QUANTITATIVE RELATION BETWEEN AGEING CONDITION OF PRESSBOARD IMPREGNATED IN MINERAL OIL AND ITS FREQUENCY DIELECTRIC RESPONSE

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Abstract: In order to use the frequency domain spectroscopy (FDS) for assessing the ageing condition of oil-paper insulation in transformers, the accelerated thermal ageing experiment of oil-paper insulation were performed at 130°C, and the oil-paper insulation samples with different ageing state were tested by FDS. The ageing and temperature effects on FDS results were quantified. Research shows that the FDS can reflect the ageing state of the oil-paper insulation. The real part of the relative complex permittivity ε_r', dissipation factor $tan\delta$ plots of oil impregnated pressboards with different degree of polymerization (DP) shifts upwards in the lower frequencies range of 10^{-3}Hz to 10^{-1}Hz with the ageing time increased. The parameters including DP, ε_r' or $tan\delta$ values at the characteristic frequencies and the ageing time *t* meet a good exponential relationship. In addition, the ε_r' and $tan\delta$ curves of aged impregnated pressboard were observed to be shifted upwards to higher values at lower frequencies with the increasing temperature. There is an exponential relationship between the ε_r' (tanδ) values at the characteristic frequencies and the testing temperature.

1 INTRODUCTION

Transformers play an important role in providing a reliable and efficient electricity supply and are one of the most critical equipments in electric power transmission and distribution systems [1, 2]. Transformer owners need to assess the status of the cellulose insulation for planning maintenance or renewal. With the advancement in digital technology, diagnostic techniques based on dielectric relaxation methods such as Return Voltage Measurement (RVM) [3, 4], Polarisation & Depolarisation Current (PDC) [4, 5] and Frequency Domain Spectroscopy (FDS) [1, 6, 7] have been developed in the 1990's. Since their introduction, these non-destructive techniques have been widely used to assess the condition of the insulation system in transformers [7-10].

There are many reports about the influence of moisture, ageing time and testing temperature on the FDS results of oil-paper insulation [1, 7, 8, 11, 12]. As reported in [13, 14], at the lowest frequencies, different ageing status can be detected using the FDS method. However, there are few reports about how to use FDS to assess the ageing condition of the oil-paper insulation. The quantitative relationship between the ageing condition of oil-paper insulation and its dielectric characteristic parameters has not been seen at the present. It has become obvious that in order to obtain the ageing condition of the oil-paper insulation in transformers by FDS with confidence, the ageing condition and testing temperature effects on FDS results are needed to be quantified.

In this paper, the oil-pressboard insulation samples were thermally aged at 130°C for different times. The ageing condition and testing temperature effect on the FDS results of the oil impregnated pressboards were analyzed, and the mechanism of dielectric parameters changing with testing temperature was also provided. The method for assessing the ageing condition of oil-paper insulation by FDS was proposed.

2 FREQUENCY DOMAIN SPECTROSCOPY

When an AC sinusoidal voltage source $u(t)=U^*\sin(\omega t)$ is applied across a parallel plate capacitor incorporating a dielectric material, the material polarize at different frequencies to a varying extend. The resulting current is made up of two components: the charging current (I_{charge}) and the loss current (I_{loss}), both being related to the complex permittivity. The total current flowing through the insulator is given by [12, 15]:

$$I=I_{charge}+I_{loss}=U^*(j\omega C+G) \quad (1)$$

Let $C=\varepsilon_r' C_0$ and $G=\omega C_0\varepsilon_r''$, then,

$$\begin{aligned} I&=U(j\omega\varepsilon_r' C_0+\omega C_0\varepsilon_r'') \\ &=j\omega C_0 U(\varepsilon_r'-j\varepsilon_r'') \\ &=j\omega C_0 U\varepsilon_r^* \end{aligned} \quad (2)$$

where C is the capacitance of the material under test between the electrodes, C_0 is the vacuum capacitance. The $\varepsilon_r^*=\varepsilon_r'-j\varepsilon_r''$, and the $tan\delta=I_{loss}/I_{charge}=\varepsilon_r''/\varepsilon_r'$

3 EXPERIMENTAL

3.1 Experiment materials and equipment

The insulation pressboard used in the experiment was Kraft Pressboard with thickness 0.3mm. The technical performances of the pressboard satisfy the international standard IEC 641-3-1. The pressboard was cut into circle samples with diameter of 32 mm. The mineral oil used in this experiment was Karamay 25# naphthenic mineral oil provided by Chuanrun Lubricant Co. Ltd, China.

The FDS measurements were carried out using Novocontrol Concept 80 Broadband Dielectric Spectroscopy equipment. The test electrode diameter for pressboard sample was 30mm. The principle of FDS is shown in Figure 1. The electrode was put into a sealed vessel enclosed in the equipment when the FDS measurement was performed. In this way, the constant moisture equilibrium and temperature can be maintained during the measurement period.

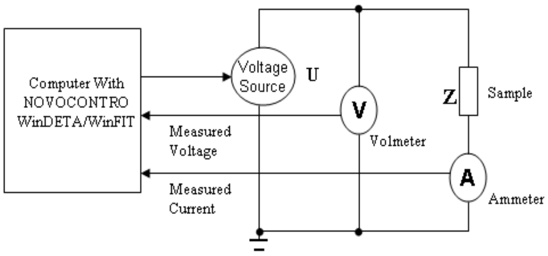


Figure 1. FDS measurement circuit

3.2 FDS of oil impregnated pressboard

The pretreatment of the samples was as following: Firstly, all pressboard samples were put into the vacuum box and were dried at 90°C for two days. Then the temperature of the vacuum box was adjusted to 40°C. Secondly, the new mineral oil was infused into the vacuum box at 40°C for immersing pressboard samples. The vacuum box was kept at 40°C for one day and then cooled down to room temperature. Thirdly, 10g pressboard samples were taken out every time and put them into a glass bottle (250ml). Then new mineral oil was poured into each bottle at the mass weight ratio of oil/paper 20:1 (each bottle has 200g oil and 10g paper). To simulate the copper ion in real transformers, 10cm^2 copper sheets were put into each bottle. After that, each bottle was filled up with dry nitrogen gas and sealed. These bottles were finally put into the ageing ovens and heated to 130°C for the accelerated thermal ageing. The initial water content of pressboard is 0.44% (<0.5%), the initial water content of new 25# mineral oil is 9 mg/Kg.

Before FDS measurements were performed, oil impregnated pressboard samples with different ageing conditions were cooled naturally to room temperature (28°C). In order to make quantitative analysis the ageing condition of oil-paper insulation, the degree of polymerization (DP) of oil impregnated pressboard aged for different time was measured according to ASTM D4243-99. Moisture often is generated when oil impregnated pressboard aged and it has a significant effect on the FDS result. The absolute moisture content of oil and oil impregnated pressboard was also measured by Karl Fischer Titration technique during the ageing process.

4 RESULTS AND DISCUSSIONS

4.1 Moisture content of aged oil-pressboard insulation samples

Moisture in oil impregnated pressboard has a significant effect on the FDS result [8, 11, 16]. There will be moisture generated in the process of oil-paper insulation sample ageing. In reality, the moisture inside the bottles tends to keep equilibrium among the pressboard, oil and air [17, 18]. The absolute moisture content of oil and oil impregnated pressboard is presented in Table 1. The moisture content values in the pressboard and oil are found to decrease at early ageing period. The initial condition of the oil and the air inside the bottles being relatively drier than the moisture condition of paper, there is always a migration of moisture from paper to the oil and then to the air. The longer the period of ageing, the higher the amount of moisture migrates out of the paper [17]. As presented in Table 1, it can be seen that the moisture content of the pressboard and the oil are very low. Thus, the effect of this 'moisture migration' may override the FDS effect of moisture produced in the ageing process.

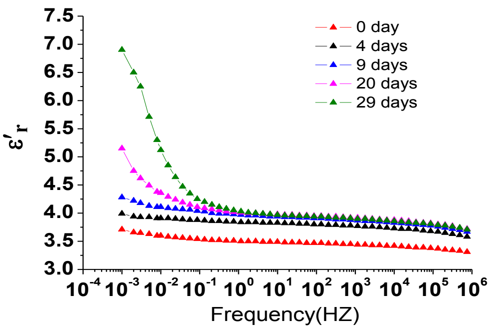
Table 1. Water content of and oil paper aged at 110°C

DP	Moisture content of pressboard (wt %)	Moisture content of oil (mg/Kg)
1 180	0.44	9.0
1 064	0.24	7.3
948	0.14	5.2
764	0.15	14.7
660	0.16	8.9

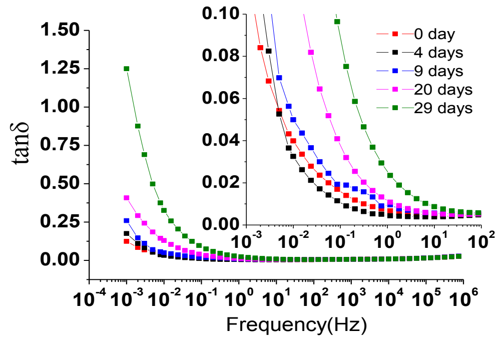
4.2 Quantitative analysis ageing condition of oil impregnated pressboard

Transformer life/ageing is mainly related to the degradation of the insulation, caused primarily by thermal stress of the insulating paper [12, 19], together with electrochemical decomposition of the insulation paper. The dielectric properties of cellulose paper have a close relation with the paper degradation degree.

Figure 2 shows the relative permittivity ε_r' and dielectric loss tanδ plots of oil impregnated pressboard with different ageing conditions, respectively. It can be seen that the ageing has an obvious effect on impregnated pressboard FDS result. At the same measurement temperature, both ε_r' and tanδ curves of aged oil impregnated pressboard noticeably shift upward with the DP reduced, especially in the lower frequency range from 10^{-3}Hz to 10^{-1}Hz. More rapid increase of ε_r' and tanδ at low frequencies (below 0.1 Hz) can be seen in the aged oil impregnated pressboard samples with lower DP. Therefore, these dielectric parameters (ε_r' and tanδ) values in the lower frequency range from 10^{-3}Hz to 10^{-1}Hz can be potentially used to make quantitative analysis of ageing condition of oil impregnated pressboard.



(a) ε_r'



(b) *tanδ*

Figure 2. ε_r' and ***tanδ* curves** of oil-paper insulation samples with different ageing condition

With the aim at investigating the quantitative relationship between dielectric parameters at lower frequencies (10^{-3}Hz to 10^{-1}Hz) and the ageing state of impregnated pressboard samples, 10^{-3}Hz, 10^{-2}Hz and 10^{-1}Hz were selected as characteristic frequencies, and ε_r' and tanδ values of impregnated pressboard samples with different DP at characteristic frequencies of 10^{-3}Hz, 10^{-2}Hz and 10^{-1}Hz were extracted respectively. The results of DP(t)/ε_r'(10^{-f},t) and DP(t)/tanδ(10^{-f},t) were calculated. DP(t) is the DP value of oil impregnated pressboard aged for t days, ε_r'(10^{-f}, t) and tanδ(10^{-f},t) is the ε_r' and tanδ value of impregnated pressboard with DP(t) at 10^{-f}Hz (f=1, 2, 3). Quantitative relationship between DP(t)/ε_r'(10^{-f}, t) of impregnated pressboard, and quantitative relationship between DP(t)/tanδ(10^{-f},t) of impregnated pressboard samples versus ageing time are presented in Figure 3, Table 2, Figure 4 and Table 3. Figure 3 and Table 2 demonstrate that there is a good exponential relationship between DP(t)/ε_r'(10^{-f}, t) and ageing time t. As can be seen in Figure 4 and Table 3, there is also a good exponential relationship between DP(t)/tanδ(10^{-f}, t) and ageing time t.

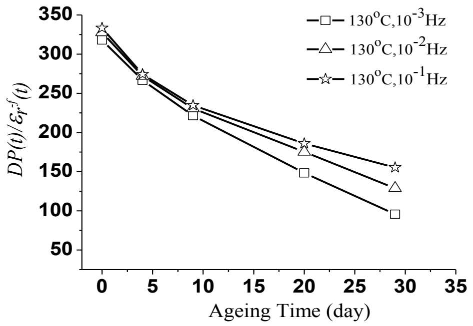


Figure 3. Relationship between $K_{DP}(t)/\varepsilon_r^{-f}(t)$ of oil-paper insulation sample versus ageing time

Table 2. Fitting equation for $DP(t)/\varepsilon_r'(10^{-f},t)$ of oil-paper insulation sample versus ageing time

$\varepsilon_r'(10^{-f}, t)$	Relationship between Y ($DP(t)/\varepsilon_r'(10^{-f}, t)$) and ageing time t	R^2
$\varepsilon_r^{-3}(t)$	$Y = 337.23\exp(-t/28.09) - 21.99$	0.99
$\varepsilon_r^{-2}(t)$	$Y = 244.60\exp(-t/19.39) + 79.05$	0.99
$\varepsilon_r^{-1}(t)$	$Y = 191.20\exp(-t/12.85) + 139.37$	0.99

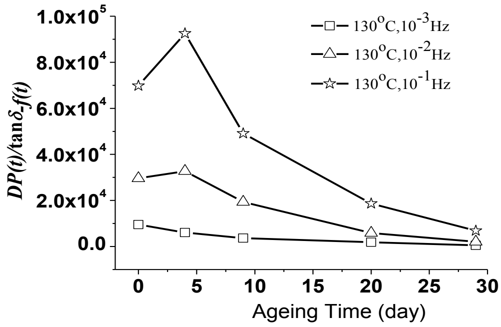


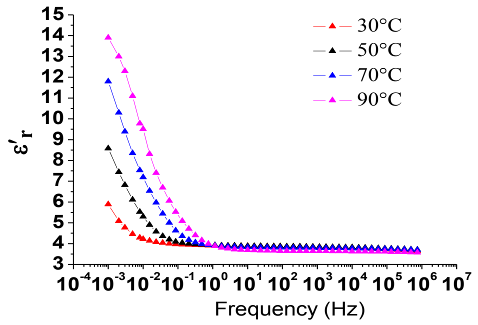
Figure 4 Relationship between $DP(t)/tan\delta_{-f}(t)$ of oil-paper insulation sample versus ageing time

Table 3. The relationship between $DP(t)/tan\delta(10^{-f},t)$ of oil-paper insulation sample versus ageing time

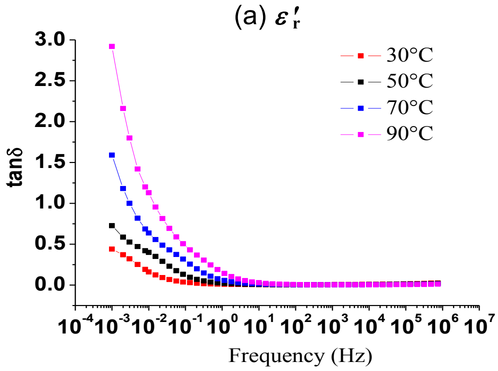
$tan\delta(10^{-f}, t)$	Relationship between Z ($DP(t)/tan\delta(10^{-f}, t)$) and ageing time t	R^2
$\tan\delta_{-3}(t)$	$Z = 10\,143.23\exp(-t/30.48) - 621.79$	0.99
$\tan\delta_{-2}(t)$	$Z = 67\,056.27\exp(-t/44.25) - 34\,201.77$	0.93
$\tan\delta_{-1}(t)$	$Z = 329\,351.12\exp(-t/105.26) - 246\,839$	0.85

4.3 Effect of temperature on the FDS results

Figure 5 shows the behaviour of the ε_r' and tanδ for the impregnated pressboard with DP=660 at four different temperatures. The results clearly show that the measurement temperature has a significant impact on the dielectric parameters of impregnated pressboard. The dipole-dipole interactions due to the increased mobility of flexible portions in the cellulose chains decrease with the increase of testing temperature, which enhances the ease of rotation and polarizability of the side groups and of other flexible portions of cellulose [20]. Thus, ε_r' and tanδ curves were observed to be shifted upwards to higher values at lower frequencies with the temperature. In addition, the oil impregnated pressboard conductivity at lower frequencies increases with temperature which also makes a contribution towards tanδ. In addition, as shown in Table 4, the ε'_r and tanδ values at 10^{-3}Hz, 10^{-2}Hz, 10^{-1}Hz increase in an exponential way with the temperature.



(a) ε'_r



(b) tanδ

Figure 5. ε'_r and tanδ curves of aged oil impregnated pressboard (DP=660) versus testing temperature

Table 4 Fitting equation for ε_r^{-f} and $\tan\delta^{-f}$ of oil impregnated pressboard at 10^{-f} Hz and temperature

Parameter	Fitting Equations	R^2
ε_r^{-3}(T)	$\varepsilon_r^{-3}(T)$=21.13-24.99exp(-T/64.22)	0.98
ε_r^{-2}(T)	$\varepsilon_r^{-2}(T)$=1.778exp(T/58.31)+1.20	0.99
ε_r^{-1}(T)	$\varepsilon_r^{-1}(T)$=0.058exp(T/26.25)+3.75	0.99
$\tan\delta_3(T)$	$\tan\delta_3(T)$=0.177exp(T/31.87)-0.05	0.99
$\tan\delta_2(T)$	$\tan\delta_2(T)$=0.1716exp(T/44.73)-0.16	0.99
$\tan\delta_1(T)$	$\tan\delta_1(T)$=0.2382exp(T/71.34)-0.33	0.99

4.4 Assessing ageing condition of transformer main insulation by FDS

The main insulation system of transformer consists of cylindrical pressboard barriers in series with oil ducts and spacers, as shown in Figure 6 [21]. By combining all oil ducts, barriers and spacers, the main insulation system can be simplified as X-Y model, as presented in Figure 7 [22]. The parameters X and Y in the model can be represented by equation (3). The dielectric response across the X-Y system can be calculated when the individual dielectric response of oil and spacers (barriers) are known. In real power transformers, X and Y vary often between 0.2-0.5 and 0.15-0.25, respectively [22]. The total relative complex permittivity of the X-Y model shown in Figure 7 at testing temperature *T* can be described as equations (4) and (5).

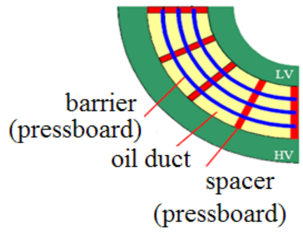


Figure 6. Section of main insulation in a core-type transformer

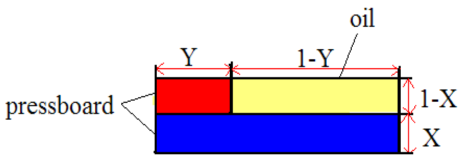


Figure 7. X–Y representation of transformer main insulation

$$X = \frac{thickness..of..total..barriers}{width..of..the..duct}$$
$$Y = \frac{total..width..of..the..spacer}{width..of..the..duct} \tag{3}$$

$$\varepsilon_r^*(\omega,T) = \frac{Y}{\frac{1-X}{\varepsilon^*_{r-spacer}(\omega,T)} + \frac{X}{\varepsilon^*_{r-barrier}(\omega,T)}} + \frac{1-Y}{\frac{1-X}{\varepsilon^*_{r-oil}(\omega,T)} + \frac{X}{\varepsilon^*_{r-barrier}(\omega,T)}} \tag{4}$$

$$\varepsilon^*_{r-spacer}(\omega,T) = \varepsilon^*_{r-barrier}(\omega,T) = \varepsilon^*_{r-pressboard}(\omega,T)$$
$$\varepsilon^*_{r-oil}(\omega,T) = \varepsilon_{r-oil} - j\frac{\sigma(T)}{\varepsilon_0\omega} \tag{5}$$

When the FDS measurement is performed on a transformer at a testing temperature *T*, the $\varepsilon^*_r(\omega,T)$ will be known. $\varepsilon^*_{r\text{-oil}}(\omega,T)$ can be easily obtained, so $\varepsilon^*_{r\text{-pressboard}}(\omega,T)$ can be calculated. After this, $\varepsilon'_{r\text{-pressboard}}(\omega,T)$ and $\varepsilon''_{r\text{-pressboard}}(\omega,T)$ will be known and $\tan\delta(\omega,T)=\varepsilon''_{r\text{-pressboard}}(\omega,T)/\varepsilon'_{r\text{-pressboard}}(\omega,T)$ will also be known. If T is 28°C, expressions in Table 2 and Table 3 can be used to assess all the ageing conditions of the transformer.

5 CONCLUSIONS

This paper describes the usefulness of FDS technique as a modern non-destructive tool for the ageing condition assessment of transformer insulation. The findings of the laboratory investigations could be used as guidelines to evaluate the extent of deterioration of oil-paper insulation in transformers. The following conclusions may be drawn from the research.

Detailed study on dielectric characteristics of thermally aged oil-paper insulation reveals that the relative permittivity (ε_r') and dielectric loss (*tanδ*) of oil impregnated pressboards shifts upwards in the lower frequency range between 10^{-3}Hz and 10^{-1}Hz as the ageing time increases. The frequency domain dielectric characteristic quantity (ε_r' and *tanδ*) of the oil-paper insulation sample in 10^{-3}-10^{-1}Hz can reflect the ageing status of insulation paper. The ε_r' and *tanδ* values at 10^{-3} Hz, 10^{-2}Hz and 10^{-1}Hz of aged pressboards have an exponential function with the *DP* of pressboard.

Temperature has a significant impact on the dielectric parameters of impregnated pressboard. ε_r' and *tanδ* curves were observed to be shifted upwards to higher values at lower frequencies with temperature in an exponential way.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] J. H. Yew, T. K. Saha, A. Thomas: “Impact of temperature on the frequency domain dielectric spectroscopy for the diagnosis of power transformer insulation”, Proceedings of the IEEE Power Engineering Society General Meeting, Montreal, Canada, pp. 1-7, 2006.

[2] Ruijin Liao, Yun Feng, Lijun Yang, Bin Xiang and Gang Liu: ”Study on generation rate of characteristic products of oil-paper insulation aging”, Proceedings of the CSEE, Vol. 28, pp. 142-147, 2008 (in Chinese).

[3] T. K. Saha, T. Y. Zheng: “Experience with return voltage measurements for assessing insulation conditions in service-aged transformers”, IEEE Trans. Power Del., Vol. 18, pp. 128-135, 2003.

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

[5] T. K. Saha, P. Purkait: “Investigation of polarisation and depolarization current measurements for the assessment of oil-paper insulation of aged transformers”, IEEE Trans. Dielect. Electr. Insul. Vol. 11, pp. 144-154, 2004.

[6] S. M. Gubanski, P. Boss, G. Csepes, et al: “Dielectric response methods for diagnostics of power transformers”, IEEE Electrical Insulation Magazine, Vol. 19, pp. 12-18, 2003.

[7] D. Linhjell, L. E. Lundgaard, U. Gafvert: “Dielectric response of mineral oil impregnated cellulose and the impact of aging”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 14, pp. 156-169, 2007.

[8] J. H. Yew, M. K. Pradhan, T. K. Saha: “Effects of moisture and temperature on the frequency domain spectroscopy analysis of power transformer insulation”, 2008 IEEE Power & Energy Society General Meeting, Pittsburgh PA, USA, pp. 2175-2182, 2008.

[9] A. Helgeson, U. Gafvert: “Dielectric response measurements in time and frequency domain on high voltage insulation with different response”, Proceedings of 1998 International Symposium on Electrical Insulating Materials, Toyohashi, Japan, pp. 393-398, 1998.

[10] W. S. Zaengl: “Applications of dielectric spectroscopy in time and frequency domain for HV power equipment”, IEEE Electrical Insulation Magazine, Vol. 19, pp. 9-22, 2003.

[11] H. Provencher, B. Noirhomme, E. David: “Influence of temperature and moisture on the dielectric response of oil-paper insulation system”, 2008 Annual Report Conference on Electrical Insulation Dielectric Phenomena, Beijing, China, pp. 125-128, 2008.

[12] C. D. Paraskevas, P. Vassiliou, C. T. Dervos: “Temperature dependent dielectric spectroscopy in frequency domain of high-voltage transformer oils compared to physicochemical results”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 13, pp. 539-546, 2006.

[13] A. Seytashmehr, I. Fofana, C. Eichler, A. Akbari, H. Borsi, E. Gockenbach: “Dielectric Spectroscopic Measurements on Transformer Oil-Paper Insulation under Controlled Laboratory Conditions”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, pp. 1100-1111, 2008.

[14] A. A. Shayegani, H. Mohseni, H. Borsi, E. Gockenbach: “Diagnostics of power transformers with dielectric response measurements”, 20th international power system conference, Amserdam, Netherlands, pp. 1-8, 2005.

[15] Hanru Li: “Introduction to diectric physics. Chengdou, China: Chendu University of Science and Technology Press, pp. 127-130, 1990 (in Chinese)

[16] D. Linhjell, U. Gäfvert, L. E. Lundgaard: “Dielectric response of oil-impregnated paper insulation: Variation with humidity and ageing level”, Proc. CEIDP 2004, Boulder, Colorado, USA, pp. 262-266, 2004.

[17] T. K. Saha, P. Purkait: “Understanding the impacts of moisture and thermal aging on transformer’s insulation by dielectric response and molecular weight measurements”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, pp. 568-582, 2008.

[18] T. V. Oommen: “Moisture Equilibrium Charts for Transformer Insulation Drying Practice”, IEEE Trans. Power App. Syst., Vol. 133, pp. 3063-3067, 1984.

[19] V. T. Morgan: “Effects of frequency, temperature, compression, and air pressure on

the dielectric properties of a multilayer stack of dry kraft paper", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 125-131, 1998.

[20] S. A. El-Henawii, S. M. Saad, I. M. El-Anwar: "Dielectric Behavior of Modified Cellulose", J. Mater. Sci. Technol. Vol. 15, pp. 164-168, 1999.

[21] T. Leibfried, A. J. Kachler, V. Der Houhanessian, A. Küchler and B. Breitenbauch: "Ageing and moisture analysis of power transformer insulation systems", CIGRE Session, Paris, pp. 1-6. 2002.

[22] Ekanayake, Chandima, S. M. Gubanski: "Fernando M. A. R. M. Application of dielectric spectroscopy measurements for estimating moisture content in power transformers", KIEE International Transactions on Electrophysics and Application, Vol. 4-c (3), pp. 81-90. 2004.