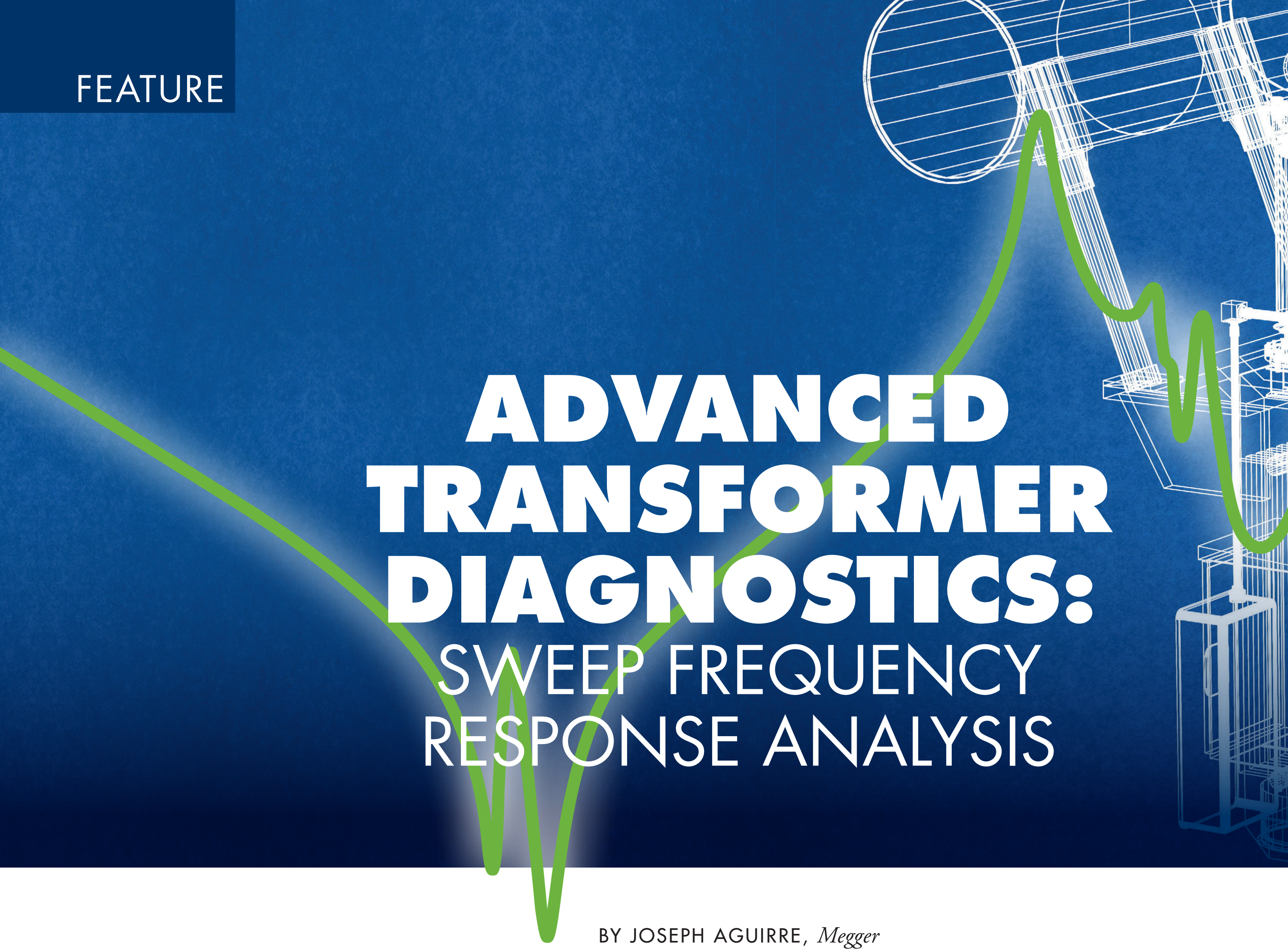

ADVANCED TRANSFORMER DIAGNOSTICS:
SWEEP FREQUENCY RESPONSE ANALYSIS

BY JOSEPH AGUIRRE, *Megger*

Transformer diagnostics play a critical role in ensuring the reliability and longevity of power systems. Understanding the condition of power transformers is essential for preventing unexpected failures and minimizing downtime, which can have significant economic and operational impacts. Sweep frequency response analysis (SFRA) emerges as a powerful tool in transformer diagnostics, offering valuable insights into the transformer's mechanical integrity, electrical characteristics, and performance.

A transformer is designed to withstand mechanical forces; however, these forces can easily be exceeded throughout its life. Mechanical deviations can occur during transportation from the factory to the site, while offloading the transformer to the transformer pad, or from short circuits close to the transformer. These events can lead to issues such as winding deformation, core movement, or insulation degradation that can be detected through SFRA testing and avoid energizing a transformer with potential defects that can escalate into critical failures.

SFRA involves subjecting transformer windings to a range of frequencies and analyzing the resulting frequency response to identify deviations from the transformer's

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expected signature or fingerprint. These signatures serve as a unique fingerprint of the transformer's structural integrity and electromagnetic properties. By comparing the SFRA results against baseline signatures or reference data from similar units, anomalies indicative of winding deformation, mechanical displacement, and core deformation can be detected with exceptional sensitivity and precision. Thus, it is imperative for the SFRA test to be the last test before departure and the first test upon arrival — and the results must then be compared.

As transformers age, they become more susceptible to mechanical stress, facing a greater risk of mechanical and insulation issues. By detecting these deviations early on, SFRA enables maintenance teams to take proactive measures to address a problem before it escalates into a critical failure.

SFRA can detect faults in all types of transformers, including oil-filled, dry-type, and gas-insulated, making it a versatile tool for power-system diagnostics. SFRA can also be used for periodic internal insights into transformer condition, providing a baseline for comparison and allowing for trend analysis. If a factory report or previous test report containing SFRA is unavailable, then the next SFRA test is considered the baseline for comparison. Any previous deformations of the mechanical structure will not be apparent until another event takes place and movement occurs.

SFRA PRINCIPLES

SFRA involves subjecting transformer windings to a range of frequencies using sinusoidal AC voltage with variable frequencies — typically, 10 hertz to 2 megahertz — and measuring the resulting responses.

The process of conducting SFRA begins with connecting the transformer to specialized test equipment, such as an SFRA analyzer. The equipment is connected to each phase of the high-voltage and low-voltage windings with all other windings open.

The input voltage and the output voltage are measured at various frequencies and the ratio of the voltage in/voltage out amplitude is measured in decibels (dB). The amplitude is calculated for each frequency change, and the results are plotted on a graph. The SFRA equipment sends these sweeps of frequencies through the transformer while simultaneously measuring the response at each frequency point. The data plotted, known as a frequency response signature, displays the magnitude and phase of the response at each frequency.

There are four measurement configurations per phase: open circuit, short circuit, capacitive inter-winding, and inductive inter-winding. The open-circuit and short-circuit tests are the most recommended tests for SFRA (Figure 1). Capacitive and inductive inter-winding tests are optional and are not typically performed in North America. The SFRA open-circuit test will primarily show the response of the core and the windings, while an SFRA short-circuit test will only show the response of the windings. This process is repeated for each winding configuration within the transformer. The responses obtained are then plotted on a graph, typically as amplitude versus frequency. By analyzing these frequency response signatures, characteristic patterns emerge that serve as indicators of the transformer's health.

Deviations from the expected signature, such as shifts in peak magnitude or changes in phase relationships, can signify mechanical issues like winding deformation, core displacement, or insulation degradation. Expertise is necessary to effectively interpret SFRA results, correlating deviations with specific faults and assessing their severity.

The frequency range of 10 Hz to 2 kHz primarily detects issues such as main core deformation, open circuits, shorted turns, and residual magnetism. In the range of 2 kHz to 20 kHz, attention is directed towards the bulk winding component and shunt impedance. Frequencies from 20 kHz to 1 MHz focus on detecting deformations within the main windings, while frequencies from 1 MHz to 10 MHz are dedicated to observing the test leads and test connections. (Figure 2) However, it's important to note that each transformer will

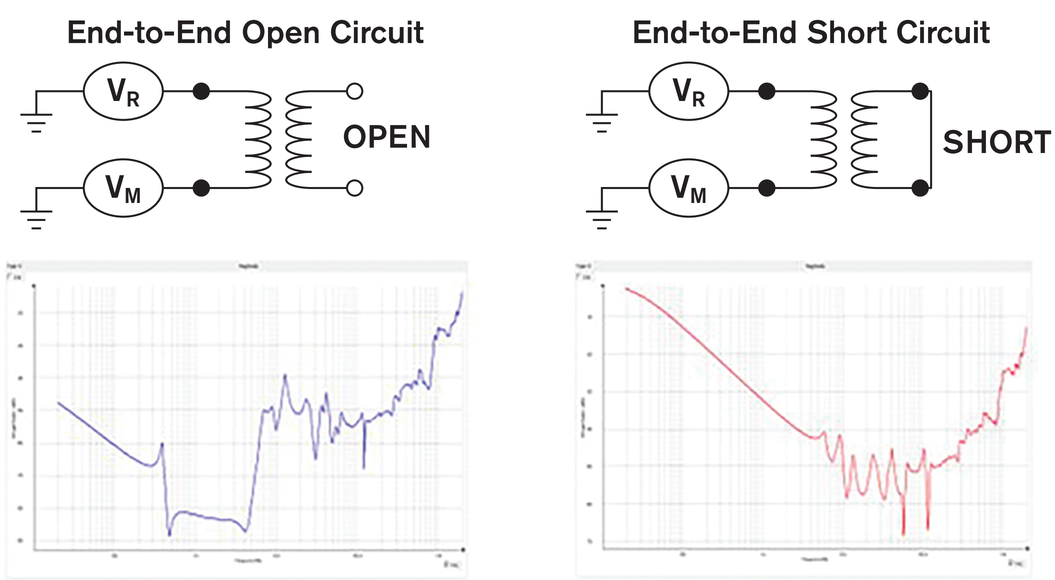

Figure 1: *Two Main Measurements Per Phase*

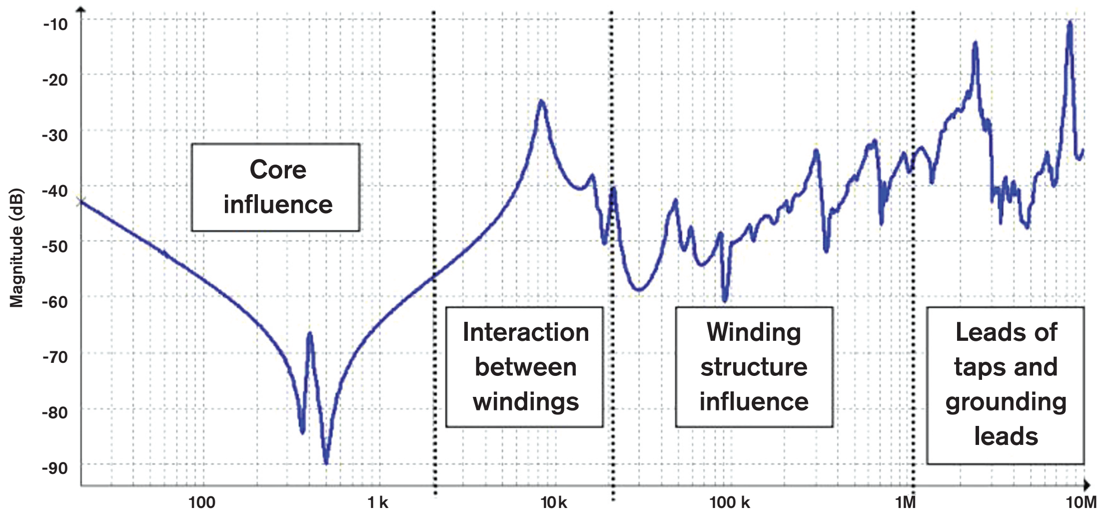

Figure 2: *FRA Trace Showing Transformer Component Influence in the Array of Frequency Regions*

yield distinct responses, and the frequency range provided serves as a general reference point.

APPLYING SFRA IN TRANSFORMER DIAGNOSTICS

Before initiating a full set of tests, it is essential to ensure the instrument's integrity by verifying its calibration and proper functioning. When tests are complete, it is also advisable to conduct a repeatability check to validate that the testing procedures haven't impacted the results. When feasible, IEEE Std. C57.149-2012, *Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers,* suggests performing a self-check of the instrument using a standard test object with a known response, which verifies the instrument and the test leads. Most test equipment manufacturers supply this field verification unit. When conducting an SFRA test, keep in mind that the lead connections have an impact on the results (Figure 3).

SFRA results can be influenced by various factors including test setup, environmental conditions, and equipment calibration. Inconsistent test conditions can lead to inaccurate interpretations or false alarms. Analyzing SFRA data requires expertise and experience due to the complexity of frequency response signatures. Differentiating between normal variations and significant deviations can be challenging, particularly for less experienced technicians.

Grounding the shield is a crucial factor in achieving accurate measurements, and the chosen grounding method significantly influences test outcomes. The standard approach involves extending the grounding cable from the top of the bushing (lead connection) to its flange. IEEE mandates precise, repeatable, and well-documented grounding techniques, including the selection of conductors, routing, and other related aspects.

The shield grounding recommendation from the International Council on Large Electric

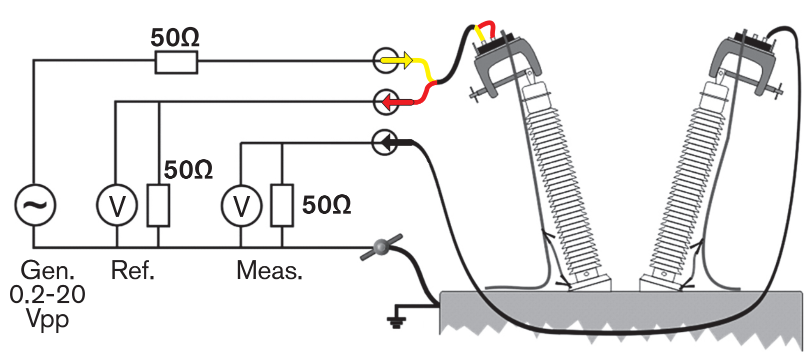

Figure 3: *An Equivalent Circuit for Measuring Frequency Response*

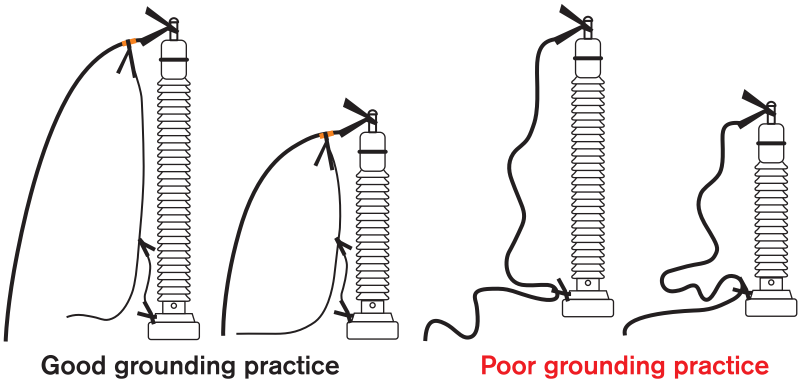

Figure 4a: *Ground Connections to a Transformer Using Shortest-Braid Technique*

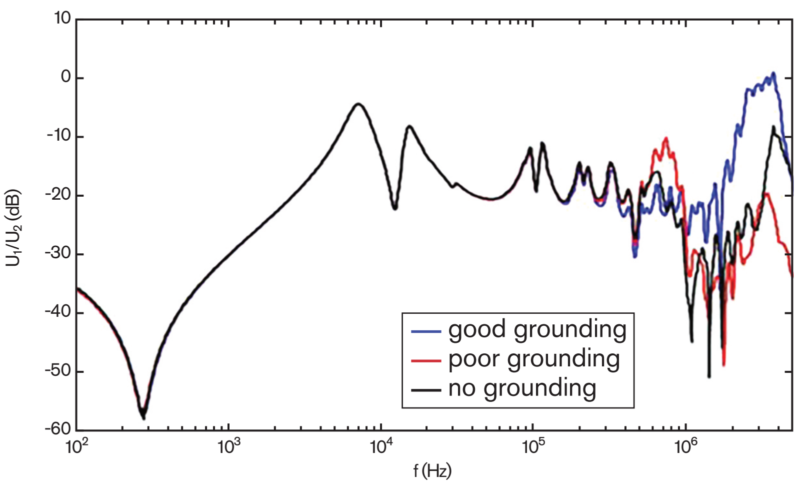

Figure 4b: *Shield Grounding Influence*

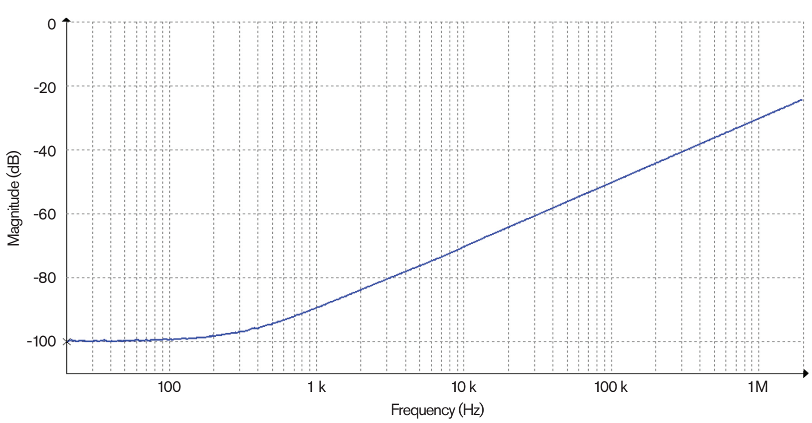

Figure 5: *Field Verification Unit with Known Frequencies*

Systems (CIGRE) is to use a grounding extension that is as short as possible, without coiling, and made with a flat braid of 20 mm minimum. To ensure a good connection, connect the shields of coaxial cables to the flange of the bushing using the shortest-braid technique (Figure 4). CIGRE also recommends not using wire for this purpose.

To achieve consistent and reliable measurements, it's crucial to carefully plan the connection of test and ground leads for each winding and phase measurement, considering both placement and method of connection. It is ideal to include photos of the connections in the test report for replication in future testing.

Once a proper test connection is made and a field verification unit with known frequencies (Figure 5) has been run, the results are deemed repeatable. The verification unit verifies the test instrument and the test leads before testing. An engineer can now analyze and interpret the results with confidence. By analyzing the frequency response of a transformer's windings, the engineer can identify mechanical displacement. This includes movement of the windings, core, or other components due to external factors such as vibrations or thermal expansion.

By analyzing the frequency response, SFRA can pinpoint the location and extent of the displacement, allowing for targeted repairs or maintenance to be performed. Note that this AC test is highly sensitive to residual magnetism. It is recommended to conduct SFRA after demagnetizing the transformer. Not doing so can lead to a false interpretation of the transformer's health (Figure 6).

Other pitfalls can affect the results. These are the questions to ask if the signatures do not align. Making detailed notes on the test setup and taking photos is imperative.

- Does the transformer have an external core ground connection?
- Was the baseline test done with or without the core ground connected?
- Is there a tertiary winding?
- If so, is it a broken delta tertiary?
- Was it open, closed, or grounded when the measurement was performed?

SFRA can also be utilized to assess core deformation in transformers. Core deformation can occur due to various factors, including electrical stresses, mechanical stresses, or thermal aging. Another important application of SFRA is its ability to compare current frequency response data against baseline signatures or reference data. By regularly conducting SFRA tests and comparing the results to previous tests, any changes or abnormalities in the transformer can be detected. This is done by overlaying the new test result with the baseline signature. When proper technique is used, the transformer signature will overlap regardless of the SFRA test equipment manufacturer (Figure 7).

A phase-to-phase comparison must be performed in all cases. When comparing traces, the engineer is searching for abnormal discrepancies. In Figure 8a, the low-voltage side is open, showing Phase A and Phase C phase alignment. The test is conducted to assess the high-voltage windings and core. A significant deviation at the lower frequency ranges is observed in Phase B.

The reason to have the low-voltage side non-shorted (open) is to see the core resonances (dips), as seen in Figure 8b. When the test was rerun with the low-voltage side shorted, Phase A and Phase C were in unison, while there was still some deviation on Phase B.

Shorting the low-voltage side removes the core resonances Figure 8b. When the transformer was detanked and inspected, results showed the Phase B winding suffered a fault resulting in a shorting and hoop buckling event.

Another method is to compare sister assets. These assets must be true sister units, indicating they have nearly identical construction. This is the only way they can be compared. A proven approach to determine whether the two power transformers are sister units is to compare serial numbers. They should be close to each other and typically within the same year. This strategy is particularly effective when comparing single-phase transformers in a three-phase system.

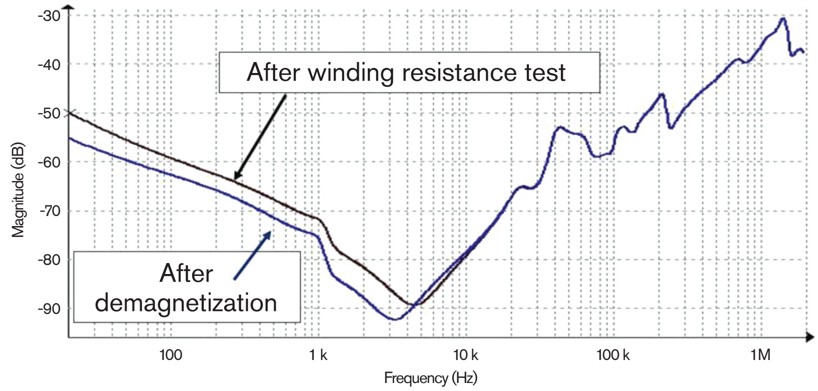

Figure 6: *Before and after demagnetization*

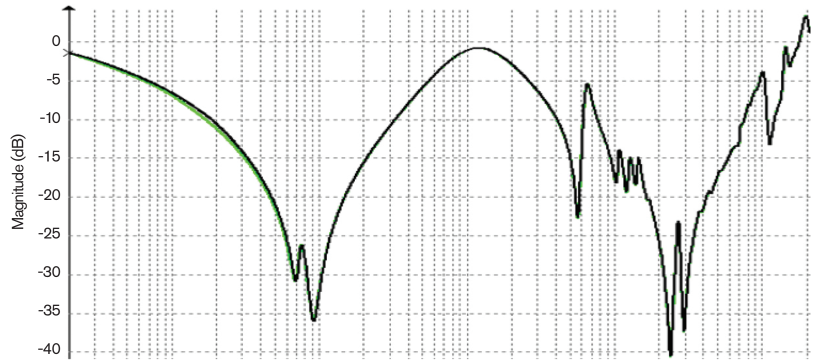

Figure 7: *Results from Three Manufacturers' Testing Units on the Same Transformer*

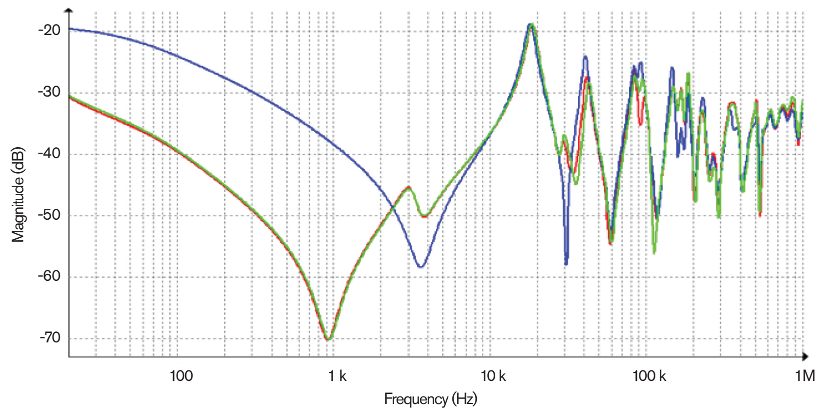

Figure 8a: *Comparison before a Fault*

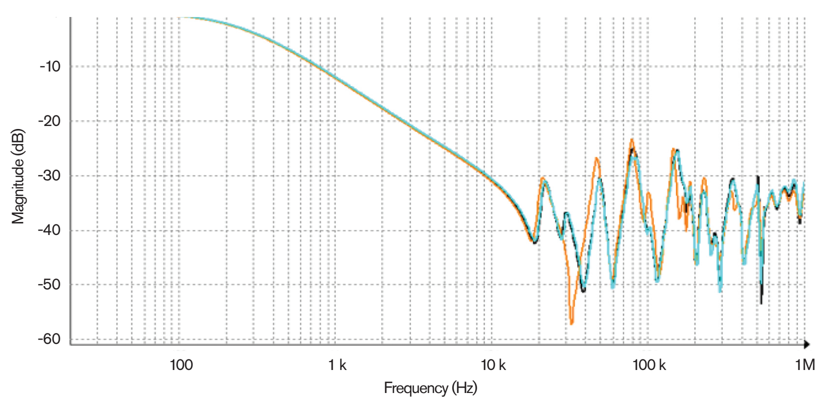

Figure 8b: *Comparison after a Fault*

BENEFITS OF SFRA TESTING

SFRA provides early warning signs of potential transformer issues. Maintenance teams can then take timely corrective actions to address these problems before they escalate into more severe malfunctions. This proactive approach helps extend transformer lifespan, minimize downtime, and optimize operational efficiency.

SFRA testing is also instrumental in preventing catastrophic transformer failures. By detecting and addressing faults before they lead to serious malfunctions, SFRA helps prevent events that could result in significant damage to equipment, disruption of power supply, and safety hazards. This preemptive approach not only saves costs associated with repairs and replacements but also ensures the uninterrupted operation of critical power infrastructure.

USING SFRA WITH OTHER TESTS

SFRA can also be used to double-check tests that were previously performed, giving the end user and asset owner a sense of confirmation when interpreting the results. If a previous mechanical integrity test such as short-circuit impedance was performed, an engineer or technician can verify the magnitude of 60 Hz on the short-circuit SFRA test and compare the results to the short-circuit impedance test. Short-circuit impedance is an AC test conducted by shorting the secondary side of the transformer and applying voltage to the transformer, then measuring the source current that flows through the primary winding of the transformer at 60 Hz ± 2%. This is also known as the leakage reactance test.

The SFRA test can also be used to evaluate an open-circuit test, commonly referred to as a no-load loss or excitation loss assessment. No-load-loss measurements are typically conducted during commissioning and post-repair evaluation of service-aged transformers to discern inter-turn shorts, core sheet shorts, and core-ground faults. It is recommended to carry out the no-load test at 380/220 V. It is acceptable to measure no-load losses at frequencies close to the rated value of 60 Hz ± 3%. The test voltage is administered to a low-voltage winding, while the remaining windings are left unconnected. In the case of three-phase transformers, the no-load loss is assessed phase-by-phase. This method enables comparison of losses across phases, aiding in identifying faulty phases and facilitating overall analysis by allowing result comparison.

CONCLUSION

Sweep frequency response analysis (SFRA) emerges as an indispensable diagnostic technique in transformer testing, offering precise fault identification, enabling proactive maintenance strategies, and averting catastrophic failures. Its superior sensitivity in detecting subtle changes in transformer geometry or winding structure underscores its significance in safeguarding transformer integrity.

The imperative is clear: Integrate SFRA into routine maintenance practices and condition monitoring programs. Adopting this technique is essential to ensure the reliability, longevity, and safety of power transformers. By harnessing SFRA's non-invasive, time-efficient, and cost-effective diagnostic capabilities, organizations can preemptively detect and address potential transformer issues, thus extending transformer lifespan, minimizing downtime, and optimizing operational efficiency.

This preventive approach not only preserves transformer assets but also fortifies power infrastructure networks, ensuring uninterrupted service for society. Therefore, it is incumbent upon industry stakeholders, utilities, maintenance providers, and regulatory bodies to recognize SFRA's importance. These entities must take decisive action to embed it into maintenance strategies and standard practices. Electrical testing upholds the reliability and safety of power systems for the benefit of society. NW

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