From Frequency Domain to Temperature Domain of Transformer Liquid Insulation

Diego M. Robalino
Megger North America
4271 Bronze Way
Dallas, TX 75237, USA

Raul E. Alvarez
IITREE – Laboratorio de Alta Tensión - FI
Universidad Nacional de La Plata
48 y 116 La Plata, Argentina

Abstract- **The dielectric response of the overall transformer insulation is an invaluable source of information for those involved in the manufacture, operation and maintenance of power and distribution transformers. One of the greatest advances in the use of the transformer insulation dielectric response is without a doubt the possibility of performing advanced diagnostics of the oil-paper insulation to determine the moisture concentration of the solid insulation and the quality of the liquid insulation. Moreover, based on the knowledge acquired, the dielectric response in the frequency domain allows correct definition of the thermal behavior of dielectric parameters such as power factor or dissipation factor. Dissipation factor or power factor are dependent on frequency and temperature. It is clear for field users that the thermal behavior of the dielectric parameters is related to the condition of the overall insulation system and not just to the construction or nameplate of the transformer. Therefore, the application of the dielectric response in the frequency domain is a more accurate method to determine the real thermal behavior of the power factor. In the context of this document, authors investigate different liquid insulation materials with different aging/quality conditions, their dielectric response in the frequency domain and the conversion of this response into the temperature domain.**

Index terms – liquid insulation, mineral oil, dielectric response, temperature, power factor, dissipation factor

I. INTRODUCTION

For over 20 years, power transformer manufacturers and field operators have witnessed the evolution of different testing and condition assessment technologies. The need for accurate and reliable information, along with minimum down time for evaluation, has triggered researchers worldwide to investigate, develop and improve different non-intrusive and non-destructive methodologies to benefit the entire electrical energy industry.

To ensure the safe and reliable operation of power transformers, the analysis of the insulation system is of utmost importance and in lieu of determining the unique condition of the unit under test (UUT), dielectric response methods in time and frequency domain are widely used nowadays [1, 2]. Historically, the analysis of oil samples have given operators good understanding of the condition of the liquid insulation inside the transformer. The great advantage of this method is that it avoids the need to remove the transformer from operation. However, the limitation of this method is that samples have to be carefully taken, temperature properly recorded and containers tightly sealed to be sent to laboratories for physical or chemical analysis in accordance with international standards. In North America ASTM and IEEE standards provide the necessary guidelines to perform the oil sampling, testing and interpretation of results.

The application of transformer oil analysis together with its dielectric response in the frequency domain and in the temperature domain is investigated in this document. Advances on dielectric response measurement in the frequency domain to minimize the effect of temperature variation and testing time are used for the experimental part of this work.

II. TRANSFORMER OIL

A. *Testing Transformer Oil*

Mineral oil, mainly used together with cellulose to build the complex insulation geometry of power transformers, is non-polar and non-dispersive. In order to properly serve the purpose of insulation and cooling, mineral oil should comply with the set of properties well described in the standards. Liquid insulation sampling does not require interruption of continuous transformer operation. Therefore, a diagnostics methodology capable of interpreting the liquid insulation condition in a fast and reliable manner is always going to be a convenient resource in the field.

Physical-chemical and dielectric analysis of the liquid insulation are essential [3, 4]. The limit requirements for transformer oil are well tabulated in [5]. A summary of the property requirements for new and service-aged mineral oil is presented in Table I. The recommended standard practices for sampling electrical insulating liquids can be found in ASTM D 923-07. Awareness of standard limits and correct testing practices derive in assertive decisions.

The neutralization number represents the total acid content in the oil. If higher than standard recommended values are observed, conductivity will increase, and so will the rate of metal corrosion of the transformer internals. Both factors shorten the life of the insulation system. Water content is also monitored and controlled to achieve adequate electrical strength, low dielectric loss characteristic and to minimize metal corrosion.

TABLE I
MINERAL OIL PROPERTY REQUIREMENTS

Property	Limit		ASTM Test Method
	≤69 kV	>69-<230 kV	
Dissipation Factor (Power Factor) @ 60 Hz, max % @ 25ºC for NEW OIL	0.05	0.05	D924
Dissipation Factor (Power Factor) @ 60 Hz, max % @ 100ºC for NEW OIL	0.4	0.4	
Dissipation Factor (Power Factor) @ 60 Hz, max % @ 25ºC for SERVICE-AGED OIL	0.5	0.5	D924
Dissipation Factor (Power Factor) @ 60 Hz, max % @ 100ºC for SERVICE-AGED oil	5.0	5.0	
Neutralization number, total acid number, max, mgKOH/g for NEW OIL	0.03	0.03	D974
Neutralization number, total acid number, max, mgKOH/g for SERVICE-AGED OIL	0.2	0.15	D974
Dielectric Breakdown Voltage @ 60Hz, VDE electrodes, min kV for NEW OIL (1mm)	25	30	D1816
Dielectric Breakdown Voltage @ 60Hz, VDE electrodes, min kV for SERVICE-AGED OIL (1mm)	23	28	D1816
Water, max ppm for NEW OIL	20	10	D1533
Water, max ppm for SERVICE-AGED OIL	35	25	D1533

A simple dielectric breakdown test in the field using VDE electrodes is sensitive to contaminants such as aging by-products and conductive particles in oil. Another simple test carried out in the field is dissipation factor (power factor) at line frequency using a test cell to determine the dielectric losses in the insulating liquid. Nevertheless, some of these practices may be misleading especially due to the effect of temperature. From this point forward, the dielectric response of the liquid insulation is discussed.

In [4] a comparative analysis between dielectric response in the time domain of the liquid insulation and physical-chemical properties of new and old oil samples were studied looking for a correlation. The time consuming measurement process and the consequent thermal variation of the oil sample were counterproductive for such comparative analysis and the conclusions were not definitive.

B. *Dielectric Response in the Frequency Domain*

The dissipation factor (DF) or power factor (PF) test method of electrical insulating liquids is described in ASTM D 924-08. The voltage level shall be maintained for comparative analysis and the frequency should be in the 45-65Hz range. Measurements are made at different temperatures- 100ºC for acceptance and 25, 85 and 100ºC for routine testing.

PF, DF (tan δ) and conductivity of the oil can be derived from the complex impedance measurement of the sample when an AC excitation signal is applied [6, 7]. DF is also expressed as the ratio of the imaginary and real components of complex permittivity as shown in (1)

$$\tan\delta(\omega,T)=\frac{\varepsilon''(\omega,T)}{\varepsilon'(\omega,T)} \tag{1}$$

where:
ε' – relative permittivity of oil
ε'' – loss factor

The complex permittivity of the liquid insulation is represented as a function of its relative permittivity and the conductivity in the dielectric response model in (2)

$$\hat{\varepsilon}_{oil}=\varepsilon'(\omega,T)-j\varepsilon''(\omega,T)=\varepsilon'-j\cdot\frac{\sigma}{\varepsilon_0\omega} \tag{2}$$

where:
$\hat{\varepsilon}_{oil}$ - complex permittivity of oil
ε_0 – permittivity of free space (8.84 pF/m)
σ - conductivity of oil
ω - angular frequency

Also, the activation energy of the sample can be calculated by consecutive measurement of DF or PF at different temperatures as a solution of the well-known Arrhenius equation [7, 8] if the material does not change inherently.

$$\tan\delta_T=\tan\delta_0\cdot e^{\left(-\frac{Ea}{k\cdot\Delta T}\right)} \tag{3}$$

The exponential behavior is true for the frequency response (4) as demonstrated in [7]. Activation energy becomes the key link between the frequency and the temperature responses.

$$\omega_T=\omega_0\cdot e^{\left(-\frac{Ea}{k\cdot\Delta T}\right)} \tag{4}$$

where:
E_a - Activation energy [eV]
k - Boltzmann constant (8.617x10^{-5} [eV·K^{-1}]
ΔT - Temperature difference
ω_0 - Angular frequency at reference temperature
ω_T - Angular frequency at temperature T

The influence of temperature on the dielectric response has been discussed in [1, 3, 6, 7, 9] and can be explained with a shift in direction of the frequency axis and a shift of direction on the permittivity axis. The frequency location of the peak in ε" defines the average relaxation time (τ) from where f_{max} is the frequency of maximum loss (5)

$$\omega_{max}(\tau) = 1 = 2\pi f_{max} \tag{5}$$

III. EXPERIMENTAL WORK

A. FR3 Analysis

The first step is to determine the geometrical capacitance of the test cell where experimentation is to be carried out, using (6)

$$C_{0_{CELL}} = \frac{A}{d} \cdot \varepsilon_0 \tag{6}$$

Once the geometrical capacitance of the test cell has been measured (62 pF in our experimental setup), the relative permittivity of the insulating liquid can be determined. The FR3 samples were tested using a HV capacitance and DF test set DELTA 4110 according to the ASTM D924 guidelines. The samples were heated up to 100ºC and PF values were recorded every 10ºC-interval while the sample cooled down.

The temperatures were selected to replicate possible field scenarios where testing can be performed. The dielectric responses in the frequency domain were obtained using the insulation diagnostic analyzer IDAX 300S and are presented in Fig. 1.

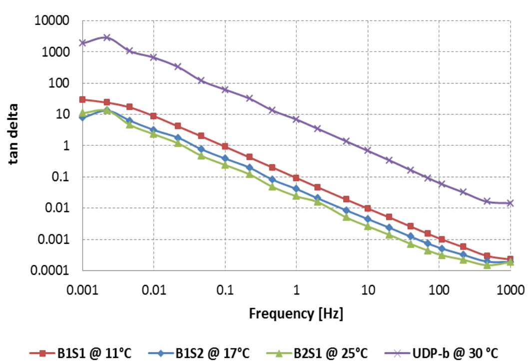


Fig. 1 Dielectric response of new FR3 samples measured at different temperatures.

Different samples of FR3 oil were prepared for dielectric frequency response (DFR) measurement. The DFR measurement is performed on samples of different conductivity. In order to prove the correlation between the DFR of the sample and the dielectric thermal response, the samples were tested as follows: UDP-b at 30ºC, B1S1 at 11ºC, B1S2 at 17ºC, and B2S1 at 25ºC.

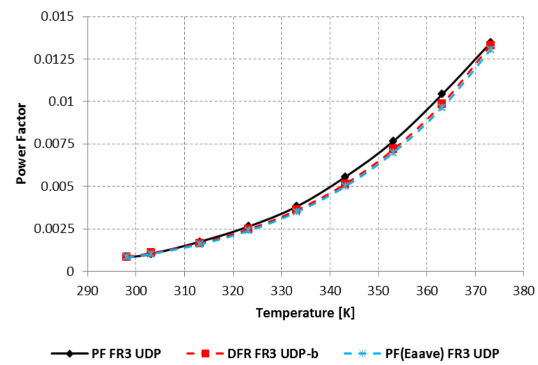
The activation energy of each sample was calculated according to (4) and an average value of the average activation energy of each sample was obtained and used later in (5) for comparative analysis.

The characteristics of the relevant FR3 samples used for this work are described in Table II.

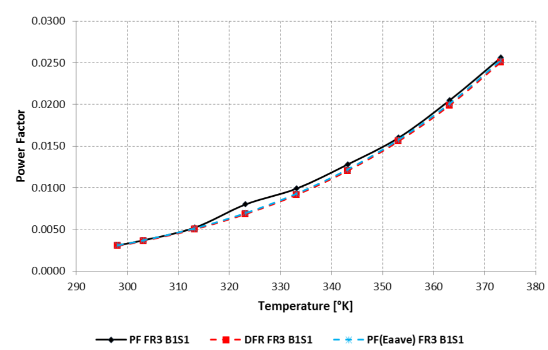
TABLE II
DESCRIPTION OF FR3 SAMPLES

Sample	ε'	Ea_{ave} [eV]	%tan δ 60Hz, 20ºC	σ [pS/m] @ 25°C
UDP-b	3.2	0.35	0.068	8.67
B1S1	3.0	0.36	0.244	26.0
B1S2	3.3	0.26	0.094	9.86
B2S1	3.0	0.27	0.04	4.65

The results presented in Fig. 2 (a), (b), (c) and (d) include the measured values of PF as a function of temperature, the calculated PF using the derived average E_a of each sample, and finally, the thermal response obtained from the DFR measurement on FR3 oil samples.



(a)



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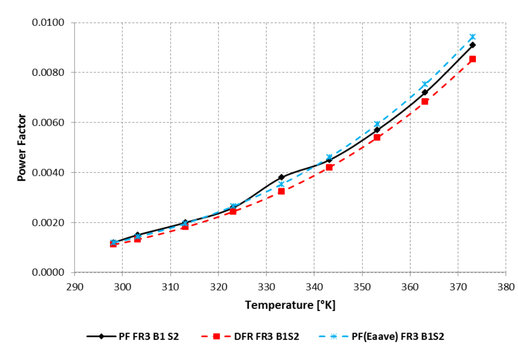
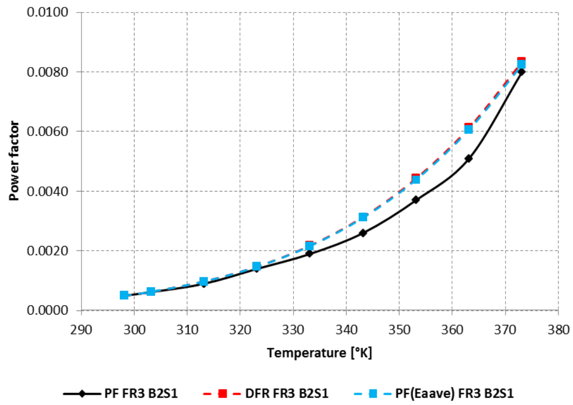


(c)



(d)

Fig. 2 Measured Power factor (PF), calculated power factor based on average activation energy (PF Ea_{ave}), and thermal response calculated from the frequency response using average Ea (DFR) for FR3 samples: (a) – UDP-b, (b) B1S1, (c) – B1S2, and (d) – B2S1.

B. *Mineral Oil Analysis*

Several publications address the analysis of the dielectric response of mineral oil. The application of frequency domain dielectric response provides faster measurement, especially with the introduction of multi-frequency sampling described in [10]. This reduces significantly the testing time, allowing for greater precision on the conversion from frequency domain to temperature domain.

Different samples of mineral oil (used and new) were analyzed using DFR measurement. The mineral oil samples were tested in a same way as the FR3 samples described above.

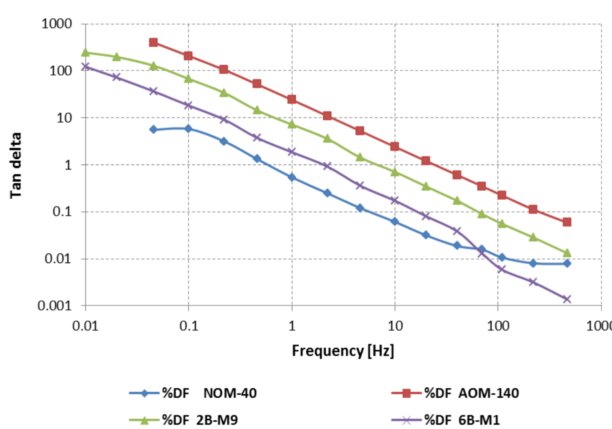


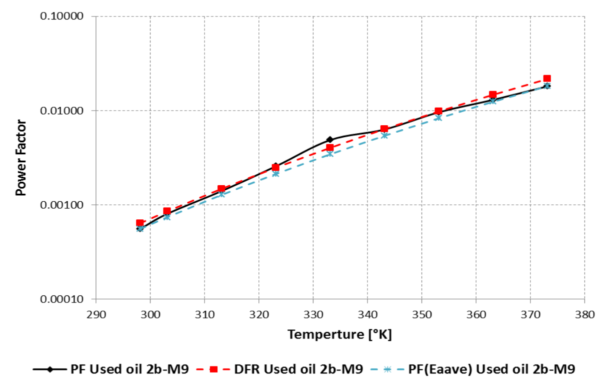
Fig. 3 Dielectric response of new and aged mineral oil samples measured at different temperatures

The samples represent different conductivity values and physical-chemical conditions. The samples were tested as follows: 6b-M1 at 22ºC, 2b-M9 at 34ºC, AOM-140 at 80ºC, and NOM-40 at 40ºC. The DFR measurement of the mineral oil samples is presented in Fig. 3.

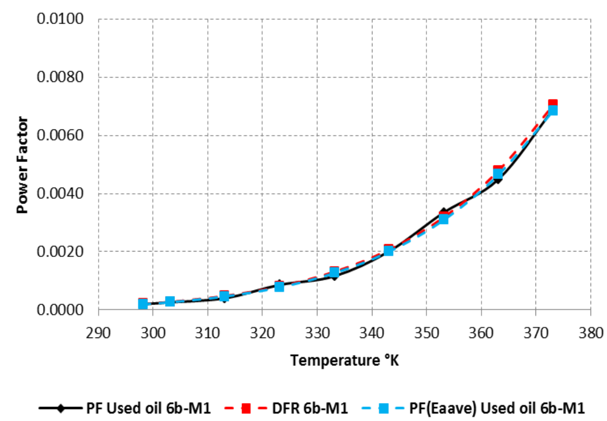
The characteristics of the relevant mineral oil samples used for this work are described in Table III.

TABLE III
DESCRIPTION OF MINERAL OIL SAMPLES

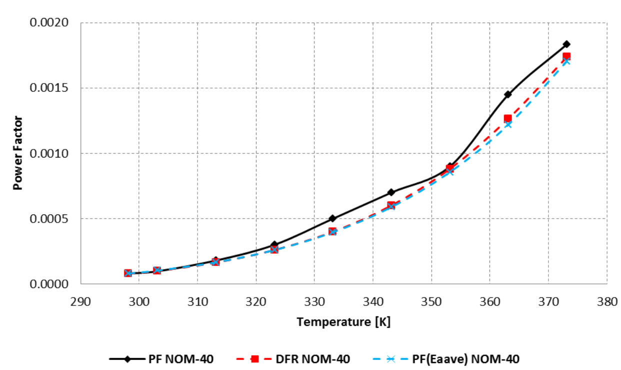
Sample	ε'	Ea_{ave} [eV]	%tan δ 60Hz, 20ºC	σ [pS/m] @ 25°C
2B-M9	2.19	0.38	0.048	4.94
6B-M1	2.23	0.45	0.015	2.4
NOM-40	2.24	0.39	0.006	0.532
AOM-140	2.22	0.45	0.028	2.61



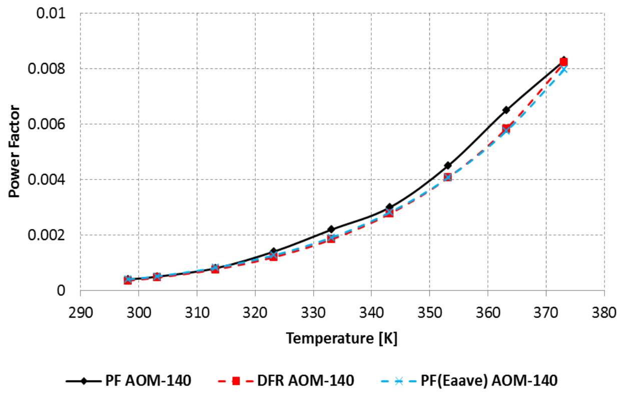
(a)



(b)



(c)



(d)

Fig. 4 Measured Power factor (PF), calculated power factor based on average activation energy (PF Eaave), and thermal response calculated from the frequency response using average Ea (DFR) for FR3 samples: (a) – NOM-40, (b) AOM-140, (c) – B1S2, and (d) – B2S1

The results presented in Fig. 4 (a), (b), (c) and (d) include the measured values of PF as a function of temperature, the calculated PF using the derived average E_a of each sample, and finally, the thermal response obtained from the DFR measurement on new and aged mineral oil samples.

C. The Use of Generic Values

In real life, operators may not have access to such detail as the one obtained here by experimental analysis. Therefore, it is fundamental to have a very good reference value for the specific type of insulating fluid being tested. The assumption of a single value of activation energy may lead to errors in the temperature compensation. The generic values used in the conversion from temperature domain into frequency domain are listed in Table IV

TABLE IV
GENERIC VALUES OF PERMITTIVITY AND ACTIVATION ENERGY

Type of oil	**ε’**	**E_a**
Mineral Oil	2.2	0.4 – 0.5
FR3	3.2	0.3 – 0.4

IV. CONCLUSIONS

The use of dielectric response in oil samples is a practical and simple approach to determine the thermal behavior of the liquid insulation dielectric parameters.

It has been proved in this work that the measurement of dielectric response of mineral oil and FR3 at any temperature is possible and the thermal response is attainable.

The use of the multi-frequency technique significantly reduces the testing time, it applies only in the dielectric response and it reduces the thermal gradient during the test.

Application of generic values is feasible in the field. The activation energy and the relative permittivity values of the oil sample are the guidelines for accurate estimation of the thermal behavior of dielectric parameters such as PF or DF.

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