ABSTRACT

Dielectric testing techniques in the time and frequency domains are increasingly being used by transformer manufacturers, power utilities and researchers for transformer oil-paper insulation systems condition assessment. Since 1997, when the first portable device designed to carry out dielectric response tests in the frequency domain in the field was put on the market, the technology has evolved and new features have been incorporated. One of these features is becoming a "must have" tool for power transformer dielectric condition assessment: individual temperature compensation.

KEYWORDS

dielectric response, temperature correction, power factor, dissipation factor

Individual temperature compensation

Benefits of dielectric response measurements

1. Introduction

A healthy insulation condition of an electrical apparatus is essential for the operational reliability of the entire electrical power network. Transformers are without a doubt one of the most critical components in the system and, for this reason, a great amount of research has been performed to better comprehend the values

obtained in routine dielectric tests such as power factor / dissipation factor (tan delta). Power factor is widely used among operators and manufacturers to set a reference value for the losses encountered in the insulation material.

Typically, Dissipation Factor (DF) or Power Factor (PF) tests are carried out at power frequency of 50/60 Hz. A voltage is applied to one electrode of the capacitive system and the total resulting current is measured. From there, the angle between the total current vector and the applied voltage vector is obtained and the cosine function given in percentage values is the power factor value of the tested capacitance. In this test, the power factor value is a function of frequency. The capacitive reactance of the object is directly related to the excitation signal frequency and therefore, a power factor test should be comparable if performed at the same frequencies. But frequency is not the only factor affecting the power factor value.

When repeating the power factor test on the same specimen, if moisture, oil condition and aging have not been altered, but the temperature of the system changes, the power factor will change as well, and the values at two different temperatures will not be comparable. In order to be comparable, the PF values must be normalized to a 20 °C reference. Therefore, temperature has a significant effect on the resulting value of the power factor and this fact should be taken into account and improve the existing methods used to compensate power factor measurements for temperature variation.

This article provides a background on dielectric response measurements in the Frequency Domain (DFR), also known as Frequency Domain Spectroscopy (FDS), and the advantages of using this testing technique in liquid–filled power transformers to assess their insulation system condition, as well as to obtain the "unique" individual thermal response of the capacitive system analyzed.

Dielectric response measurement in the frequency domain provides a tool to better interpret the thermal behaviour of the dielectric characteristics of oil-paper insulation systems

2. The routine dissipation factor / power factor test at power frequencies

The PF and capacitance test is one of the most effective methods of assessing the overall condition of a transformer. An AC signal is applied to the insulation system at a voltage high enough to allow easy measurement under substation interference conditions, but not too high as to stress the system. Test voltages in the field test instrument range from below 100 V to as high as 12 kV. Field tests are usually performed at rated voltage or a maximum of 10 kV. The AC signal is typically applied at two different frequencies which are very close to the power frequency. The use of two different frequencies is called frequency variation suppression mode, and instead of running one single test at power frequency (50 or 60 Hz), the test is carried out at two frequency values close to the reference line frequency. The AC capacitance test is part of the PF test because the capacitance value and its associated charging current are required to calculate the PF value of that specific capacitive (insulating) system later.

PF testing of transformers is carried out to assess the level of contamination of the insulation system and reference limits have been set in international standards [1] [2] to determine the possibility of dielectric degradation/contamination or mechanical damage of the insulation material. Following the limits set by the different international references [3] [4], PF is a trigger to announce potential accelerated aging or degradation of the insulation system.

It is necessary for this test to record the insulation system temperature to later normalize measured values to the 20 °C reference. The dissipation factor of insulation can be more or less sensitive to the effect of temperature depending on the condition of the bulk insulation system. So far, the method used to normalize power

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factor values obtained at temperatures different from 20 °C has been to apply correction factors. Correction factors may be available from equipment manufacturers and test equipment manufacturers and are only based on nameplate data. Generic correction factors were available in IEEE standard C57.12.90-2006, section 10.10.5, but were removed in C57.12.90-2010 [5] with the following note on page 48:

"NOTE 3.b) Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases."

A PF test at power frequency by itself is capable of detecting moisture and contamination in a transformer; however, it cannot differentiate whether the source of power factor values beyond recommended limits or in an unexpected accelerated growth from historical values correspond to moisture in the solid insulation or contamination on the liquid insulation. Further analysis is performed to investigate the cause of values beyond the established limits and field users should perform other tests including physicochemical analysis of oil, DGA and of course DFR.

The recommended limits for new and service aged power transformer insulation power factor at 20 °C are detailed in Table 18 of IEEE C57.152-2013 [1], and are presented in Table 1:

3. Temperature dependence

To be able to determine the correct temperature correction factor, the temperature dependence of the insulation system must be investigated. The susceptibility of the insulation material can be expressed as a function of frequency and temperature [6]:

$$X(\omega,T) = A(T)\cdot F\left(\frac{\omega}{\omega_c(T)}\right) \qquad (1)$$

Where *A(T)* is a temperature dependent amplitude factor, *F(x)* a spectral function and $\omega_c(T)$ a characteristic frequency. *A(T)* is constant for cellulose. It means that the shape of the spectrum remains unchanged at different temperatures. The dielectric response moves to higher frequency with temperature increase, or conversely, to higher temperature as frequency increases. One can obtain the same effect by increasing the frequency or increasing the temperature. However, the shape is usually not changed. In the special case of an ideal Debye function, the complex permittivity can be written as:

$$\varepsilon = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + j\omega\tau\cdot e^{\left(-E_a/kT\right)}} \qquad (2)$$

Where E_a is the activation energy, a term best regarded as an experimentally determined parameter that indicates the sensitivity of the reaction rate to temperature, *k* is the Boltzmann constant (8.6173324(78) x10^{-5} eVK^{-1}); and, τ is the relaxation time. From (2) it is clear that the permittivity is a function of $\left(\frac{-E_a}{kT}\right)$ in the logarithmic scale.

The activation energy of oil-impregnated cellulose is about 0.9-1.1 eV, while mineral oil has activation energy of 0.4-0.5 eV. The general shape of the curve is often preserved if the data is plotted on a log-log scale.

The correction factor curves for different temperatures and three different activation energies are shown in Fig. 1.

Equation (1) indicates that the increase of temperature has the same effect as the increase of frequency. To what extent they are related to each other is represented by the activation energy as presented in (2). The curves are examples showing that for a certain increase of temperature, the material with larger activation energy needs to be measured at higher frequency in order to obtain the same permittivity.

4. The influence of moisture in the cellulose

Dielectric response measurements together with insulation mathematical modelling using the so called XY-model [3] are today one of the preferred methods for measuring moisture content of the cellulose insulation in power transformers. The results are normally presented as capacitance and/or dissipation factor / power factor versus a wide frequency spectrum that typically ranges from 1 kHz down to 1 mHz.

New power transformers are expected to have no more than 0.5 % moisture

Table 1. Power factor recommended limits for power transformers as per IEEE C57.152-2013

Insulating liquid	kV rating	Nominal/New PF limit	Serviceability aged limit
Mineral oil	< 230 kV	0.5 %	1.0 %
Mineral oil	≥ 230 kV	0.4 %	1.0 %
Natural ester	All	1.0 %	1.0 %

"The numbers shown here for natural esters are only provisional as there are no correction curves established by the industry yet."

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concentration in cellulose. Throughout service life, normal aging process and the factors stressing the insulation in the transformer will increase the moisture concentration in the cellulose. Operators worldwide will prefer not to exceed 3.5 % moisture in cellulose, as it severely increases the aging process and the risk of failure.

An example of a combined mineral oil and paper insulation inter-winding capacitance is shown in Fig. 2. The moisture concentration of the sample is 1 % and measurements are taken at 5, 20, 35 and 50 °C.

Taking only the 60 Hz values and collecting those in a table, one can see that the PF at 60 Hz may only increase or decrease depending on the temperature condition of the insulation, and, in this case, where the specimen is with only 1 % moisture concentration, the correction factor along the thermal spectrum of 5 °C and 50 °C is very close to unity. The obtained values can be summarized in Fig. 3 and Fig. 4.

The temperature-frequency model makes possible the normalization of dielectric parameters such as power factor / dissipation factor to the selected reference temperature (20 °C) at the selected frequency (50 or 60 Hz)

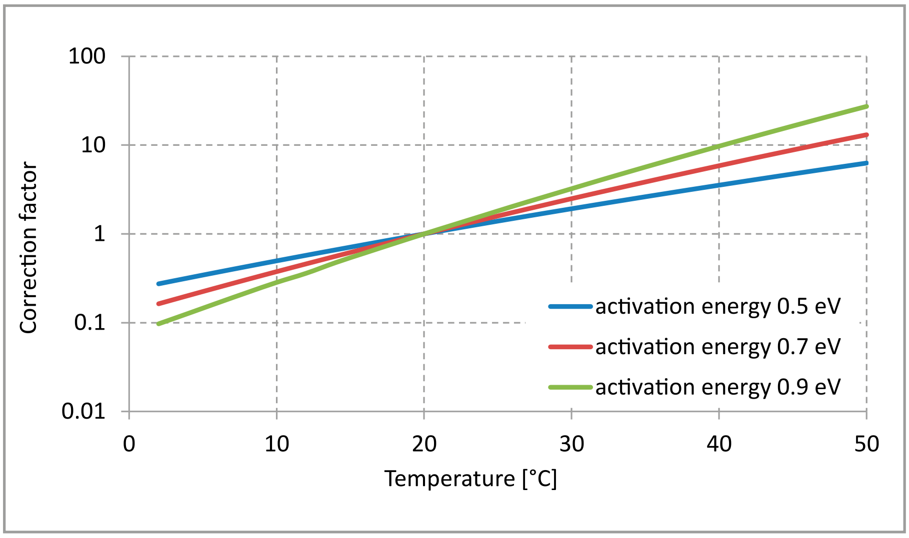

Figure 1. Correction factor curves for different activation energy values

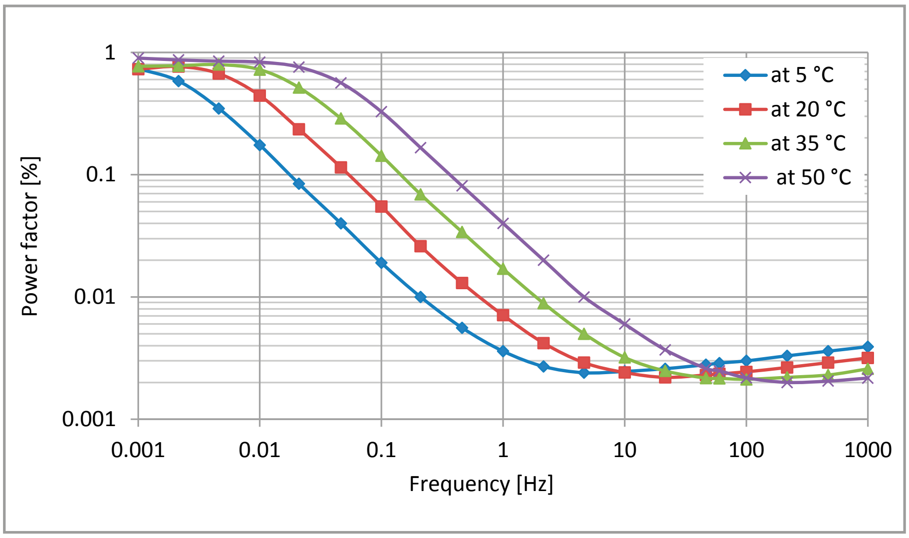

Figure 2. Dielectric response in the frequency domain for a sample with 1 % moisture concentration in the cellulose at 5, 20, 35 and 50 °C

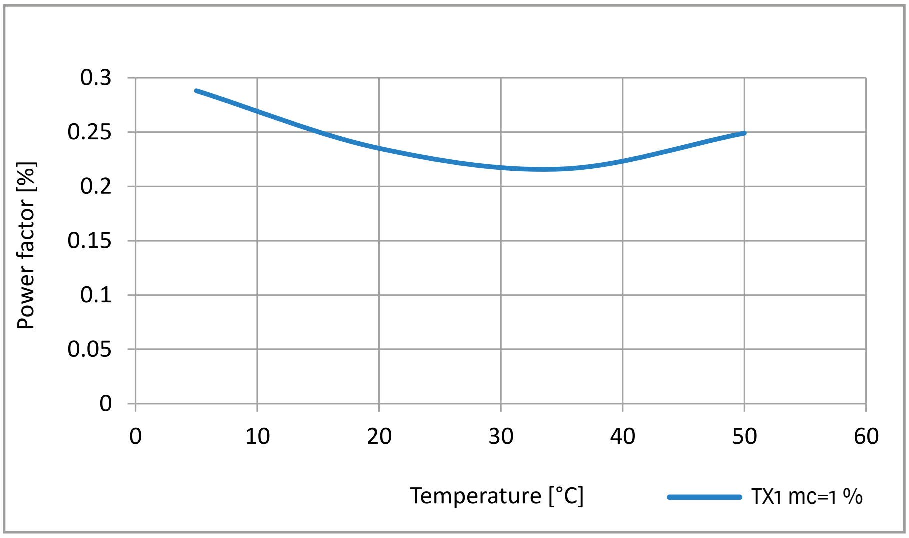

Figure 3. Thermal behaviour of the PF for the sample with 1 % moisture concentration in the cellulose

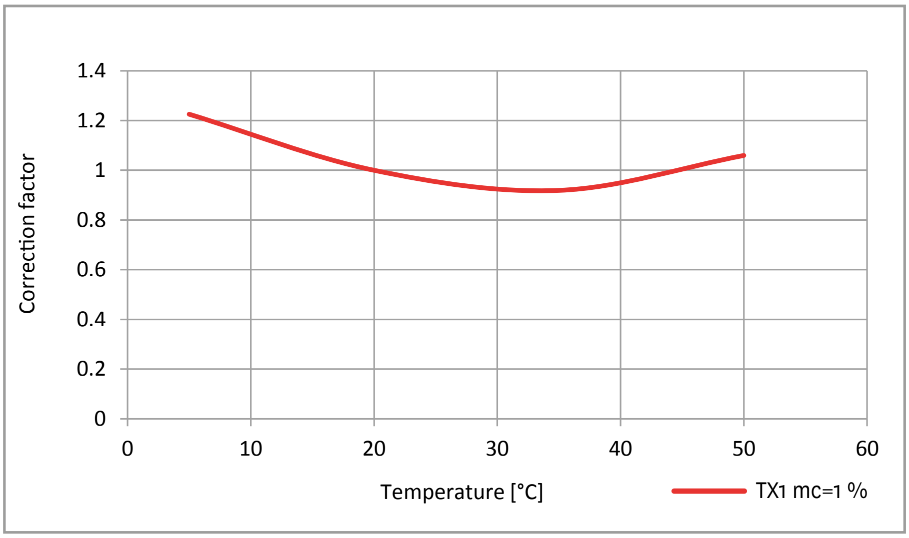

Figure 4. Correction factors for PF based on thermal behaviour for the sample with 1 % moisture concentration

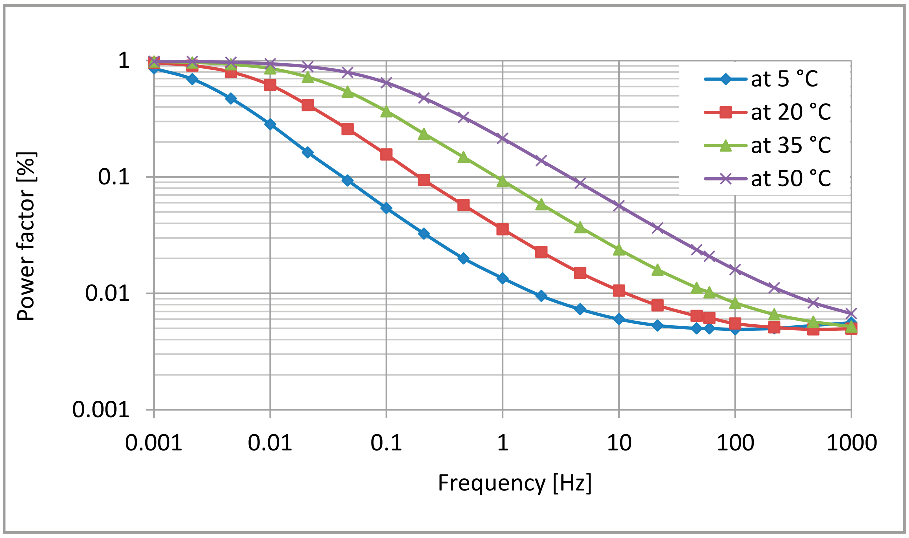

Figure 5. Dielectric response in the frequency domain for a sample with 3.5 % moisture concentration in the cellulose at 5, 20, 35 and 50 °C

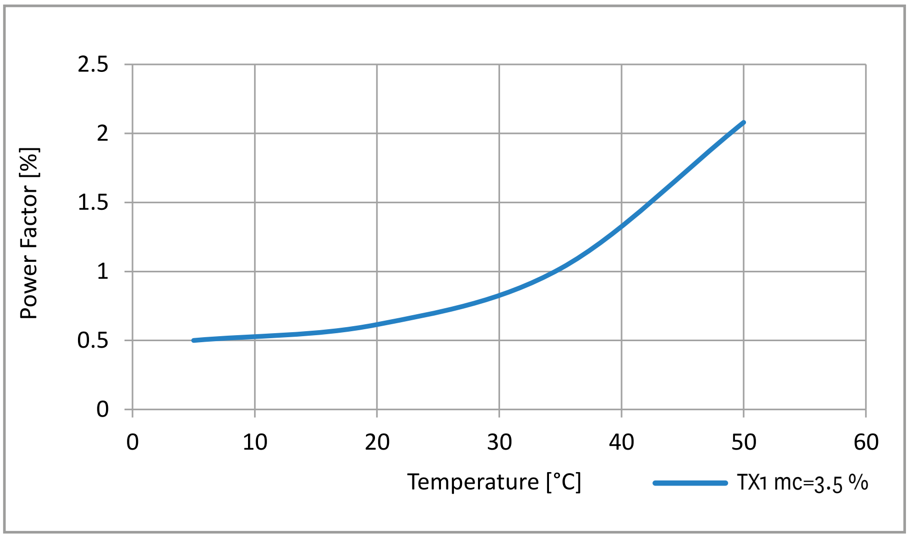

Figure 6. Thermal behaviour of the PF for the sample with 3.5 % moisture concentration

> **The temperature correction factor is not a single curve for all conditions**

Important to highlight here is that all the dielectric responses shown in Fig. 2 develop only one thermal response, as shown in Fig. 3.

The same sample tested at high moisture concentration (3.5 %) in the same thermal spectrum provides a different dielectric response (Fig. 5).

Following the same procedure as that with a low moisture concentration, the power factor values measured at 60 Hz are presented separately in Fig. 6 and Fig. 7.

As it can clearly be seen, the temperature correction factor is not a single curve for all conditions. Aging, moisture and contamination will have an effect on the dielectric response and one main way to obtain an accurate normalization of power factor values is by using DFR's feature - individual temperature compensation. The dielectric response of a fluid-filled transformer is unique, as is its dielectric thermal behaviour. Incorrect correction of power factor values may lead to erratic decisions overestimating its value or underestimating the risk of failure.

Conclusion

The dielectric frequency response method is nowadays widely used to estimate the moisture concentration of the solid insulation in fluid-filled transformers in terms of capacitance and dissipation factor as a function of frequency. The measured power factor at one specific frequency of an insulation system depends not only on temperature, but also" on the individual condition of the insulation system under test. When the test is restricted to power frequency measurements only, the accurate effect of temperature is unknown.

The dielectric frequency response taken at only one voltage level and constant temperature allows conversion from the frequency domain into the time domain

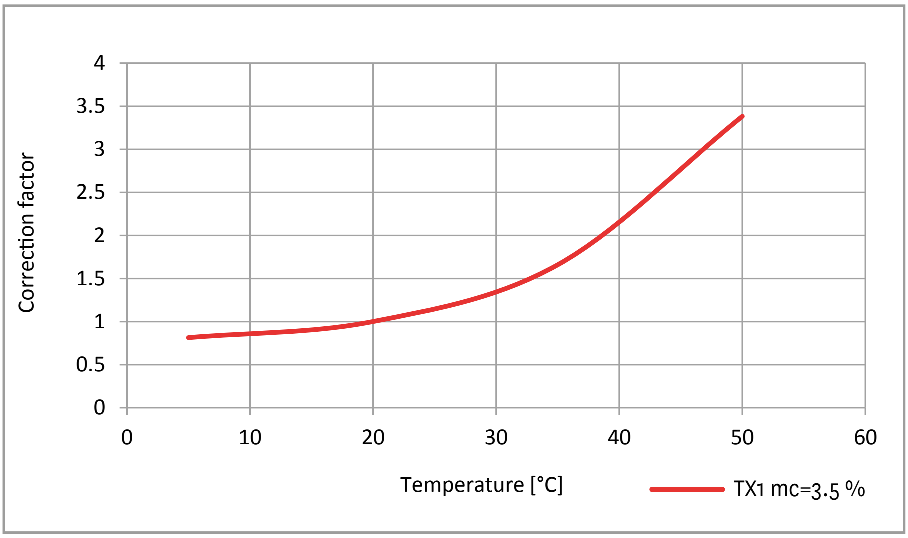

Figure 7. Correction factors for PF based on thermal behaviour for the sample with 3.5 % moisture concentration

and, as it has been demonstrated in this article, from frequency domain to the temperature domain. The temperature-frequency model is essential because it makes possible the normalization of dielectric parameters such as power factor / dissipation factor to the selected reference temperature (20 °C) at the selected frequency (50 or 60 Hz). An extended application of the mathematical approach allows normalizing power factor values to any temperature between 5 °C and 60 °C at any frequency value within the frequency measurement range.

Bibliography

[1] IEEE C57.152 – 2013 Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors

[2] NETA ATS – 2013 Standard for Acceptance Testing Specifications for Electrical Power Equipment and Systems

[3] CIGRE TB 445 - Guide for Transformer Maintenance

[4] IEEE Std C57.106-2006 Guide for Acceptance and Maintenance of Insulating Oil in Equipment

[5] IEEE Std C57.12.90-2010 - IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

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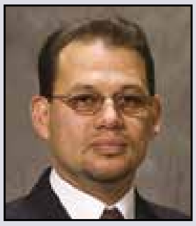

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