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Technological innovation article

Evaluation of Dielectric Reliability in Oil-Insulated Transformers Using Scilab: Impact of Temperature and Electric Field Frequency

Evaluación de la fiabilidad dieléctrica en transformadores aislados en aceite mediante Scilab: impacto de la temperatura y frecuencia del campo eléctrico

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ABSTRACT/*RESUMEN*
This article presents a study on the dielectric behavior of insulating oil in power transformers, using Scilab simulations as a primary tool. The research aims to analyze the impact of temperature, electric field frequency, and oil aging on dielectric properties like relative permittivity and dielectric strength. The study is crucial for transformers' operation and lifespan, as deteriorating dielectric properties can lead to failures and costly service interruptions. The study uses Scilab simulation to model and evaluate transformer insulation systems under different conditions, allowing for prediction of performance under different electrical stresses. The results provide valuable insights for transformer design, optimization, and diagnosis, contributing to a better understanding of insulating oil behavior. The findings also offer tools for developing more efficient equipment and implementing predictive maintenance strategies, ensuring continuity of electrical service and minimizing operational costs.
Keywords: dielectric behavior, frequency and temperature, oil-insulated transformers, relative permittivity, Scilab.

Este artículo presenta un estudio sobre el comportamiento dieléctrico del aceite aislante en transformadores de potencia, utilizando simulaciones en Scilab como herramienta principal. El objetivo es analizar la influencia de la temperatura, la frecuencia del campo eléctrico en las propiedades dieléctricas, como la permitividad relativa y la rigidez dieléctrica. La investigación se justifica por la importancia del aceite aislante en el funcionamiento y la vida útil de los transformadores, ya que el deterioro de sus propiedades dieléctricas puede provocar fallas y costosas interrupciones del servicio. A través de la simulación en Scilab, se modela el sistema de aislamiento del transformador y se evalúa su comportamiento bajo diversas condiciones de operación. Este enfoque permite predecir el rendimiento del sistema de aislamiento a partir de analizar cómo la temperatura y la frecuencia afectan las propiedades dieléctricas del aceite, así como el impacto del envejecimiento en el rendimiento del transformador. El estudio se basa en datos de la literatura técnica y fichas técnicas de fabricantes de aceite aislante. Los resultados proporcionan información valiosa para el diseño, optimización y diagnóstico de transformadores, contribuyendo a una mejor comprensión del comportamiento del aceite aislante. Además, se ofrecen herramientas para el desarrollo de equipos más eficientes y confiables, así como para la implementación de estrategias de mantenimiento predictivo, lo que es fundamental para garantizar la continuidad del servicio eléctrico y minimizar costos operativos.
***Palabras clave**: comportamiento dieléctrico, frecuencia y temperatura, transformadores en aceite, permitividad relativa, Scilab.*

INTRODUCTION

Power transformers are essential components in electrical systems, as they enable the efficient transmission of electrical energy over long distances and its distribution at appropriate levels for consumption. Their main function is to increase or decrease the electrical voltage, which helps minimize energy losses during transmission and ensures the stability of the electrical supply [1]. According to the works cited in references [2, 3], among the various types of transformers, those that use mineral oil as an insulation and cooling medium stand out.

This type of transformer, commonly known as an oil-immersed transformer, is fundamental in modern electrical infrastructure due to its superior characteristics that allow for safe and efficient operation in high-power applications. Mineral oil not only acts as an excellent electrical insulator but also plays an essential role in the cooling of the transformer. During their operation, transformers generate heat due to resistive losses and electrical load. Mineral oil circulates through the system, absorbing this heat and helping to maintain the internal temperature within safe limits. This not only prevents overheating but also extends the equipment's lifespan by reducing the wear on internal components. Moreover, the ability of these transformers to operate at high voltages makes them an ideal choice for applications in electrical substations and long-distance energy transmission. By increasing the voltage, Joule effect losses during transportation are minimized, resulting in greater energy efficiency. For these reasons, oil-insulated transformers are essential to ensure a reliable and safe power supply in various industries and residential environments.

In that sense, the research [4], assert that transformer oil is a specialized fluid used in electrical transformers and similar electrical equipment to provide electrical insulation and cooling. This oil is found inside transformers and other electrical equipment, where it plays an important role in the protection and efficient operation of these systems, providing the necessary insulation and cooling for safe and efficient operation. Its ability to maintain chemical and thermal stability, along with its corrosion inhibition properties, ensures that the equipment operates reliably over long periods of time.
According to the authors themselves, among the main characteristics of transformer oil are:

- The insulating properties that prevent electrical conduction between the transformer's components, such as the core and the coils.
- It ensures that the transformer operates safely, preventing short circuits and electrical failures that could damage the equipment or pose safety risks.
- The oil helps dissipate the heat generated during the operation of the transformer, circulating through the equipment and transferring the heat to the cooling system.
- It prevents the transformer from overheating, ensuring its efficient operation and prolonging its lifespan.
- It is formulated to maintain its chemical and thermal integrity during long periods of operation, even at high temperatures.
- The chemical and thermal stability of the oil ensures that it does not degrade or form corrosive compounds, which could affect the performance of the transformer.
- It contains additives that protect the internal metal parts of the transformer against corrosion and deterioration.
- It helps keep the internal parts of the transformer in good condition, preventing damage from corrosion and extending the equipment's lifespan.
- It has an extremely low electrical conductivity, which minimizes the risk of electric shock and ensures effective insulation.
- Low electrical conductivity is essential to avoid energy loss and the risk of electrical failures.

On the other hand, the authors of reference [5], suggest that the insulation properties of oil-immersed transformers are evaluated through various testing methods to assess their dielectric strength, thermal performance, and overall integrity. Dielectric tests are commonly performed to measure the insulation's ability to withstand electrical stresses without breaking. One of the most commonly used dielectric tests is the power factor test, which evaluates the dissipation factor of the insulation. A high-power factor value may indicate the presence of moisture, contaminants, or insulation degradation, which requires further investigation and maintenance.

Another important dielectric test is the AC withstand voltage test, which subjects the insulation to high voltage to confirm its ability to withstand electrical stresses without failing. Thermal tests, such as the temperature rise test, evaluate the insulation's ability to withstand heat and maintain its dielectric properties within the specified temperature limits. The temperature rise test involves energizing the transformer at full load to measure the temperature rise of the insulation and ensure it remains within acceptable limits.

In addition to dielectric and thermal tests, mechanical tests, such as the short-circuit test and the impulse voltage test, evaluate the insulation's ability to withstand mechanical and transient stresses. The short-circuit test subjects the transformer to high fault currents to confirm the integrity of the insulation and the overall mechanical strength of the transformer. Likewise, the impulse voltage test simulates lightning and switching over voltages to verify the insulation's ability to withstand transient voltage stresses.It is important to note that these insulation property testing methods are fundamental for assessing the condition of the transformer's insulation system and ensuring its reliability. Routine testing, combined with preventive maintenance, helps identify any potential issues with the insulation and allows for timely corrective actions, thereby extending the life of the transformer.

Authors of studies such as [6-11], assert that there are several factors that can influence the insulation performance of oil-immersed transformers, affecting their reliability and longevity. Environmental conditions, such as temperature, humidity, and pollution, can have a significant impact on the insulation properties of a transformer. High temperatures can accelerate the degradation of insulating materials, while excessive humidity can affect the dielectric strength of the insulation. Contamination, including dust, salt, and chemical contaminants, can also degrade insulation and create conductive paths between electrical components, which could lead to electrical failures.

Moreover, the stress voltage that insulating materials experience is a critical factor in determining their performance. Higher voltage transformers require thicker and more robust insulation to withstand the increase in electrical tension. Similarly, the mechanical stresses resulting from short circuits and transient events can affect the integrity of the insulation, requiring thorough testing and evaluations to ensure the reliability of the transformer.

The design and construction of the transformer, including the arrangement of the coils, insulation materials, and cooling system, can also affect the insulation performance. Appropriate design considerations, such as the selection of insulation materials and suitable cooling methods, can improve the insulation properties of the transformer and enhance its overall reliability.Given all the above, the objective of this research article is to analyze the influence of temperature, electric field frequency, and oil aging on dielectric properties, such as relative permittivity.

MATERIALS AND METHODS

To achieve the objective of this research, it was necessary to review existing theoretical studies and seek out accumulated scientific knowledge regarding the analysis of the variation of the dielectric properties of oil, specifically the relative permittivity with temperature and frequency. This involved consulting various bibliographic sources, as well as catalogs and technical standards. This allowed the development of the following methodology shown in figure 1.

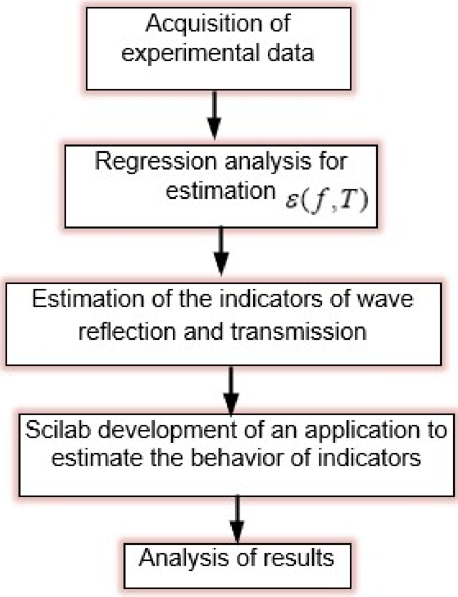

Fig. 1. Proposed methodology for the analysis of reflection and transmission wave indicators in insulating oils of power transformers

DISCUSSION AND RESULTS

As already mentioned, temperature is one of the most influential factors in the degradation of insulating oil and solid materials in a transformer. At elevated temperatures, the oxidation process and the presence of polar compounds in the oil accelerate, which increases dielectric losses and affects the insulation rigidity. Additionally, the moisture absorbed by the cellulose contributes to deterioration, increasing losses and reducing insulation capacity.

The frequency of the electric field also plays a relevant role in the behavior of the insulation. At higher frequencies, insulating materials can experience an increase in induced electrical stress, leading to greater strain on the insulation system. This interaction is particularly critical in applications where the operating frequencies are not limited to the standard grid of 50 or 60 Hz, but include harmonics and transient fluctuations [11, 12].The evaluation of the condition of insulation systems is carried out through the measurement and analysis of electrical properties, using various methods that include absorption/reabsorption current, dielectric response in the time domain, as well as dielectric response at high or low frequencies and partial discharge levels, among others.

Therefore, it is important to have diagnostic factors and criteria that indicate the end of the useful life of an insulation system, which should be quick and not interfere with the normal operation of the system. Based on the relative permittivity values of a material at different temperatures and frequencies, an approximation of its operational state can be obtained.In this regard, based on the studies conducted by [13-17], data on the relative permittivity and its behavior as a function of temperature and frequency were obtained, as shown in table 1.

Table 1. Experimental values of relative permeability and loss tangent as a function of temperature and frequency

Parameter	Conditions (temperature, frequency)	Typical Value
Relative permittivity	25 °C, 50 Hz	2,2 – 2,4
Loss tangent	25 °C, 50 Hz	0,001 – 0,005
Relative permittivity	90 °C, 50 Hz	2,5 – 2,7
Loss tangent	90 °C, 50 Hz	0,01 – 0,02
Relative permittivity	25 °C, 1 kHz	2,1 – 2,3
Loss tangent	25 °C, 1 kHz	0,0005 – 0,003

The term tan(δ), or loss tangent, is a parameter that measures the dielectric losses of an insulating material when subjected to an alternating electric field. This value indicates the efficiency of the material as an insulator, reflecting the proportion of energy that is dissipated as heat compared to the energy that is stored. In simple terms, the higher the tan(δ), the more energy is lost, which suggests greater degradation or the presence of impurities, moisture, or other factors that affect the insulation performance.

From table 1, the following observations can be made:

- **Temperature**: As the temperature increases, the relative permittivity and dielectric losses (tan(δ)) tend to rise due to greater thermal agitation and molecular polarization.
- **Frequency**: As the frequency increases, the relative permittivity generally decreases, as the material cannot keep up with the alternation of the electric field as quickly, which reduces the effective polarization.

Now then, reference [18], suggests that, based on knowing the relative permittivity, indicators of reflection and transmission of waves with normal incidence to the surface of the insulations can be calculated. On one hand, the reflection coefficient (Γ) is given by equation (1):

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad (1)$$

Where:

η_1, η_2: intrinsic impedances of the source material and the destination material of the wave. They are calculated as shown in equation (2):

$$\eta = \sqrt{\frac{\mu}{\varepsilon}} \quad (2)$$

It is important to highlight, as stated in [19], that the magnetic permeability of the oil used in transformers generally approximates the permeability of a vacuum. However, the insulating oil may have a slightly higher permeability due to its chemical composition. For practical applications, an approximate value of 1 H/m can be used to simplify calculations, as the variation is minimal compared to other magnetic materials. Additionally, considering that the incident wave comes from the vacuum/air and penetrates into the insulation, equation (1), can be rewritten as shown in equation (3), where (ε_0) is the electric permittivity of free space:

$$\Gamma = \frac{\sqrt{\varepsilon_{r,aislamiento}(f,T)} - \sqrt{\varepsilon_0}}{\sqrt{\varepsilon_{r,aislamiento}(f,T)} + \sqrt{\varepsilon_0}} \quad (3)$$

Similarly, the transmission coefficient (τ) is calculated as shown in equation (4):

$$\tau = 1 + \Gamma \quad (4)$$

On the other hand, the percentage of power transmitted from the vacuum to the dielectric can be approximated as shown in equation (5):

$$\frac{S_2}{S_1} = 1 - \left|\Gamma\right|^2 \quad (5)$$

Now, with the aim of more accurately modeling the previously described reflection and transmission indicators, a multivariable regression analysis will be conducted using the data provided in table 1.

Formulation of the multivariable regression model

The general model that describes the regression analysis to model the dielectric permittivity of insulating oils as a function of frequency and temperature is shown in equation (6):

$$\varepsilon(f,T) = \beta_0 + \beta_1 f + \beta_2 T \quad (6)$$

Where:

- ε(f,T): is the dielectric permittivity as a function of frequency and temperature.
- f: it is the frequency.
- T: it is the temperature.
- $\beta_{0,1,2}$: these are the model parameters that need to be estimated.

In multiple regression, the betas ($\beta_{0,1,2}$) are calculated by solving the system of normal equations, which can be expressed in matrix form. To explain the method, it will be assumed that there are n observations of ε, f, T, and they are arranged in a vector Y (of dimension n×1) of the permittivities, and in the matrix X (of dimension n×3) of the predictor variables.The matrix X is constructed by adding a column of ones (β_0), as shown in equation (7):

$$X = \begin{pmatrix} 1 & f_1 & T_1 \\ 1 & f_2 & T_2 \\ . & . & . \\ . & . & . \\ . & . & . \\ 1 & f_n & T_n \end{pmatrix} \tag{7}$$

The vector Y is as shown in equation (8):

$$Y = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ . \\ \varepsilon_n \end{pmatrix} \tag{8}$$

The coefficient β vector is as shown in equation (9):

$$\beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} \tag{9}$$

The general formula for calculating the coefficients is shown in equation (10):

$$\beta = (X^T X)^{-1} X^T Y \tag{10}$$

Where:

- X^T: is the transpose of the matrix X.
- $(X^T X)^{-1}$ is the inverse of this matrix.
- This system of equations will give you the values of β.

The multiple linear regression analysis with the provided data results as shown in equation (11):

$$\varepsilon = 2,0899 - 0,0001 \cdot f + 0,0046 \cdot T \tag{11}$$

where:

- ε is the permittivity.
- f it is the frequency in Hz.
- T is the temperature in °C.

From this model, the following can be interpreted:

- The coefficient of f= -0,0001 indicates that the permittivity slightly decreases with the increase in frequency.
- Coefficient of T = 0,0046, indicates that the permittivity slightly increases with the increase in temperature.

Similar conclusions can be drawn by analyzing the data in table 1, as mentioned earlier. It is important to note that, as a limitation of the model, it is based on a very small dataset - only 3 points - so its predictive capacity is limited, but generality in the analysis intended to be carried out is not lost. From the regression model of equation (11), the values of the indicators described above can be estimated for different values of temperature and frequency as shown in the graphs of figures 3, 4, 5, and 6. To obtain the graphs, a graphical application was developed in the free software Scilab, as shown in figure 2, based on the research of the authors [20].

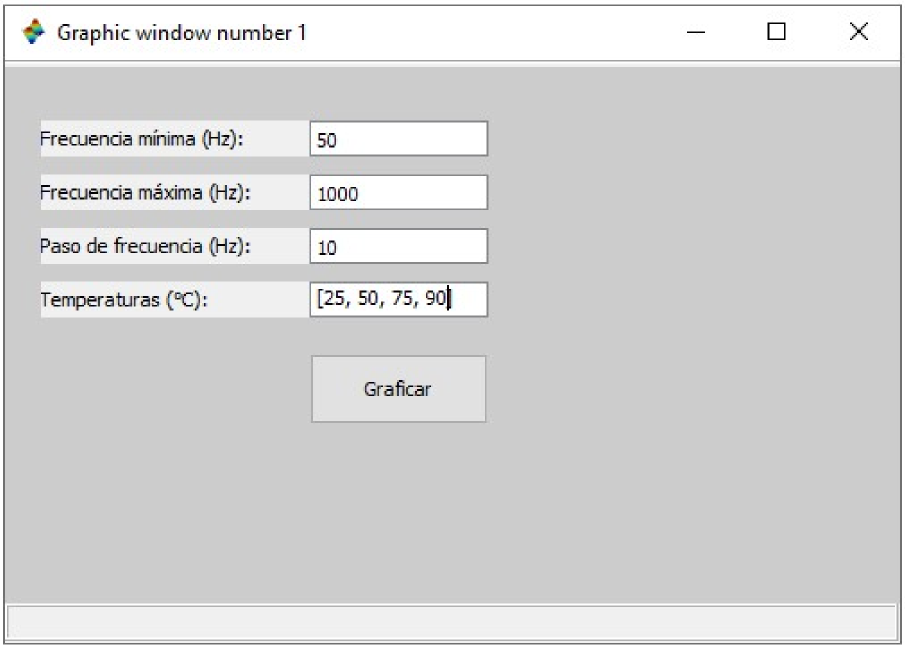

Fig.2. Graphical application in the free software Scilab to estimate the behavior of the indicators

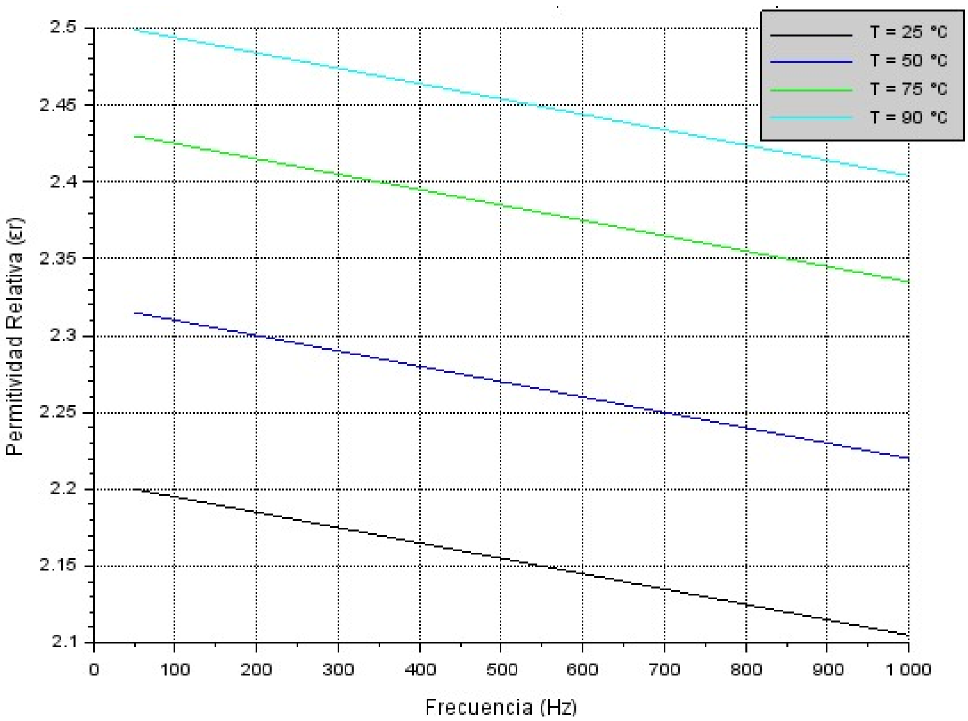

Fig. 3. Estimation of the relative permittivity of a transformer insulation system for different temperature and frequency values

From the graph in figure 3, the following conclusions can be drawn:

- **Dependence of permittivity on frequency**: The presented graph indicates that the relative permittivity of the insulating oil decreases as the frequency increases, regardless of the temperature. This phenomenon is characteristic of dielectric materials, in which the polarization of the material cannot adequately adjust to the variations of a high-frequency electric field. As a result, a reduction in permittivity is observed at higher frequencies. This behavior indicates the importance of considering both the frequency and the dielectric properties of the material in electrical and electronic applications, where performance can be affected by these variations.
- **Effect of temperature on permittivity**: It is observed that the relative permittivity is higher at higher temperatures across the entire range of frequencies studied. This implies that the insulating oil is more polarizable when heated, which is consistent with the fact that at higher temperatures the molecules have greater kinetic energy, facilitating better alignment with the applied electric field. This increase in permittivity with temperature may indicate that, under operating conditions at higher temperatures, the oil could offer a greater capacity for storing electrical energy in the electric field.
- **Implications for the operation of power transformers**: the variation of permittivity with frequency and temperature is an important factor for the design and operation of power transformers, as it affects the dielectric properties of the insulating oil. At higher temperatures, although the permittivity is greater, there may also be an increase in conductivity and a reduction in dielectric strength, which must be considered to avoid insulation failures.

The decrease in permittivity with the increase in frequency suggests that, under high-frequency operating conditions (such as those generated by transients or harmonics), the charge storage capacity of the oil is reduced, which can influence the performance of insulation systems.

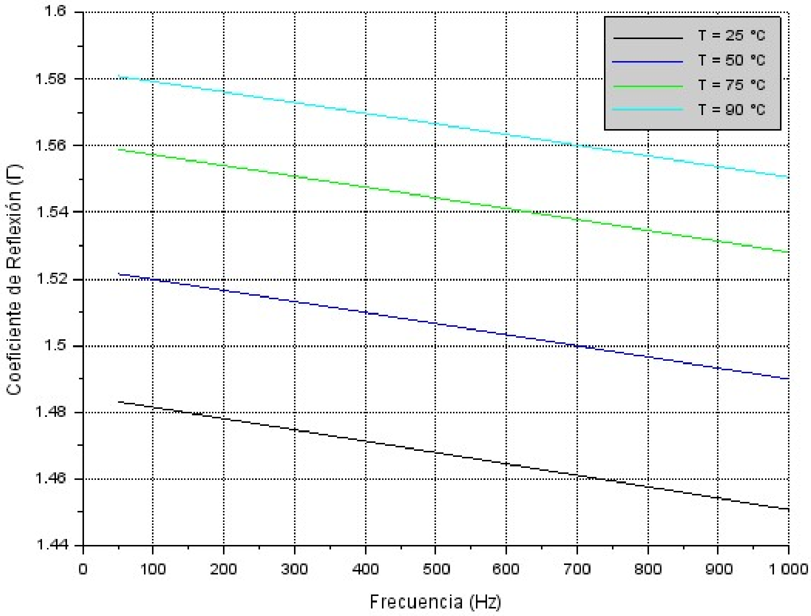

Fig. 4. Reflection coefficient (Γ) of the transformer insulation system for different values of temperature and frequency

From the graph in figure 4, the following conclusions can be drawn:

- **Tendency of the reflection coefficient with frequency:** The graph shows that the reflection coefficient gradually decreases as the frequency increases, regardless of the temperature. This suggests that, at higher frequencies, the interaction between the incident electric field and the material causes less reflection.
- **Influence of temperature on the reflection coefficient:** It is observed that at higher temperatures (for example, 75 °C and 90 °C), the reflection coefficient is higher compared to lower temperatures (such as 25 °C and 50 °C) across the entire frequency range analyzed. This indicates that the material reflects more energy when it is at a higher temperature.The increase in the reflection coefficient with temperature may be related to an increase in the polarizability of the insulating oil, which in turn can modify the material's response to the incident electric field.
- **Implications for the operation of power transformers:** a higher reflection coefficient at higher temperatures implies that a significant portion of the incident wave is reflected and not transmitted into the material. This can influence the efficiency of insulation and energy dissipation in the transformer system. The decrease in the reflection coefficient with frequency suggests that, under high-frequency operating conditions, the material reflects less energy, which could be beneficial for reducing losses in high-frequency situations or electrical transients.

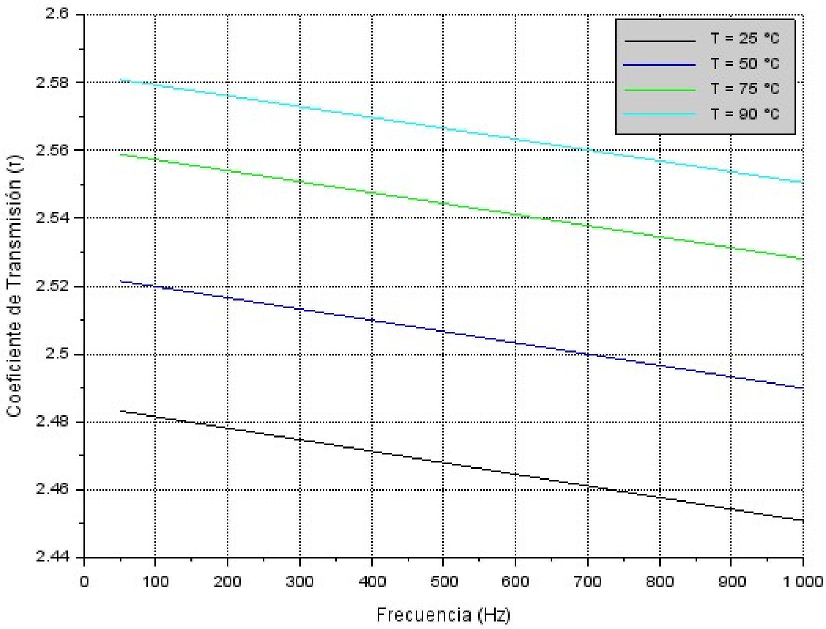

Fig. 5. Transmission coefficient of the transformer insulation system for different values of temperature and frequency

From the graph in figure 5, the following conclusions can be drawn:

- **Tendency of the transmission coefficient with frequency**: the transmission coefficient decreases as the frequency increases, this is observed in all curves, regardless of the temperature. As the frequency increases, the transmission coefficient of the oil decreases linearly. This indicates that the insulating oil becomes less "transparent" to higher frequency signals, meaning the electric field is significantly attenuated as it passes through the oil.
- **The transmission coefficient decreases as the temperature increases**: For a given frequency, the transmission coefficient is lower at higher temperatures. This suggests that the insulating oil loses its dielectric properties as the temperature increases. As a consequence, the insulating oil experiences:
  - Decrease in viscosity: allows greater ion mobility, increasing conductivity and reducing insulation.
  - Decrease in the dielectric constant: reduces the oil's ability to store electrical energy, affecting its capacity to resist the flow of current.
  - Increased dielectric losses: Greater energy dissipation in the form of heat, which reduces insulation efficiency and increases signal attenuation.

Therefore, the transmission coefficient, as an indicator of the oil's ability to allow the passage of an electrical signal, is directly affected by the dielectric properties of the oil:

- Higher conductivity: an increase in the oil's conductivity due to the decrease in viscosity implies that a larger portion of the signal is lost in the form of conduction current instead of being transmitted through the oil.
- Less energy storage capacity: the decrease in the dielectric constant reduces the oil's ability to store electrical energy, which affects signal propagation and increases attenuation.
- Greater dielectric losses: the increase in dielectric losses implies a greater dissipation of signal energy in the form of heat, which reduces the intensity of the transmitted signal.

On the other hand, the influence of temperature on the transmission coefficient is more pronounced at low frequencies. The curves for different temperatures are more separated at low frequencies and tend to converge as the frequency increases. This indicates that the effect of temperature on the transmission coefficient is more significant in the low-frequencyrange.Implications for power transformers:

- Monitoring the condition of the oil: the transmission coefficient could be a useful parameter for monitoring the condition of the insulating oil in transformers. An increase in the transmission coefficient at a given frequency could indicate oil degradation or an increase in operating temperature.
- Transformer design: the dependence of the transmission coefficient on frequency and temperature must be considered in transformer design, especially those operating at high frequencies or temperatures.
- Transformer efficiency: The decrease in the transmission coefficient with temperature could affect the efficiency of the transformer, as a larger portion of the energy could be dissipated in the insulating oil.

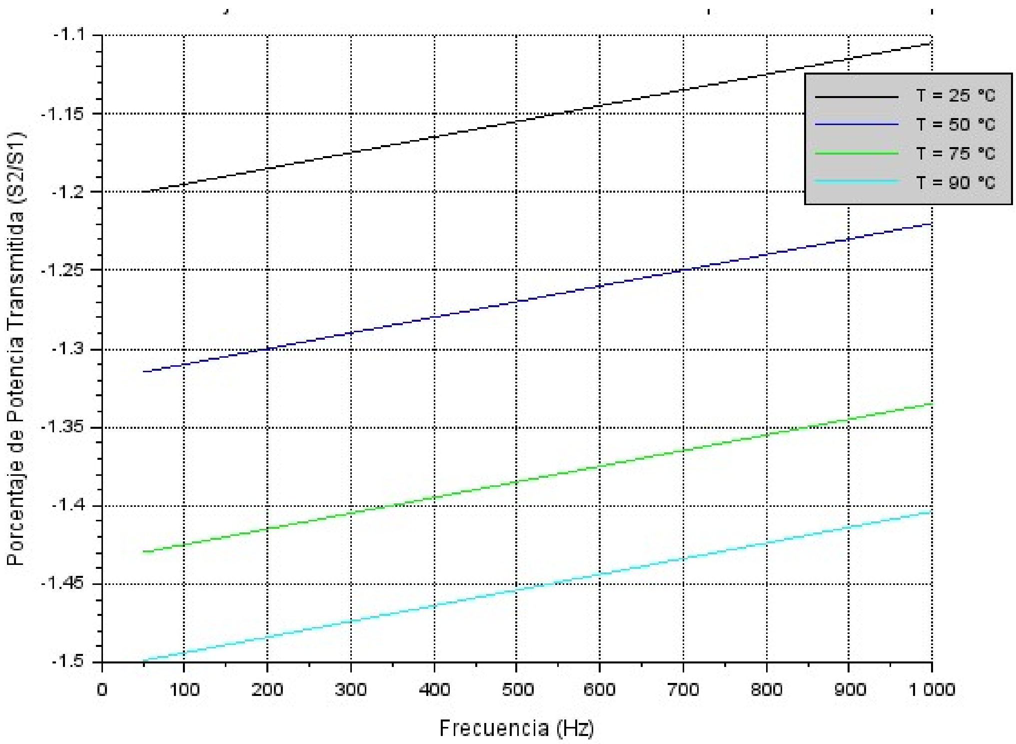

Fig. 6. Percentage of power transmitted to the insulation system of a transformer for different values of temperature and frequency

From the graph in figure 6, the following conclusions can be drawn:

- The percentage of transmitted power increases with frequency: a clear upward trend is observed in all curves, indicating that as the frequency increases, the percentage of power transmitted through the insulating oil also increases.
- The percentage of transmitted power decreases with temperature: for a given frequency, the percentage of transmitted power is lower at higher temperatures. This suggests that the increase in temperature negatively affects the dielectric properties of the insulating oil, increasing losses and reducing the efficiency in energy transmission.
- Implications for the design and operation of transformers:
    - Energy efficiency: The dependence of the percentage of transmitted power on frequency and temperature must be considered in transformer design, especially in high-frequency applications or in environments with elevated temperatures.
    - Heating: The increase in temperature in the insulation can generate a positive feedback loop, where greater losses further increase the temperature, which in turn increases the losses. It is crucial to control the operating temperature of the transformer to avoid this effect and ensure its lifespan.
    - Selection of materials: The choice of the appropriate insulating material is essential to optimize the efficiency of the transformer. Materials with low dielectric losses should be considered, especially in high-frequency or high-temperature applications.

CONCLUSIONS

Based on the results of the work, it can be concluded that:

- The relative permittivity of the insulating oil decreases with increasing frequency and increases with temperature.
- The reflection coefficient increases with temperature and decreases with frequency.
- The transmission coefficient decreases with the increase in frequency and temperature.
- The percentage of transmitted power increases with frequency and decreases with temperature.
- The variation of relative permittivity with frequency and temperature affects the dielectric properties of insulating oil and must be considered in transformer design.
- The increase in the reflection coefficient with temperature can influence the efficiency of insulation and energy dissipation in the transformer.
- The decrease in the transmission coefficient with frequency and temperature can affect the efficiency of the transformer and its ability to transmit energy effectively.
- The percentage of transmitted power is an important indicator of transformer efficiency, and its dependence on frequency and temperature must be considered in design and operation.
- Relative permittivity is a key parameter for evaluating the operational state of a transformer's insulation system.
- The analysis of relative permittivity as a function of frequency and temperature provides valuable information about the behavior of the insulating oil and its influence on the transformer's performance. A methodology was developed to estimate reflection and transmission indicators of waves in insulating oils, using measurements of relative permittivity as a function of frequency and temperature. This methodology provides a valuable tool for evaluating the behavior of insulating oil and its impact on transformer performance.
- Regression analysis is used to establish mathematical relationships between relative permittivity, frequency, temperature, and reflection and transmission indicators.
- The use of Scilab, a free software tool for numerical calculations, is highlighted for data analysis and the estimation of reflection and transmission indicators. The use of Scilab facilitates data processing and the obtaining of precise results.
- The study of relative permittivity and other indicators of wave reflection and transmission in insulating oils provides tools for the design, optimization, and diagnosis of transformers. This information contributes to the development of more efficient and reliable equipment and the implementation of predictive maintenance strategies.

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CONFLICT OF INTERESTS

Los autores declaran que no existe conflicto de intereses.

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