no. 3, 2012, pp. 821-830.

[14] R. Neimanis, L. Arvidsson, P. Werelius, "Dielectric Spectroscopy Characteristics of Aged Transformer Oils," *Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference,* 2003, pp. 289-293.

[15] R. B. Jadav, C. Ekanayake, T. K. Saha, "Dielectric Response of Transformer Insulation – Comparison of Time Domain and Frequency Domain Measurements," *IEEE Proceedings of Conference on IPEC,* 2010, pp. 199-204.

[16] T. K. Saha, P. Purkait, "Investigation of Temperature Effects on the Dielectric Response Measurements of Transformer Oil-Paper Insulation System," *IEEE Transactions on Power Delivery,* vol. 23, no. 1, 2008, pp. 252-260.

[17] Shiqiang Wang, Jianlin Wei, Shuangsuo Yang, Ming Dong, Guanjun Zhang, "Temperature and Thermal Aging Effects on the Frequency Domain Spectroscopy Measurement of Oil-Paper Insulation," *IEEE Proceedings of the 9th International Conference on Properties and Applications of Dielectric Materials,* Harbin, China, 2009, pp. 329-332.