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THE SFRA TECHNIQUE AND ITS PRACTICAL EVALUATION - A STUDY BASED ON MEASUREMENTS AND MODELS

Daniel C. P. Araujo*
Treetech Sistemas Digitais Ltda.
UFMG – Universidade Federal de Minas Gerais

Marcos E. G. Alves
Treetech Sistemas Digitais Ltda.

Joseph L. Silvino
UFMG – Universidade Federal de Minas Gerais

Peterson de Resende
UFMG – Universidade Federal de Minas Gerais

Breno D. Rodrigues
UFMG – Universidade Federal de Minas Gerais

ABSTRACT

When a transformer is subject to high currents caused by short circuit, electromechanical internal stresses can cause geometric changes in the windings such as strains and displacements. These strains are harmful because they can reduce the ability of the transformer to withstand short circuit and power surges, reduce its service life and precipitate failures which can cause it to be taken out of service.
The mechanical changes inside the transformer result in a change in the internal inductances and capacitances.

Using different frequencies for transformer excitation, it is possible to enhance the inductive and capacitive effects and therefore improve measurement sensitivity. The frequency response tests measure the terminal impedances and the transformer transformation relationships through scanning at a frequency band and obtain the equipment transference functions for the frequency domain that are equipment signatures.
Analyzing the transformer signatures through comparisons, it is possible to detect failure due to winding strain, core displacement, short circuit between spires or even dielectric material aging.

KEYWORDS

Mechanical faults, frequency response, frequency scanning, FRA, transfer function, transformer diagnoses, terminal impedance, SFRA, specialist systems.

1.0 - INTRODUCTION

Whenever a transformer is subject to high currents caused by a short circuit, electromechanical internal strains can cause geometric changes in the windings such as deformations and displacements. These deformations are harmful because they can reduce the ability of the transformer to withstand short circuit and power surges, reduce its service life and precipitate failures which can cause it to be taken out of service (1). The mechanical changes inside the transformer result in a change in the internal inductances and capacitances.
Among the existing techniques to assess the operational status of power transformers, only specific tests like the Frequency Response Analysis (FRA) are sensitive to more localized problems, caused mostly by winding deformation due to mechanical stresses.
Using different frequencies for transformer excitation, it is possible to enhance the inductive and capacitive effects and therefore increase measurement sensitivity. The frequency response tests measure the terminal impedances and the transformer transformation relationships through frequency band scanning, and obtain the equipment transference functions for the frequency domain that are equipment signatures. Analyzing the transformer

(*) Rua José Alvim, 100 - Centro - Atibaia - Sao Paulo - Brazil
Email: carrijo@cpdee.ufmg.com.br

signatures through comparisons, it is possible to detect failure due to deformations in the winding, core displacement, short circuit between spires or even dielectric material aging.
As variant modes of the frequency response test there are the stress-stress tests and the terminal impedance measurements. Measurement of the transformation ratio for different frequencies can be taken by applying a senoidal signal with a variable frequency inside a certain range to one of the transformer windings and measuring the transference of this signal to another winding. This type of measurement allows amplification (resonance) assessment and attenuation in normalized values, indicating the frequency where they occur.
Terminal impedance measuring tests seek to describe the impedance of each winding of the transformer according to the variation of the senoidal signal frequency applied, obtaining a module curve and a phase that will represent the transformer signature, an image of the inside constructive conditions at the time the test is being applied, like in the stress-stress tests.
Initially, the tests used a 2 MHz maximum frequency. Subsequently the scanning maximum frequency was increased to 10 MHz so that full characterization of the transformer was done in a wider frequency range.

2.0 - STRAIN ON THE WINDINGS, CORE AND MECHANICAL FAULTS

Geometric changes which can be commonly observed in the windings as a result of the mechanical stresses previously described are radial and axial strains and the displacements. Although they usually do not cause a failure that may take the transformer out of service such shifts contribute for the degradation of project characteristics that are responsible for the safe operation under regimen conditions.
The axial strain is a displacement that is manifested as a removal or compression of the spires together in the same direction as the winding axis. It may cause coil conductors to twist, which degrades the paper insulation on its surface and compromises the spacers and other winding supporting elements, by crushing. Decreased mechanical stiffness of the assembly has the effect to allow winding displacement, vibrations and connection fatigue, thus reducing the capacity of the transformer to bear short-circuit currents and voltage surges. Figure 1 Figure 1 illustrates how this type of deformation takes place.

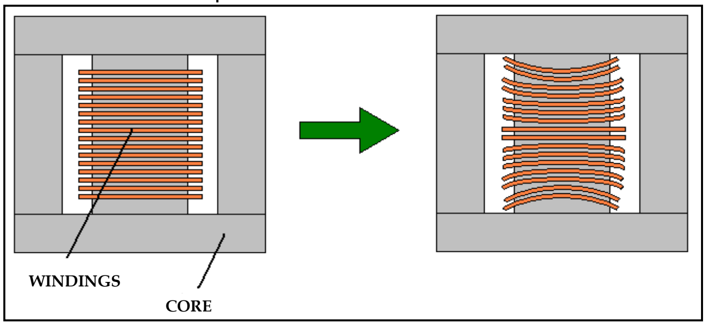

Figure 1 : Schematic of the axial strain process of a winding

The radial deformation is the one that separates the outside and inside conductors from the high and low voltage windings at the radial direction. Whenever the transformer is built with overlapping high and low voltage windings, there is a trend for the inside windings to compress towards the core, and the outside winding to expand towards the tank. In this type of deformation, the insulating paper stretches over the conductor surface due to strain, which degrades the insulation and reduces the ability to withstand voltage surges.
Moreover, reducing the distance between the inner winding and the core reduces the levels of insulation and alters the distribution of the internal electric field, which may increase the stress at specific points of the insulation. This deformation also contributes to loosen the tie-ins, which reduces the mechanical rigidity of the assembly and causes fatigue of connections and supporting parts. Figure illustrates how the radial strain takes place in a winding.

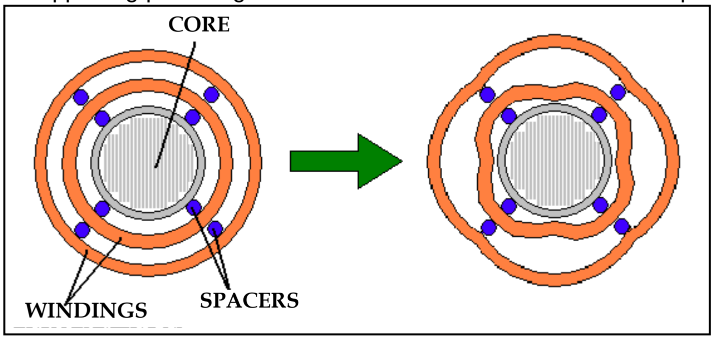

Figure 2 : Schematic of a radial deformation on a winding

In situations where the supporting and fastening structures are already fatigued enough, the mechanical forces to which the windings are subject can be sufficient to cause the spire assembly to move as a whole, thus configuring a displacement. In such cases the coil is usually off its axis. The consequences of such geometric changes are the same as the ones mentioned for the other types of displacements, such as insulation minimum distances and vibration generation. Figure 3 illustrates how a winding displacement takes place.

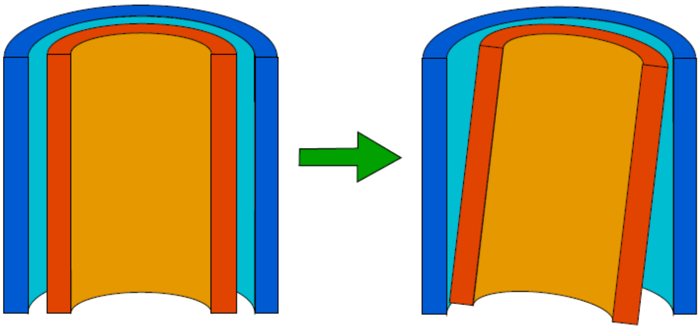

Figure 3 : A diagram illustrating a winding displacement in a power transformer. (2)

In addition to the displacement of windings subject to mechanical forces, the displacements of parts of the magnetic core may be observed less often. Due to the high mechanical strength, stresses that are typically seen on the transformer core due to electrical stresses are not able to cause visible changes. However, mechanical impacts due to transportation can cause changes in the geometry of the transformer core that can translate into insulation and fastening structures stresses, causing vibrations and the reduction of the service life of the transformer, because other degenerative processes are facilitated, such as the winding displacements themselves.
The power transformer is designed so that the set is capable of withstanding the mechanical forces arising from the nominal operation safely. However, some electrical stresses at work may exceed the maximum supportability threshold or generate fatigue. Among such efforts, the short-circuit currents and energization stand out. Another type of stress that can result in a displacement or mechanical failure is transportation accidents.
The short-circuit currents are the main responsible factor for mechanical displacements of electrical origin, due to the high intensity of the currents involved. Since the short impedance may be very low, the short current that circulates through the transformer windings may reach extremely high levels, of dozens of times the rated current. Although the duration of such currents is generally low due to the performance of the system protection, the high current amplitude may cause the action of high intensity magnetic forces of short duration enough to cause supporting structure fatigue or even cause a displacement themselves.
Besides these, there are the energization currents during shunting operations, also known as inrush currents. They may be generated at the time the transformer is energized when the applied voltage is not in phase with the induced current, which generates high current circulation due to core ferromagnetic material saturation. Such currents last for a relatively short time with an amplitude that does not exceed, in general, about eight times the nominal current, but they are responsible for much of the mechanical stress of supporting and fastening material because they occur very frequently along the transformer service life.
The mechanical impacts in the transformer during transportation are another type of cause of mechanical changes which may be mentioned. Due to the transformer's size and high weight, as well as to the difficulties inherent in its transportation from the factory to the substation, this equipment may be subject to impacts that may be enough to displacement windings or cause transformer core strain.

2.1 Characterization of the Transformer in the Frequency Domain

The association of internal capacitances and inductances of the transformer form a complex impedance network. These figures (capacitance and inductance) are strongly dependent on the geometry of the winding and the dielectric and magnetic constants of the materials used in building the equipment. Figure 4 illustrates the parasitic capacitances that arise from power transformer construction.

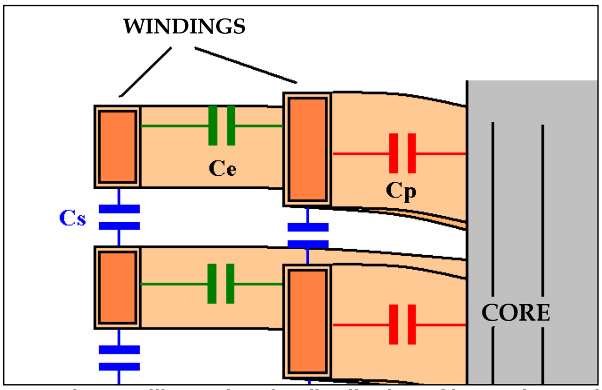

Figure 4 : A Diagram illustrating the distribution of internal capacitances

In a wide frequency band one can see that the resulting impedance behavior is typically non-linear and that the capacitive effects can become more expressive than the inductive effects in certain resonance frequencies. In Figure 5 a typical terminal impedance behavior of a power transformer winding over a wide frequency band can be seen.

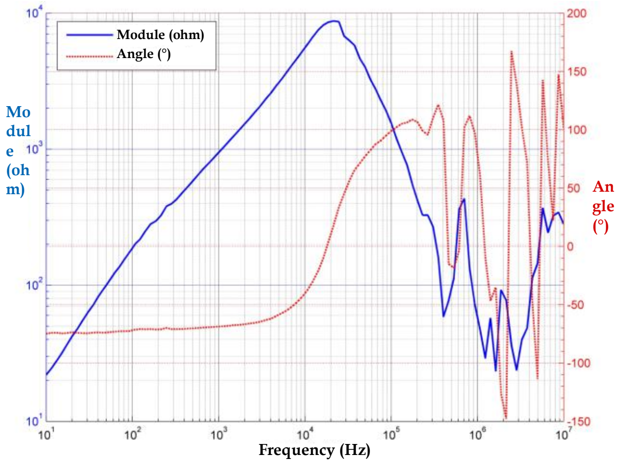

Figure 5 : Typical curve of a terminal impedance measurement test.

This behavior must be taken into consideration in studying transient phenomena and atmospheric impulse discharges that may affect the system because they generate high voltage disturbances in wide frequency bands. Whenever there are mechanical flaws in the transformer there is a change in winding geometry and consequently a change in the internal capacitance and inductance. As a result of these changes, a significant change is expected to occur in the terminal impedance curves as well as a transformation relation for the transformer windings in the frequency domain, a principle on which studies that aim to obtain a FRA mechanical flaw diagnostic methodology in power transformers is based.

3.0 - CORE DISPLACEMENT TESTS

The core displacement tests performed on this item sought to verify the impact caused by the variation of the geometry of the transformer core and the sensitivity of the FRA testing in relation to those changes. Changes in winding layout (eventually derived from extreme mechanical demands under short conditions) or core layout (impacts taken during transportation, for example) can initiate failure processes. At the same time, such changes also modify the distribution of parasitic capacitances in the transformer and can be expected to be recognized through observation of changes in the FRA curves.
The transformer used for the tests involved a core, with exposed and pressed plates. A first core displacement test was done to check the sensitivity of the test through a subtle change: the loosening of the plates that press the transformer core, as shown in Figure 6 and Figure 7 , therefore creating some distance between consecutive plates and bringing the spires closer together in relation to the mass.

Figure 6: Transformer core plate separation process.

Figure 7: Core blade detail.

Note: Through the findings in Figure 8 and

Figure 9 it is possible to observe that even with a very subtle change in the core geometry it was possible to identify deviations in the curves, especially the terminal impedance curves.

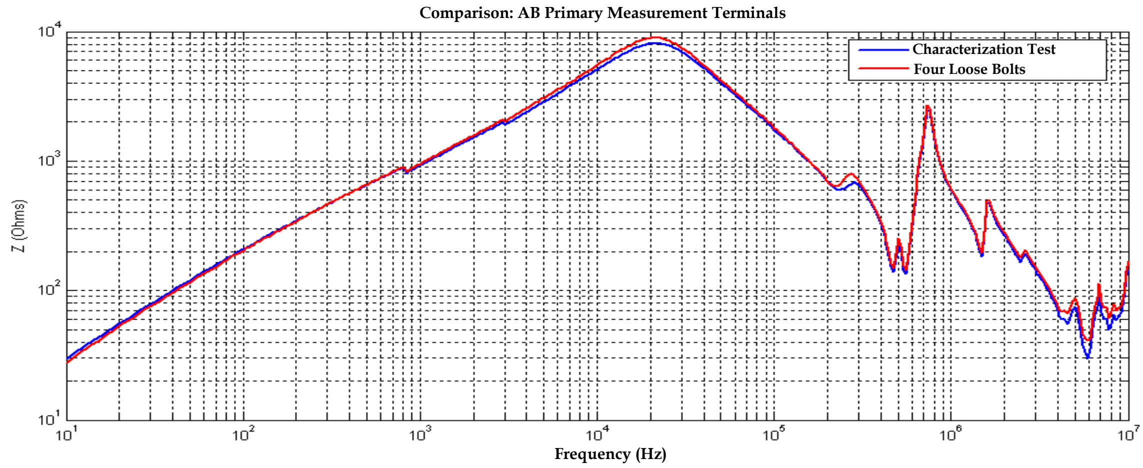

Figure 8: Terminal impedance results without plate supporting screws.

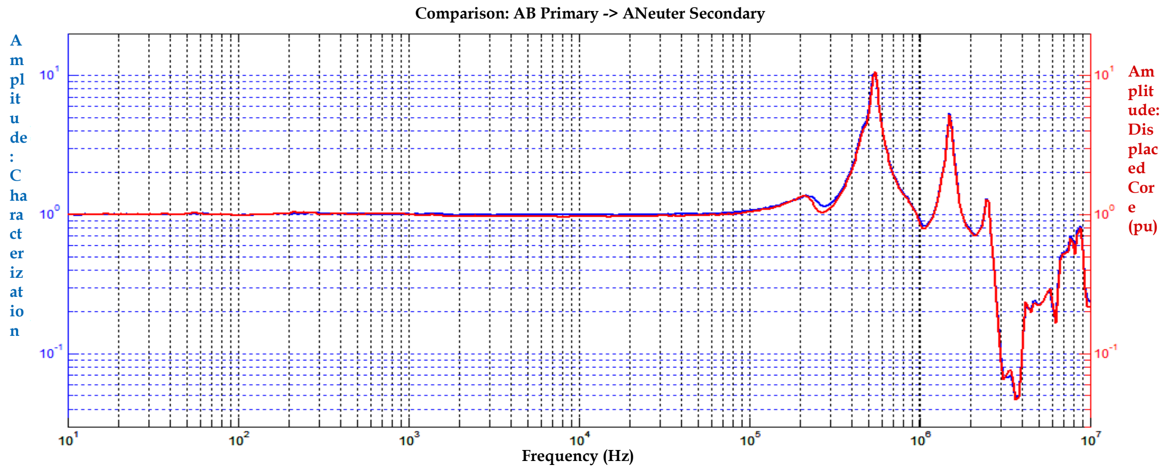

Figure 9: Terminal impedance results without plate supporting screws.

Whenever the displacement imposed on the core plates is even greater, the deviation in the FRA curves increases, as seen in Figure 10 ,Figure 11 and Figure 12.
Figure 12

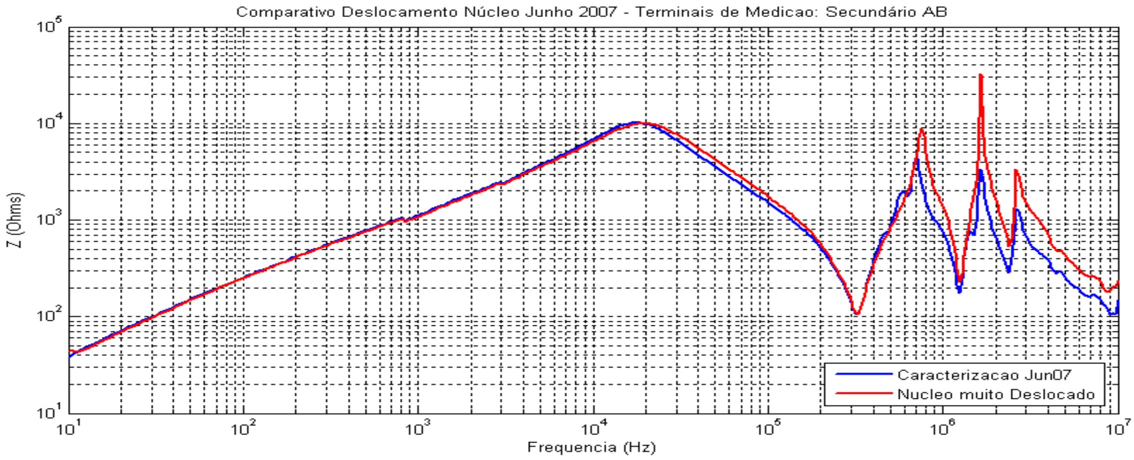

Figure 10: Impedance measurement for a considerably displaced core - Module

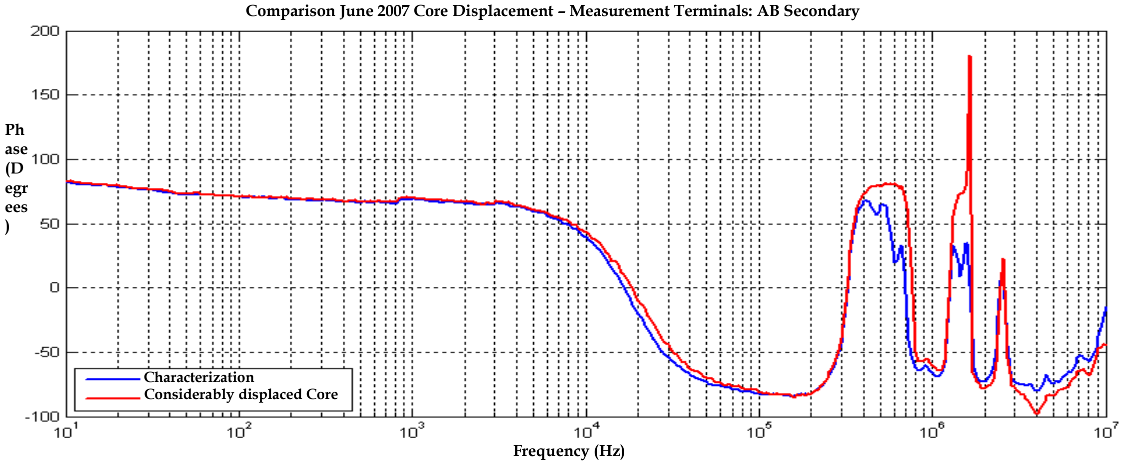

Figure 11: Impedance measurement for a considerably displaced core – Phase

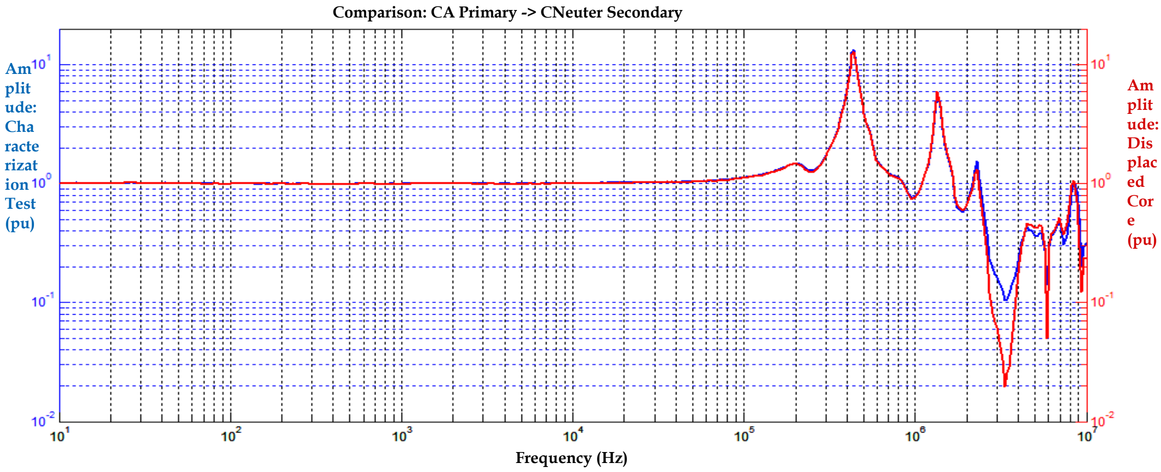

Figure 12: Transformation relation measurement for a considerably displaced core

The above results suggest that the testing methodology adopted is sensitive to coil or core displacements, supported by the excellent repeatability obtained in the tests, since, after the transformer is reassembled, with plates pressed, the FRA curves match the ones referring to the original state before the fault (Figure 13). This result supports a future diagnosis of mechanical failure more reliably.

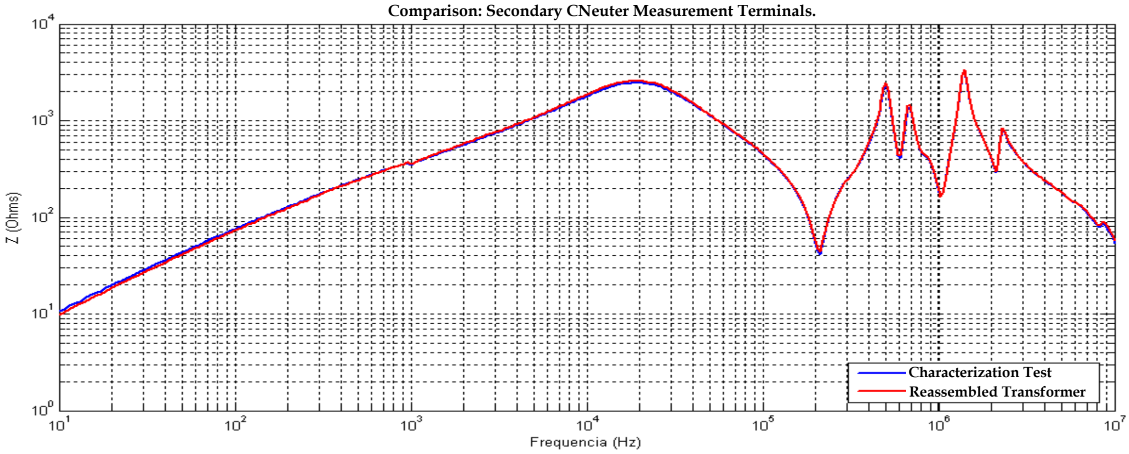

Figure 13: Results of terminal impedance measurement with the reassembled transformer.

4.0 - CONCLUSIONS

In addition to the FRA sensitivity of the FRA test to induced failure, one can notice that the failure patterns that were observed repeat themselves for the studied case, to a greater or lesser extent. This observation is crucial to establish an effective FRA diagnosis methodology. A more comprehensive study, involving the creation of an extensive database of measurements in transformers of various sizes and in laboratory and field conditions can support the development of a diagnostic methodology that, combined with a well-defined testing methodology, can be a very useful tool. This would allow greater safety when making decisions since it makes the obtained diagnosis more reliable.

5.0 - REFERENCES

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