FREQUENCY DOMAIN SPECTROSCOPIC MEASUREMENTS OF OIL IMPREGNATED PAPER INSULATION SYSTEM UNDER THERMAL RUNAWAY

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Abstract: In the current research work, systematic investigations on the influence of thermal transients on the results of the Frequency Domain Spectroscopy (FDS) measurements are presented. The test object consisted in a laboratory made oil paper condenser. A series of experiments have been performed under controlled temperature conditions on an oil impregnated bushing model. Along with the FDS measured parameters, the temperature was simultaneously recorded. Some detailed investigations were made to study the effect of temperature variation on the interpretation of FDS measurements. The obtained results indicate that better interpretation is obtained when using the temperature values registered at the beginning of the measurements.

1 INTRODUCTION

In these last decades, increasing requirements for appropriate techniques to diagnose power equipments insulation non-destructively and reliably in the field drive the development of diagnostic tools based on changes of the dielectric properties of the insulation. Among these non-destructive monitoring techniques Frequency Domain Spectroscopy (FDS) technique provides indication of the general ageing status and moisture content of the oil-paper insulation of transformer [1-11]. Because, results from this technique are influenced by several environmental factors, predominantly the temperature, practical measurements issues that need to be considered have to be addressed, particularly when field measurements are performed just after de-energizing the transformer. Indeed, it is often experienced in actual field testing that the transformer to be tested was previously connected to the electricity grid. During normal operating conditions, the temperature inside a transformer is much higher than ambient, depending upon the loading condition. Under such circumstances, large thermal variations may affect the results, since moisture distribution inside the insulation is not in complete equilibrium condition. Because field measurements, last hours after switching off the transformer, the final temperature may be much lower than the initial. For example, the transformer is switched off at an operating temperature of 65°C, the dielectric measurement starts at 60°C and in the end of the measurement the transformer is at 25°C. Thus at onsite measurements, the water migration is commonly running, the transformer is in a non equilibrium state. This influence can lead to mistaken interpretation of insulation condition. Care is therefore required to interpret the results.

2 FREQUENCY DOMAIN SPECTROSCOPY

An alternative method for studying the polarization in the time domain is the study of the dielectric response in the frequency domain when an AC sinusoidal voltage U(ω) is applied. Applying Fourier transforms the polarisation current yields [8]:

$$\widehat{I}(\omega) = j\omega C_0 \left[\underbrace{\varepsilon_\infty + \chi'(\omega)}_{\varepsilon'(\omega)} - j \underbrace{\left(\frac{\sigma_0}{\varepsilon_0 \omega} + \chi''(\omega) \right)}_{\varepsilon''(\omega)} \right] \widehat{U}(\omega) \qquad (1)$$

Where $\chi(\omega) = \chi'(\omega) - j\chi''(\omega)$ is the Fourier transform of the dielectric response function f(t), defined as the complex dielectric susceptibility. Given that $\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$, the loss factor tan δ can be defined as [6]:

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} = \frac{\dfrac{\sigma_o}{\varepsilon_o \omega} + \chi''(\omega)}{\varepsilon_\infty + \chi'(\omega)} \qquad (2)$$

where σ_0 is the dc conductivity of the dielectric material, ε_0 = 8.852 10^{-12} As/Vm is the vacuum permittivity, ε'(ω) and ε''(ω) are real and imaginary components of the complex permittivity.

Both quantities *C* and *tan*δ depend on frequency. As aging effects will change these quantities in quite different and specific frequency ranges, new diagnostic tools will monitor and detect this effect.

Frequency domain spectroscopy (FDS) has been implemented in the Insulation Diagnostic Analyzer IDA 200 [12]. This instrument allows frequency scanning of the capacitance, power factor, dielectric constant and dielectric loss from 0.1 mHz to 1 kHz.

Figure 1 shows the schematic diagram of the IDA 200 system measurement, a digital signal processing (DSP) unit generates a test signal with the desired frequency. This signal is amplified with an internal amplifier and then applied to the specimen. The voltage over and the current through the specimen are measured with high accuracy using a voltage divider and an electrometer.

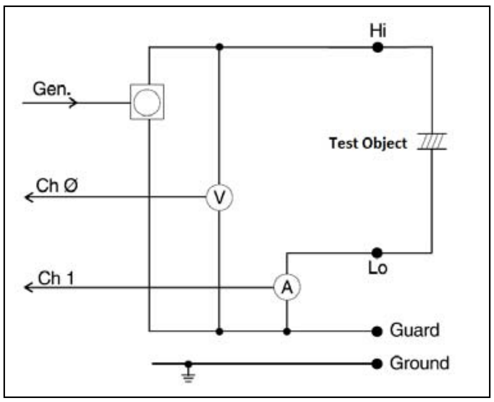

Figure 1. Schematic block diagram of the IDA 200-system measurement

Frequency domain spectroscopy allows distinguishing different materials at different frequencies. Each frequency at which measurements have to be performed requires an own measurement at stationary conditions. The prevailing method of representation consists in plotting the C-tanδ frequency scans in a log/log scale as depicted in Figure 2.

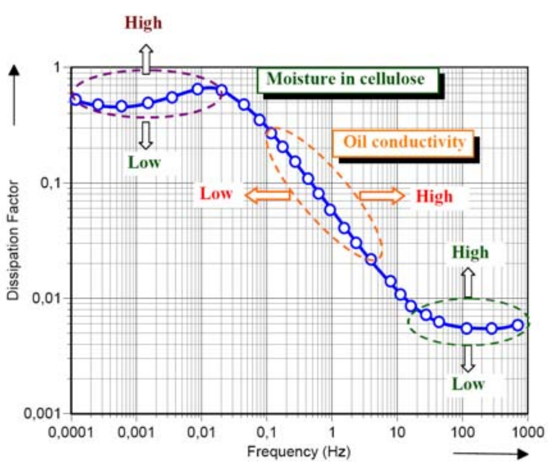

Figure 2. Separate impacts of oil conductivity and moisture in cellulose on Frequency Domain Spectroscopy (FDS).

It is important to notice that different parts of the response, in frequency axis, are separately sensitive to properties of oil and solid parts of the insulation, as illustrated in Figure 2. At the very low frequency range (< 10^{-2} Hz), the response is mainly influenced by the properties of the pressboard. The same is true for the higher frequency range (> 10 Hz) [13]. The central part of the response is, on the other hand, influenced by the properties of the oil, mainly by its conductivity.

3 EXPERIMENTAL SETUP

Figure 3 shows the test arrangement used during the FDS measurements system by IDA 200. During the experiments, the temperature inside the oil impregnated paper (OIP) bushing was recorded via a Pt 100 temperature sensor by acquiring the data using a LabVIEW™ program.

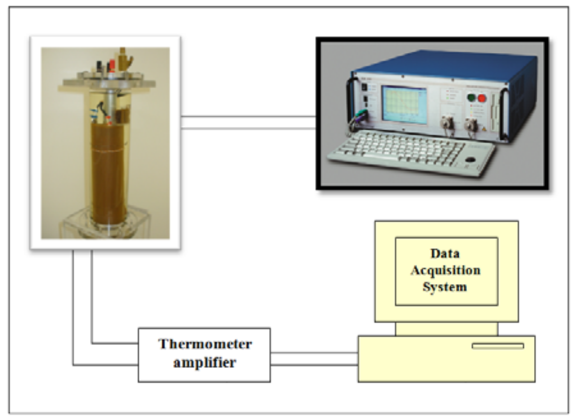

Figure 3. Test arrangement for the FDS and temperature measuring

The test object consisted in a laboratory made oil paper condenser. This bushing model was constructed by wrapping a conductor with cellulose paper and aluminium foils to get concentric capacitance layers in series. Cellulose paper used in the OIP laboratory bushing model was a Diamond Pattern Paper (DPP), manufactured by Weidmann [12] having a thickness d_{layer} = 0.125 mm and a dielectric value $V_{B,layer}$ = 8.5 kV, performed according to ASTM D-202, Section 143. The oil paper condenser model was carefully dried under vacuum (<1 mbar, 48 hours at 105 °C) before impregnation.

Then, impregnation with degassed and dried commercial grade mineral oil was performed. In order to investigate the influence of thermal transient on the FDS measurement, the following scenario is considered for an onsite measurement: the equipment is switched off, the dielectric measurement starts at a temperature of 65°C and in the end of the measurement the transformer is at 25°C. A mechanical convection oven was used in this study. Four series of experiments were carried out. Three at constant temperatures, that is the initial (25°C), the final (65°C), and an average temperature (42°C); and another experiment under

thermal runaway conditions, that is for a temperature decreasing from 65 to 25°C.
Performing the FDS measurements just after temperature settlement to constant value (25, 42 or 65°C) will not reflect the true insulation condition, since complex dynamic processes occur as moisture diffuses. Consequently, reasonable time delay (about 2 weeks) has been given before commencing measurements, to attain stable temperature and moisture equilibrium. The moisture content was controlled immediately after each measurement by Karl Fisher titration. Table 1 shows the values of moisture content at the end of each experiment.

TABLE 1. Moisture content inside paper measured, by Karl Fisher titration at the end of each experiment.

Temperature (˚C)	Paper moisture content inside paper (%)
Constant at 25°C	3.7
decreasing from 65 to 25°C	3.1
Constant at 65°C	2.2
Constant at 42°C	3.2

4 RESULTS AND DISCUSSIONS

IDA 200 was used to evaluate frequency scan of insulation material properties in a large frequency range, starting from 0.1 mHz to 1 kHz. The frequency scans of the capacitance, dissipation factor, real and imaginary part of the permittivity, were measured along the insulation temperature.

4.1 Effect of temperature on insulation parameters

For constant temperatures, the frequency scans of the capacitance and dissipation factor are represented in Figures 4 and 5.
Out of Figure 2, it can be seen that below 1 Hz the capacitance values increase with decreasing frequency. Low frequency measurements appear to be very helpful for accurately monitoring the condition of insulation. This is agreement with investigations reported by other authors [10,15,15]. The capacitance values increase with temperature at low frequency and tend to saturation at higher frequencies.

The Dielectric Dissipation Factor (DDF) is plotted in Figure 5. It is evident that DDF increases with temperature and contrary to the capacitance results; there is significant variation at all frequencies.

It can be seen that there is no linear increment in the dissipation factor results when increasing the insulation temperature. This can be seen in the capacitance scan results at very low frequencies. The complex permittivity can be used to characterize the insulation. This is a dimensionless quantity consisting of a real part ε' representing the energy stored in the electric field within the sample, and an imaginary part ε" representing the energy losses [9].

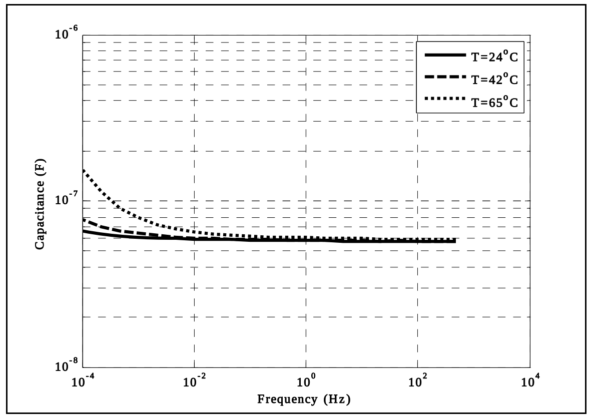

Figure 4. Effect of temperature on capacitance value.

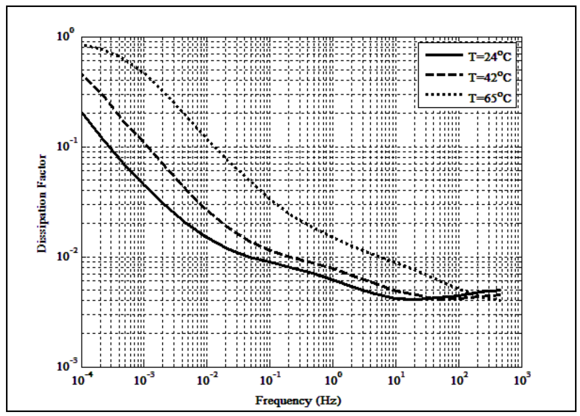

Figure 5. Effect of temperature on dissipation factor.

Figures 6 and 7 show the real and imaginary parts of the complex permittivity for different temperatures.

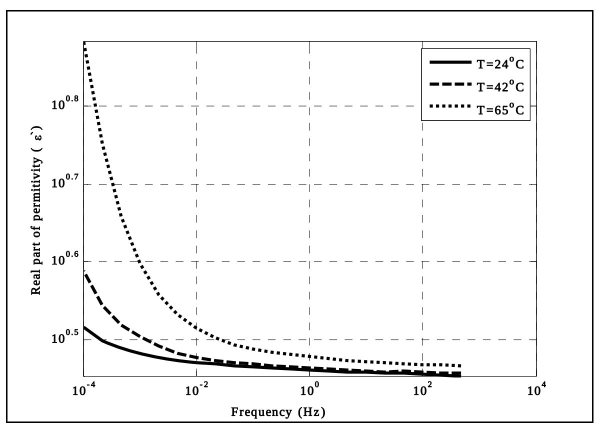

Figure 6. Effect of temperature on real part of permittivity.

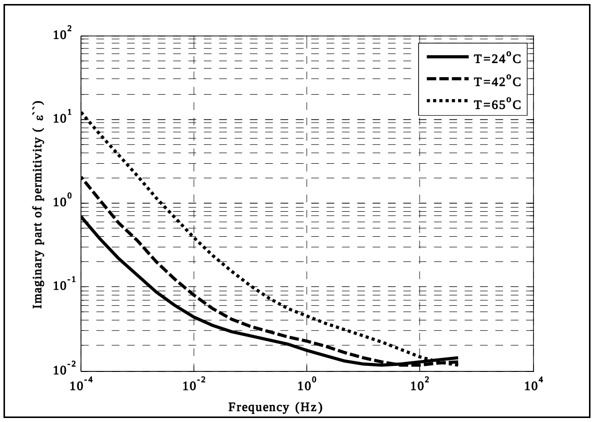

Figure 7. Effect of temperature on imaginary part of permittivity.

Their behaviours are similar to that of the capacitance and dissipation factor (Figures 4 and 5) for real part values, the difference is large at low frequencies. This increase could be due to increased losses at low frequency.

4.2 Effect of temperature transition on insulation parameters

Figures 8 to 11 show, respectively the frequency scans of capacity, dissipation factor, real and imaginary part of the permittivity under two constant temperatures (24°C and 65°C) and, a thermal runaway (from 65 to 24°C).

In the all figures it can be observed that during the temperature transition, FDS result starts with 65°C and at the end of the test, tend to the values measured at 24°C.

By knowing the frequency, time and temperature of the separation point, the test results can be better interpreted.

By measuring these points in the Figures 8 to 11, it has been found that the average frequency of the separation point is about 0.004 Hz By measuring the frequency-time relation of the IDA200 system, the time to reach this point is about 1241 seconds and regarding to the temperature recorded by Labview system, at this time the object has a temperature of 53°C.

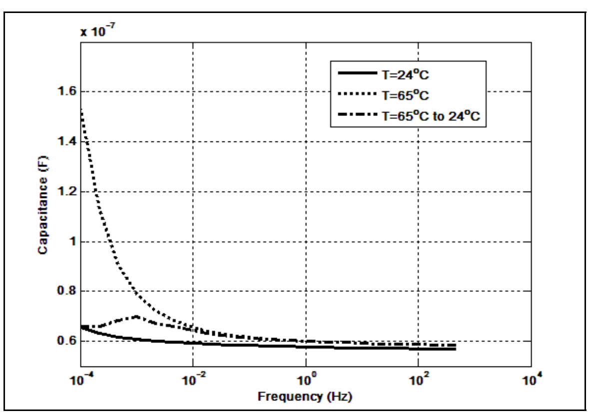

Figure 8. Effect of temperature transition on capacitance value.

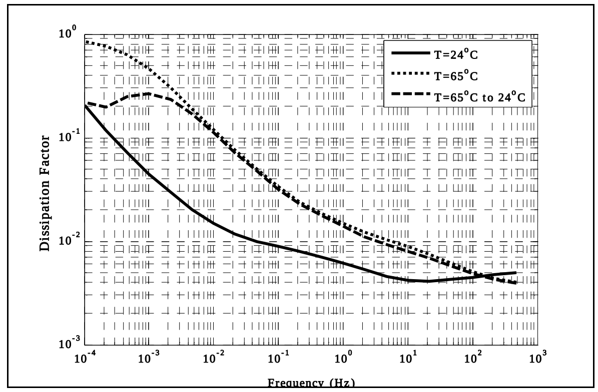

Figure 9. Effect of temperature transition on dissipation factor.

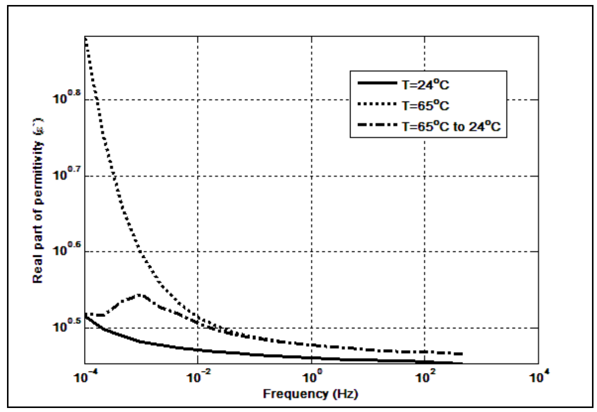

Figure 10. Effect of temperature transition on real part of permittivity.

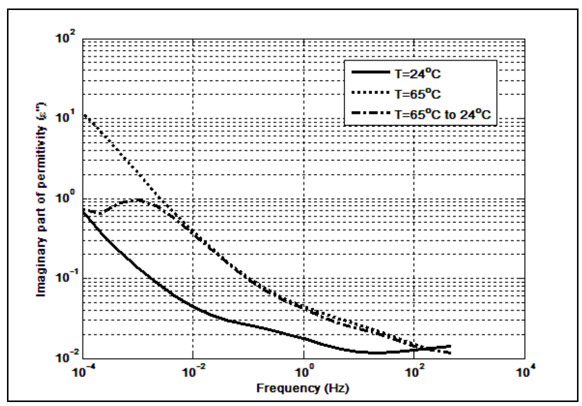

Figure 11. Effect of temperature transition on imaginary part of permittivity.

Therefore, the thermal runaway results start with starting temperature (65°C) and leave it when the temperature falls down to 53°C and continue to reach the final temperature results.

5 CONCLUSION

The advantage of dielectric spectroscopy with frequency scan is that the measurements are very reliable and the obtained results give more accurate evaluation of the insulation system than the measurements performed only at power frequency. Interpretation of FDS test results still remains a difficult task as it is believed to be influenced by various parameters including insulation ageing condition, moisture content and also by environmental condition like the operating temperature. In this paper, the frequency domain spectroscopy (FDS) has been used to investigate dielectric response of oil paper insulation under thermal runaway. The obtained results show that temperature of insulation has great influence on the FDS measurements. Analyzes have also shown that better interpretation is obtained when using the temperature values registered at the beginning of the measurements. However it would be worth investigating if the interpretation of the results would benefit from a compensation of the temporally varying temperature.

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7 REFERENCES

[1] D Woodcock, “Risk-Based Reinvestment - Trends in Upgrading the Aged T&D System”, available online: http://www.energypulse.net/centers/article/article_display.cfm?a_id=638

[2] T. K. Saha and P. Purkait, “Investigations of Temperature Effects on the Dielectric Response Measurements of Transformer Oil-Paper Insulation System”, IEEE Trans. on Power Delivery, Vol. 23, No. 1; 2008, pp. 252-260.

[3] U. Gafvert, “Condition assessment of insulation systems: analysis of dielectric response methods”, [Digests of Nordic Insulation Symp. Trondheim, Norway, 1996].

[4] W.S. Zaengl, “Dielectric Spectroscopy in Time and Frequency Domain for HV Power Equipment, Part I: Theoretical Considerations”, IEEE Elec. Insul Magazine, Vol. 19 No. 5, 2003, pp. 5-19.

[5] Zaengl, W.S. “Application of Dielectric Spectroscopy in Time and Frequency Domain for HV Power Equipment”, IEEE Elec. Insul. Magazine, Vol. 19 No. 6, 2003, pp. 9-22.

[6] T. K. Saha, “Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers”, IEEE Trans. on Diel. and Elec. Insul. Vol. 10, No. 5; 2003, pp. 903-917.

[7] A. Küchler and T. Bedel, “Dielectric diagnosis of water content in transformer insulation systems,” Eur. Trans. Electr. Power, vol. 11, No. 1, 2001, pp. 65–68.

[8] A. Seytashmehr, I. Fofana, C. Eichler, A. Akbari, H. Borsi and E. Gockenbach, “Dielectric Spectroscopic Measurements on Transformer Oil-Paper Insulation under Controlled Laboratory Conditions”, IEEE Trans. on Diel. and Elec. Insul., Vol. 15, No. 4, pp. 1100-1111, 2008.

[9] A. Bouaïcha, I. Fofana, M. Farzaneh, A. Seytashmehr, H. Borsi, E. Gockenbach, A. Béroual and N. T. Aka, “On the Usability of Dielectric Spectroscopy Techniques as Quality Control Tool”, IEEE Electrical Insulation Magazine, Vol. 25, No. 1, 2009, pp. 6-14.

[10] Cigre Task Force 15.01.09: “Dielectric Response Methods for Diagnostics of Power Transformers”, Electra No. 202, 2002, pp. 25-36.

[11] M. de Nigris, R. Passaglia, R. Berti, L. Bergonzi and R. Maggi, “Application of modern techniques for the condition assessment of power transformers”**,** [Digests of the CIGRE Session 2004, Paper A2-207, Paris, 2004].

[12] Weidmann Electrical Technology, "Metric data sheet, diamond pattern data sheet".

[13] J. Blennow, C. Ekanayake, K. Walczak and S. M. Gubanski, "Field experiences with measurements of dielectric response in frequency domain for power transformer diagnostics", IEEE Transactions on Power Delivery, Vol. 21, No. 2, pp. 681-688, 2006.

[14] J. H. Yew, T. K. Saha, and 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, 2006.

[15] J. L. Wei, G. J. Zhang, M. Dong, H. B. Mu and Zh. Yan, "Research Progress on Insulation Condition Estimation for Oil-Immersed Power Transformer," Proceedings of 2008 International Symposium on Electrical Insulating Materials, pp. 32 - 35, 2008.