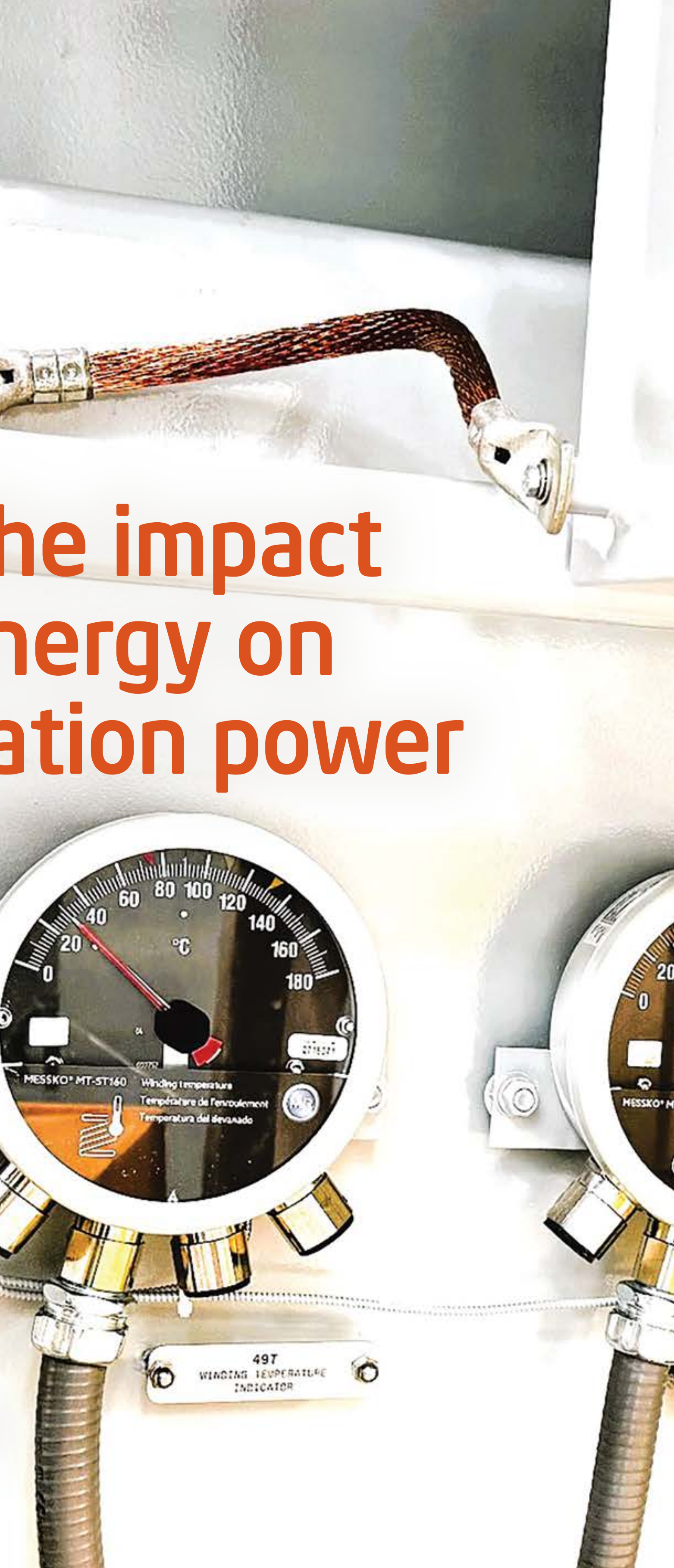
Investigating the impact of activation energy on dielectric insulation power factor

Existing power factor temperature correction methods may be overlooking the key role of activation energy

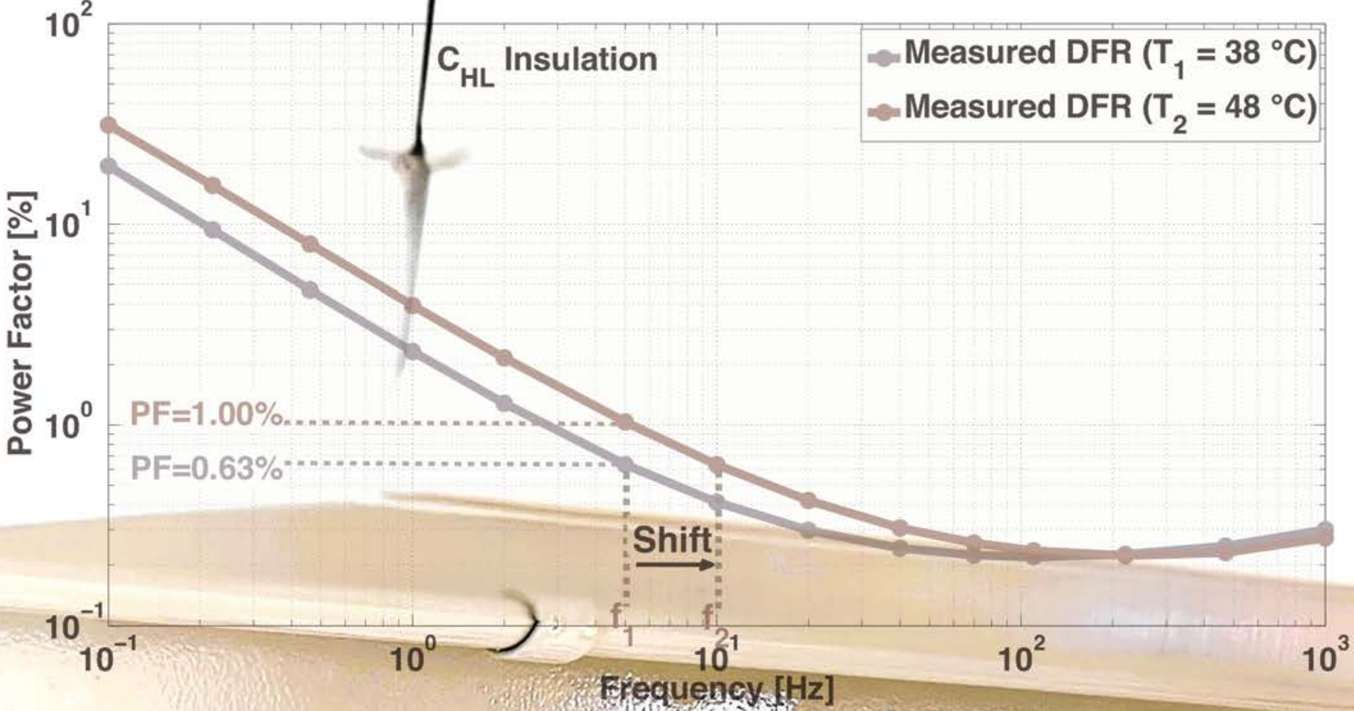


ABSTRACT

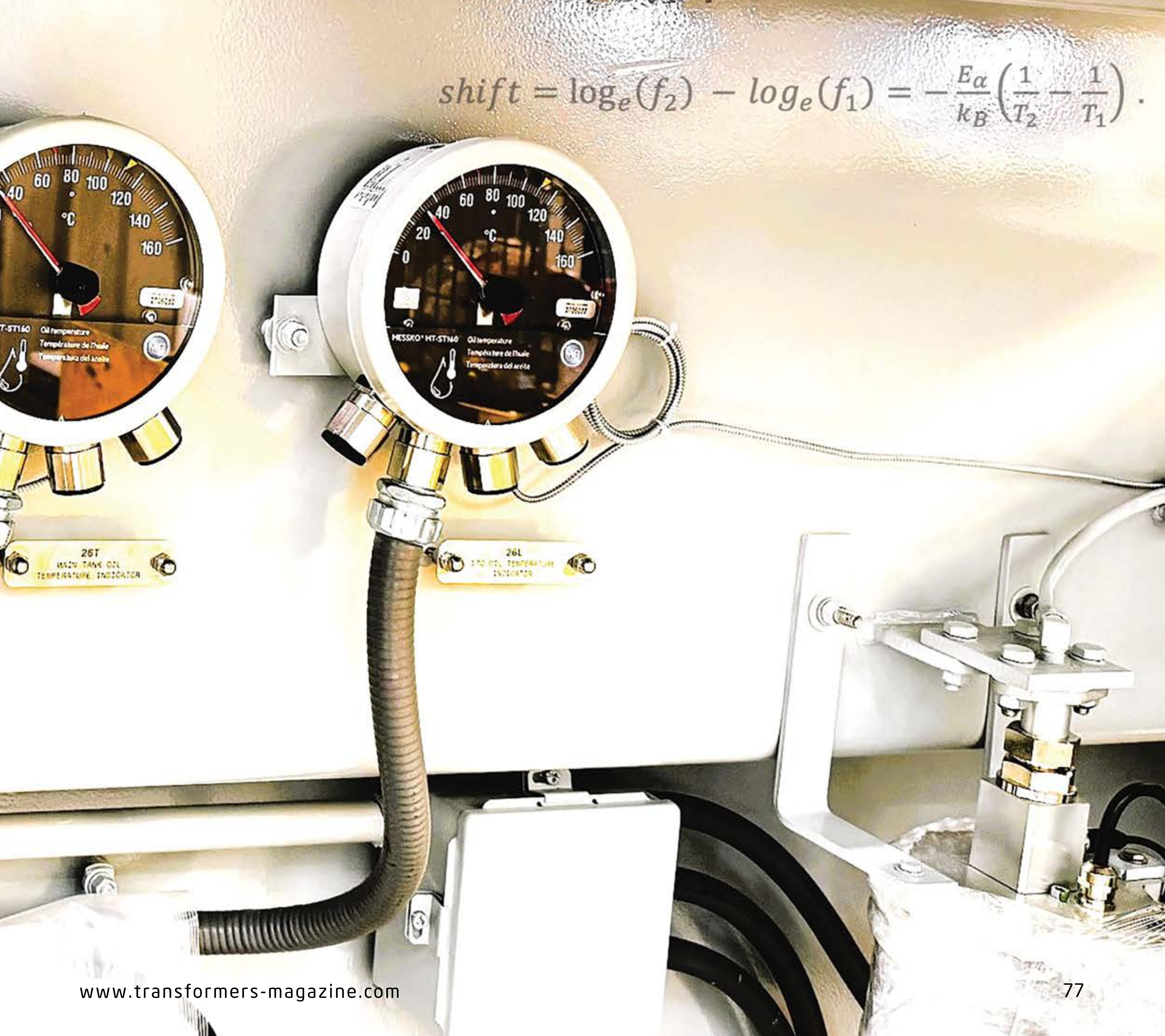
The dielectric frequency response of insulation in power system apparatus is influenced by frequency and temperature [1]. Specifically, temperature is governed by a parameter known as activation energy. This article explores the significance of activation energy in estimating the power factor of dielectric insulation over a range of temperatures and frequencies when using the Arrhenius equation. Several case studies with empirical data are presented to support this investigation.

KEYWORDS:

activation energy, power factor, temperature correction, Arrhenius equation, insulation



$$shift = \log_e(f_2) - log_e(f_1) = -\frac{E_\alpha}{k_B}\left(\frac{1}{T_2} - \frac{1}{T_1}\right).$$



DFR and VFPF tests are dependent on frequency and temperature, with the latter being influenced by a parameter called activation energy Eα

Introduction

When testing insulating materials, the response of the dielectric in the frequency domain is referred to as Dielectric Frequency Response (DFR) [2]. The test typically records parameters such as power factor (PF) and capacitance over a frequency range from 0.1 mHz to 1 kHz at a voltage of 140 V. An alternative test is Variable Frequency Power Factor (VFPF), which operates between 15 Hz and 400 Hz with voltages up to 4 kV. These tests are dependent on frequency and temperature, with the latter being influenced by a parameter called activation energy (E_a).

Introduced by Swedish physicist Svante Arrhenius in 1889, activation energy is the minimum energy required to trigger a specific chemical reaction [3]. The higher the activation energy, the more difficult it is for a reaction to occur. Arrhenius demonstrated that the relationship between the temperature and the rate of a reaction follows an exponential pattern, as described by the well-known Arrhenius equation:

$$k(T) = Ae^{\frac{-E_\alpha}{k_B T}} , \quad (1)$$

where *k(T)* represents the reaction rate constant, which is, essentially, the number of particle collisions per second that lead to a reaction; and *A* is the pre-exponential factor or the number of collisions per second, though not all result in a reaction. In the argument of the exponential function (1), E_a refers to the activation energy, measured in electron volts (eV); *T* is the temperature in Kelvin (K); and k_B is the Boltzmann constant (8.617×10^{-5} eV/K). As a result, the argument of the exponential function represents the proportion of collisions that possess sufficient energy to overcome the activation barrier at a given temperature *T*.

Regardless of the application, it is important to clearly identify the property or parameter to which the thermally activated process modeled by the Arrhenius equation is applied

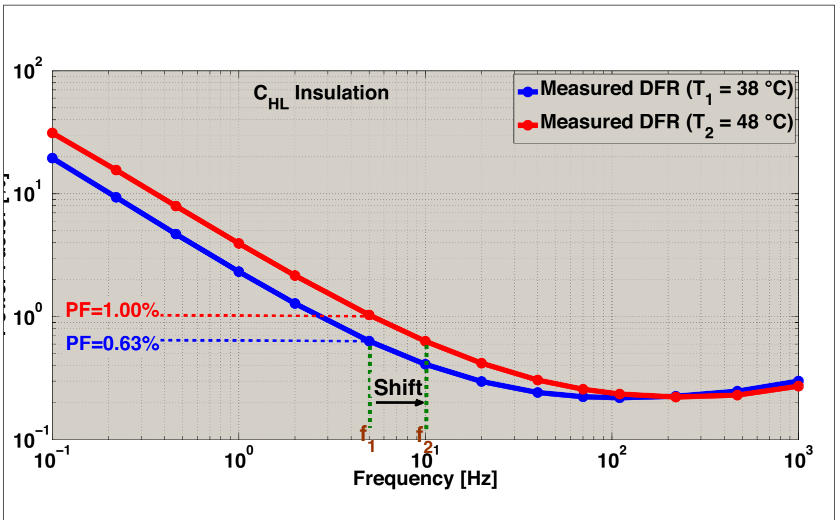


Figure 1. Logarithmic representation of Arrhenius equation applied to DFR

Though initially applied in chemistry, the Arrhenius equation has since been used in other applications, such as explaining how the internal chemical changes in insulation materials affect their physical and electrical properties. Thomas Dakin was among the first to apply this equation to describe the thermal aging of insulating materials [4]. Activation energy now plays a role in various time scales beyond chemical reactions, such as diffusion rates, reorientation times, viscosity, and dielectric relaxation times [5]. Regardless of the application, it is important to clearly identify the property or parameter to which the thermally activated process modeled by the Arrhenius equation is applied [6].

The spectral shape of a material's dielectric frequency response typically shows minimal changes with temperature, i.e., the shape is preserved, provided the material's structure remains intact [1]. Consequently, the temperature dependence of the dielectric response can be modeled using a logarithmic form of the Arrhenius equation as in (2):

$$shift = \log_e(f_2) - log_e(f_1) = -\frac{E_\alpha}{k_B}\left(\frac{1}{T_2} - \frac{1}{T_1}\right). \quad (2)$$

Fig. 1 graphically depicts (2) where the blue curve shows the dielectric response of a transformer C_{HL} insulation at T_1 = 38°C, while the red curve represents the same insulation tested at T_2 = 48°C. Despite the temperature change, the shape of the curve is preserved, although it is shifted. This allows the estimation of the dielectric response at T_2 by shifting the T_1 response, based on (2), without the need to test the insulation at T_2. Using this approach, the power factor at T_1 and frequency f_1 (i.e., PF = 0.63%) can be temperature corrected to T_2 at the same frequency f_1, resulting in corrected PF = 1.00%. It is worth clarifying that while *temperature correction* is the terminology accepted by the industry, the method actually estimates the power factor at a temperature other than the actual temperature at which the insulation was originally tested, based on a model with some constraints. These estimates are valid if *a correct value for the activation energy of the system is chosen* since the shift depends on E_a (in addition to T_1 and T_2) as given by (2). It is also important to obtain an accurate temperature measurement that represents a stable thermal condition of insulation. Thus, it is not recommended to perform the dielectric frequency response test and register the resulting insulation temperature just after the transformer has been de-energized.

It is important to fully understand the impact of activation energy on PF temperature correction. Errors can arise when using a wrong E_a value in the Arrhenius equation to estimate the 50/60 Hz power factor of apparatus insulation at other temperatures, such as 20°C. In particular, the widely accepted practice in the industry to correct a measured power factor to 20°C offers a standard reference point that ensures a consistent baseline for analysis and comparison across different environments. Existing temperature correction methods, as commonly used in the industry, may overlook the key role of activation energy, leading to inaccuracies. While the activation energies for materials like pressboard (0.9 eV) [7] and mineral oil (0.4 eV) [8] have been established, limited data exists for more complex systems such as transformers and bushings insulation.

This article aims to address the following questions regarding the dielectric response of these systems:

- How does the type of insulation affect activation energy?
- Does insulation aging alter the activation energy?
- Is the Arrhenius equation valid for deteriorated insulation?

The case studies presented in this investigation explore these questions using empirical data from field and factory tests and laboratory experiments on transformers and bushings.

Case study 1: In-service bushing's C_1 insulation in good condition

This LAPP POC (Paper-Oil-Capacitor) 25 kV bushing was in service for several years before it was tested. The bushing was mounted vertically on a metal test stand with the flange grounded securely to the station ground. By comparing the nameplate power factor and capacitance data with the test results, the bushing's condition was determined to be good.

The spectral shape of a material's dielectric frequency response typically shows minimal changes with temperature, i.e., the shape is preserved provided the material's structure remains intact

Fig. 2 shows the comparison of the dielectric responses of the bushing's C_1 insulation tested at two different temperatures (37°C and 22°C). The resulting activation energy was calculated to be 0.631 eV, obtained by solving (2) for the unknown E_a value.

If the DFR test result obtained at 37°C is to be used to predict the dielectric response of the insulation at a different temperature, such as 22°C, without performing additional tests, (2) could be applied to determine the shift, provided the activation energy of the system is known. Fig. 3 illustrates the shift (i.e., temperature correction) of the 37°C trace (green) to 22°C, by using E_a = 0.631 eV. For comparison, the actual DFR measurement at 22°C (gray) is also shown, demonstrating an excellent agreement with the temperature-corrected curve.

By employing this method, it becomes possible to determine the power factor at a specific temperature and frequency, for example, at 20°C and 60 Hz, by locating the new position of the shifted curve and identifying its intersection with the desired frequency. However, what if the actual E_a value of the insulation is unknown? In most practical situations, it is not feasible to test the same insulation structure at two different temperatures (hence the need for PF temperature correction) to directly obtain the activation energy. Consequently, selecting the correct E_a is important in order to estimate the temperature-corrected PF accurately.

In most practical situations, it is not feasible to test the same insulation structure at two different temperatures to directly obtain the activation energy

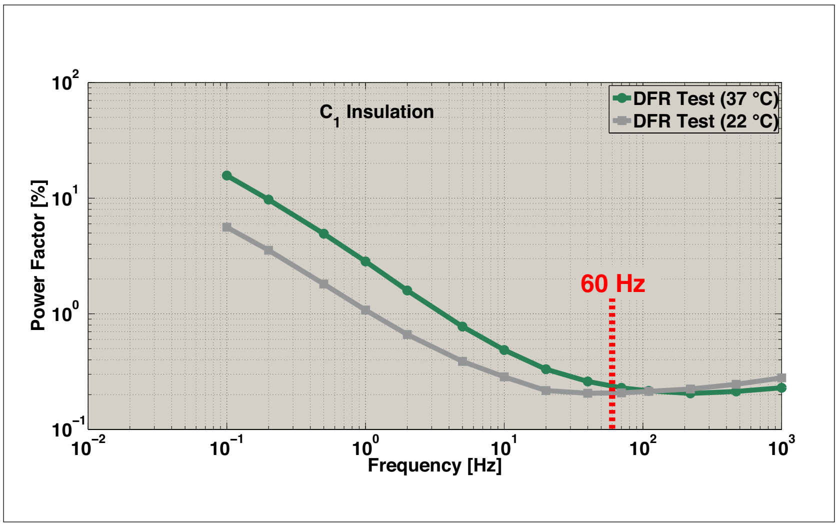


Figure 2. In-service POC bushing's C_1 insulation in good condition tested at two different temperatures

Table 1. 60 Hz temperature-corrected PF obtained by shifting the DFR curve tested at 37°C for different activation energy values (in-service POC bushing's C1 insulation in good condition)

E_α [eV]	Temperature-Corrected PF [%]	
	22 °C Benchmark (Measured) PF = 0.21%	20 °C
0,300	0,22%	0,21%
0,400	0,21%	0,21%
0,500	0,21%	0,21%
0,631	0,21%	0,20%
0,700	0,20%	0,21%
0,800	0,21%	0,21%
0,900	0,21%	0,21%
1,000	0,21%	0,21%

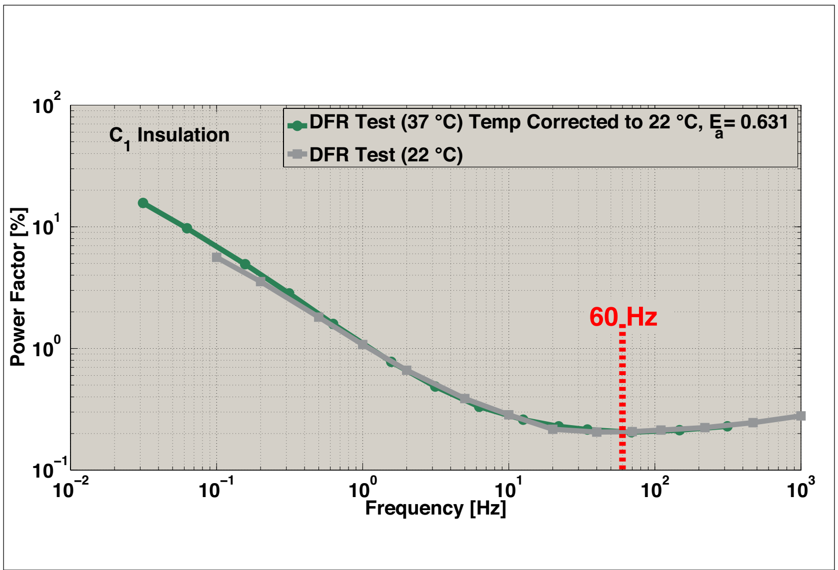


Figure 3. Temperature correction to 22 °C of DFR curve tested at 37 °C (in-service POC bushing's C1 insulation in good condition)

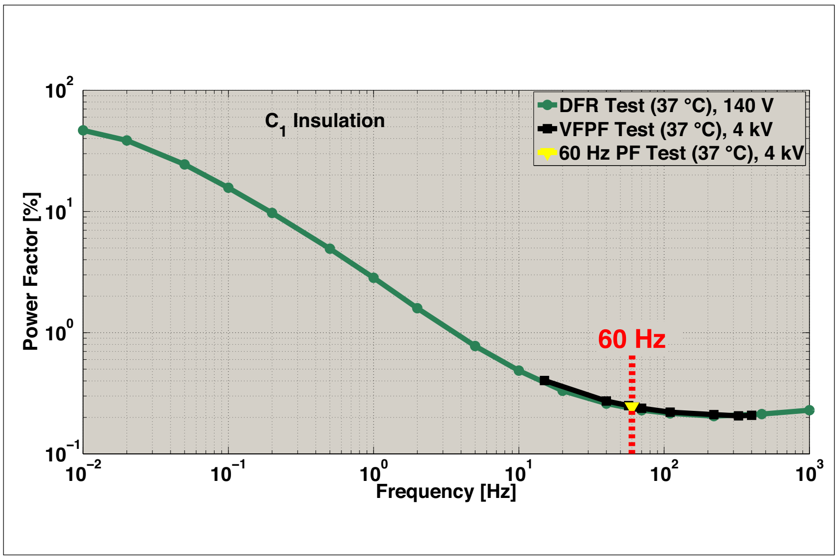


Figure 4. Comparison of DFR, VFPF and 60 Hz 4 kV PF tests at 37 °C (in-service POC bushing's C1 insulation in good condition)

Under good insulation conditions, a PF temperature correction obtained from data measured at a lower test voltage can be applied to the PF measured at a higher test voltage

Table 1 demonstrates the impact of E_a on the estimated 60 Hz C_1 PF at both 22°C (second column) and 20°C (third column) by using the shifted DFR curve tested at 37°C. The PF benchmark value at 22°C corresponds to 0.21%, which is the actual measured 60 Hz PF at 22 °C. As expected, the use of the known E_a of the tested insulation (i.e., 0.631 eV) produces the correct estimated PF = 0.21%. Nevertheless, a similar result is also obtained by using other values of E_a. In fact, for this particular case study, varying E_a from 0.3 to 1.0 does not significantly impact the resulting temperature-corrected PF. The reason for this behavior can be explained by the mild slope (almost flat) of the DFR curve around the 60 Hz region. However, this situation does not occur in all cases since the shifting mechanism in (2) implies that if the slope around 60 Hz is steeper, changes in E_a will have a significant impact on the temperature-corrected PF. Hence, selecting a representative E_a value for the tested insulation in such conditions is crucial.

Fig. 4 shows a comparison of three different tests conducted at 37°C on the same in-service C_1 insulation: 140 V DFR (green), 4 kV VFPF (black), and 60 Hz 4 kV PF (yellow). Similar to the behavior observed when testing new apparatus insulation in the factory [9], this bushing's C_1 insulation in good condition shows no impact of the test voltage on the resulting PF values. It means that, under these good insulation conditions, a PF temperature correction obtained from data measured at a lower test voltage can be applied to the PF measured at a higher test voltage. However, the latter is not valid when the PF

The shifting mechanism in Arrhenius equation implies that if the slope of the dielectric response around 60 Hz is steeper, changes in Eα will have a significant impact on the temperature-corrected PF

is voltage dependent (i.e., if there is a PF tip-up), as is illustrated in case study 2.

Case study 2: In-service transformer's C_{HL} wet insulation

This case study involves a three-phase 161-13.09GrdY kV transformer (12/16/20/22 MVA) that had been in service for almost 10 years. Its CHL insulation was tested in the field at two temperatures (29°C and 23°C). Based on the DFR-moisture analysis performed on the CHL insulation, it was determined that the solid insulation moisture content was 3.3%, indicating a wet condition.

Fig. 5 and Fig. 6 show the use of PF temperature correction for the CHL insulation, again using the Arrhenius equation as outlined in case study 1. The calculated activation energy was 0.581 eV. Specifically, Fig. 6 demonstrates that even with wet CHL insulation, an Arrhenius-like behavior persists, as indicated by the near-perfect alignment between the shifted curve (orange) and the benchmark curve (purple).

Table 2 highlights the impact of activation energy on the estimated 60 Hz CHL PF at both 23°C (second column) and 20°C (third column) by shifting the DFR curve tested at 29°C. A noticeable feature here is the broader range of variation in temperature-corrected PF values due to an activation energy change between 0.3 and 1.0. This variation contrasts with the behavior in case study 1, where estimated PF values showed a mild change. The reason

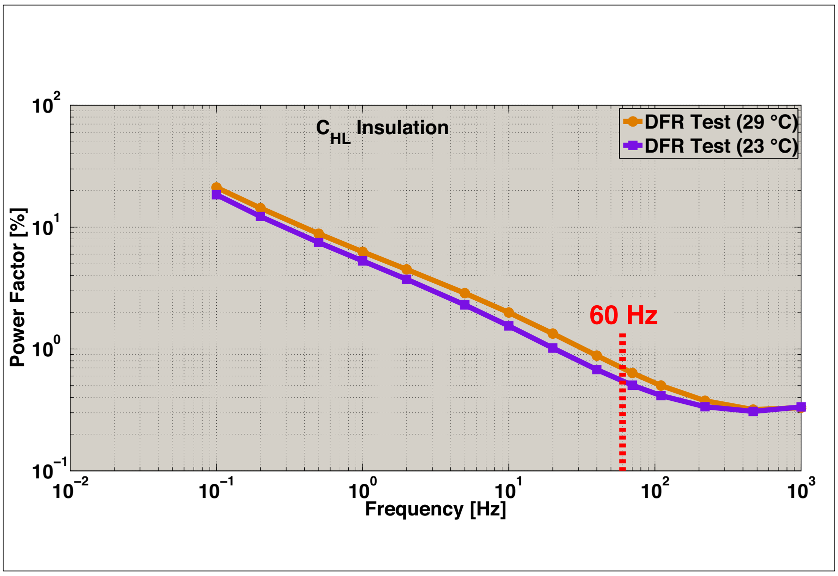


Figure 5. In-service transformer's C_{HL} wet insulation tested at two different temperatures

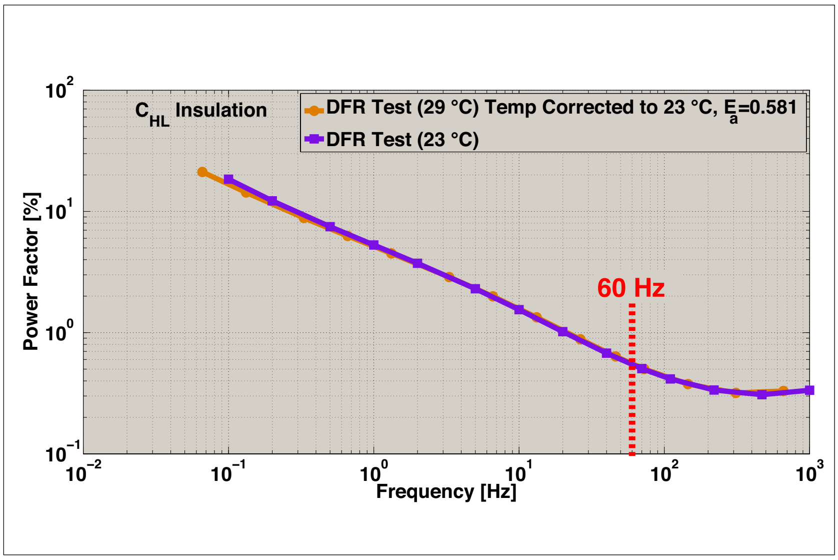


Figure 6. Temperature correction to 23 °C of DFR curve tested at 29 °C (in-service transformer's C_{HL} wet insulation)

Table 2. 60 Hz temperature-corrected PF obtained by shifting the DFR curve tested at 29°C for different activation energy values (in-service transformer's C_{HL} wet insulation)

E_α [eV]	Temperature-Corrected PF [%]	
	23 °C Benchmark (Measured) PF = 0.54%	20 °C
0,300	0,61%	0,57%
0,400	0,58%	0,54%
0,500	0,56%	0,51%
0,581	0,54%	0,48%
0,700	0,52%	0,45%
0,800	0,50%	0,43%
0,900	0,48%	0,41%
1,000	0,46%	0,39%

Under contaminated insulation conditions, the Arrhenius-like behavior may no longer exist, so the Arrhenius equation may not be used for PF temperature correction under these conditions

for this difference is the steep slope of the DFR curve around the 60 Hz region (Fig. 5). Under these conditions, using an incorrect E_a value for the insulation system could result in an erroneous temperature-corrected PF value at 60 Hz.

Fig. 7 presents a comparison of three different tests performed on the same in-service CHL wet insulation at 29°C: 140 V DFR (orange), 4 kV VFPF (black), and 60 Hz 10 kV PF (yellow). Unlike the previous case study, where insulation in good condition showed no voltage-dependent behavior for PF at different test voltages, in case study 2, the dielectric response at lower test voltages (orange) does not align with the higher test voltage results (black and yellow) at frequencies above 40 Hz. Therefore, a PF temperature correction based on low-voltage test data may not be suitable for correcting PF measured at higher test voltages under aging insulation conditions with failure modes that may produce a PF tip-up.

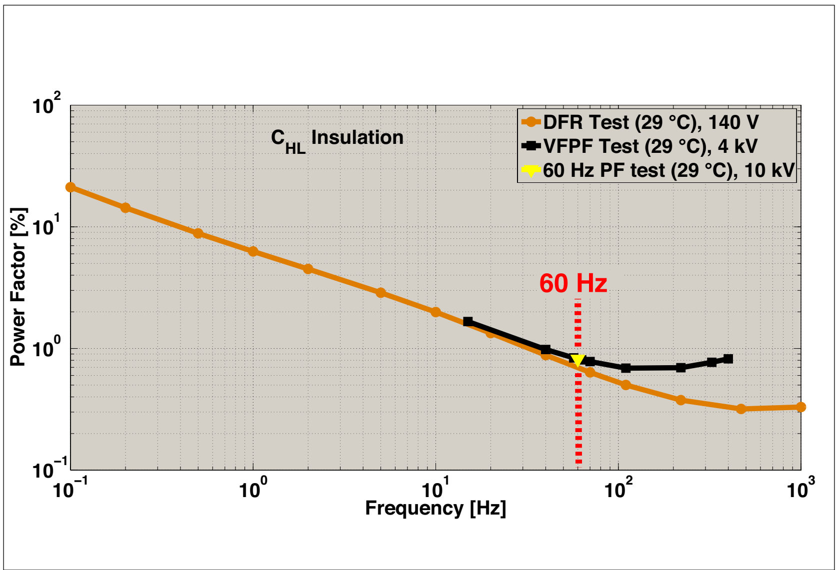


Figure 7. Comparison of DFR, VFPF and 60 Hz 10 kV PF tests at 29 °C (in-service transformer's C_{HL} wet insulation)

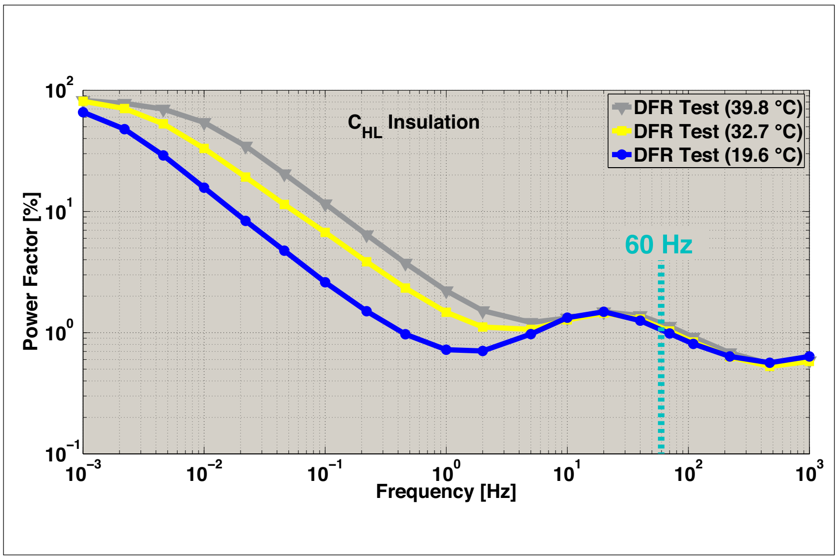


Figure 8. Retired transformer's CHL contaminated insulation tested at three different temperatures

Case study 3: A retired transformer's C_{HL} contaminated insulation

This case investigated a three-phase 110-22.9GrdY kV 2.5/3.75 MVA transformer that had been in service for several decades. After the unit was retired, it was brought to the Doble HV laboratory for inspection and testing. Upon initial inspection, contamination particles were found dispersed throughout the insulation.

The CHL insulation was tested at three different temperatures (39.8°C, 32.7°C, and 19.6°C) using DFR during the cooling process following hot oil circulation (Fig. 8). As is seen in the figure, an unusual "hump" is present within the frequency range of 2 – 400 Hz. This phenomenon is documented in the literature as being indicative of the presence of conductive materials [10, 11], which could potentially be metal particles or copper sulfide contamination.

Under this contaminated condition, the Arrhenius-like behavior typically seen in the previous cases no longer exists, so (2) cannot be used for PF temperature correction under these conditions. The curve shape is not preserved with temperature changes, as there is no shift between the curves across the entire spectrum, e.g., the yellow curve (32.7°C) will not coincide with the blue curve (19.6°C) when the former is shifted towards the latter by using (2). This behavior results, in part, because the PF values at frequencies above 10 Hz remained relatively constant at different temperatures.

Fig. 9 provides a comparison of the dielectric responses of this contaminated CHL insulation tested at different volt-

ages, ranging from 140 V (DFR) to 4 kV (VFPF). A power factor tip-up is noted at frequencies above 30 Hz, indicating that the power factor is voltage-dependent under contaminated conditions.

Conclusion

The case studies reveal that the Arrhenius-like behavior — where the DFR/VFPF curve shape is preserved with temperature changes — may not be observed when the insulation is seriously contaminated or deteriorated.

Of particular interest is the finding that, for transformers and bushings with mineral-oil-impregnated insulation that exhibit Arrhenius-like behavior, the activation energy does not vary significantly based on the apparatus type or insulation condition. In these cases, a representative activation energy value of approximately 0.6 eV seems to be a reliable choice for an acceptable temperature correction of the 60 Hz PF when the actual activation energy of the insulation system is unknown. This is consistent with the findings reported in [9].

Additionally, it was found that if a power factor tip-up is absent and the Arrhenius-like behavior exists, PF temperature corrections derived from

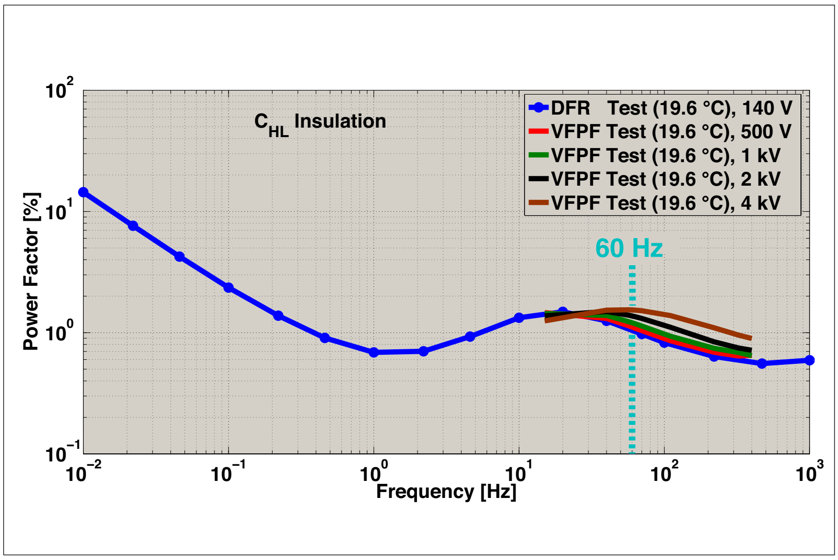


Figure 9. Comparison of DFR and VFPF tests at different test voltages and 19.6 C (retired transformer's C_{HL} contaminated insulation)

low-voltage test data can be applied to PF measurements performed at higher voltages accurately. In contrast, if both power factor tip-up and Arrhenius-like behavior exist, it is recommended to perform the PF temperature correction by using data obtained at a higher voltage, e.g., via VFPF (15 — 400 Hz, 4 kV).

Further research is necessary to address one of the questions raised in the introduction section of this article, mainly whether the activation energy remains constant or varies as the insulation ages. Answering this question requires repeated testing of the same insulation over an extended period of time (on the order of years) by following the methodology described in this article.

Bibliography

[1] A. K. Jonscher, *Dielectric Relaxation in Solids*, Second Edition, Chelsea Dielectrics Press Ltd., London, UK, 1983.

[2] *Guide for Dielectric Frequency Response Test*, IEEE Standard C57.161-2018.

[3] https://www.chemeurope.com/en/encyclopedia/Activation_energy.html

[4] Thomas W. Dakin, *Electrical Insulation Deterioration Treated as a Chemical Rate Phenomenon*, AIEE Transactions, Volume 67, 1948.

[5] Zeke A. Piskulich, Oluwaseun O. Mesele, Ward H. Thompson, Activation Energies and Beyond, The Journal of Physical Chemistry A, 2019, Vol. 123, pp. 7185-7194.

[6] Emmanuel I. Koufakis, Constantinos D. Halevidis, Aikaterini Polykrati, Panagiotis T. Tsarabaris, *Calculation of the Activation Energy of Oil-Paper Insulation in a Distribution Transformer*, IEEE Electrical Insulation Magazine, Vol. 28, No. 2, pp. 52-58, March/April 2012.

[7] Uno Gafvert, George Frimpong, Jitka Fuhr, *Modelling of Dielectric Measurements on Power Transformers*, Proc. 37th Session Large High Voltage Electric Systems (CIGRE): Group 15 – Materials for Electrotechnology, paper 103, Paris, France, 1998.

[8] Chandima Ekanayake, *Diagnosis of Moisture in Transformer Insulation*, Ph.D. Dissertation, Chalmers University of Technology, Sweden, January 2006.

[9] Ronald D. Hernández, Mark F. Lachman, *Influence of Activation Energy on Dielectric Frequency Response (DFR) Analysis*, Proceedings of the 89th Annual International Conference of Doble Clients, Sec. T-7, Boston, USA, 2022.

[10] Paul Griffin, Lance Lewand, *Corrosive Sulfur Problems in Electric Apparatus: Causes, Prevention and Mitigation*, Doble Collaborative Study (internal use), Doble Engineering Company, January 2007.

[11] Clair Claiborne, George Frimpong, Wayne Ball, Arne Hjortsberg, *Transformer Oils, Corrosive Sulfur and Effects on Transformers*, Proceedings of the 74th Annual International Conference of Doble Clients, Sec. IM-5, Boston, USA, 2007.

Authors

Ronald D. Hernández, joined Doble Engineering in 2012 and is currently its Diagnostic Analysis Research Manager. He has developed applications in the fields of moisture in insulation systems, dielectric frequency response, and statistical analysis of bushing test data and transformer failure rates. Dr. Hernández holds both Ph.D. and M.S. in EE from Northeastern University, Boston MA, USA, B.S. in EE from the Technological University of Panama, and a global MBA from IE Business School, Madrid, Spain. He is a member of the Electrical and Computer Engineering "Honor Society Eta Kappa Nu" and the IEEE Power & Energy Society. He is also a member of the IEEE Transformer Committee where he is active in several working groups.

Mark F. Lachman, Ph.D., P.E. has been with the power industry for over 40 years. His experience includes development of off-line and on-line diagnostics as well factory testing of power transformers. As Director of Diagnostic Analyses at Doble, he contributes to advancing interpretation of apparatus diagnostic data.

Andre Lux is a Senior Principal Client Service Engineer at Doble Engineering. He has thirty-five years experience in the electric power industry working for electric equipment manufacturers, electric utilities, and consulting organizations. Andre is currently the Secretary for the Doble Transformers Committee. He received a BSEE from Texas Tech University and a MSEE from Mississippi State University.

John J. Foschia is a Principal Client Service Engineer at Doble Engineering. He started with Doble in 2021 after eight years with SPX Transformer Solutions where he most recently served as Product Test Manager. His experience includes factory acceptance testing and quality control of power transformers in addition to the diagnostic testing and condition assessment of high-voltage electrical apparatus. John is currently an Assistant Secretary for the Doble Transformers Committee and has participated in several IEEE Transformer Committee working groups. He received his Bachelor of Science degrees in Electrical Engineering and Computer Engineering from North Carolina State University.