ABSTRACT

The Sweep Frequency Response Analysis (SFRA) has become a standard method to assess the mechanical and electrical integrity of the power transformer's active part. It provides a very high sensitivity to evaluate possible damages after transportation or for troubleshooting after a specific event such as a near failure with high short-circuit forces. However, users often struggle to reach a high reproducibility which is essential for a reliable condition assessment. Deviations, caused by reproducibility issues, can lead to misinterpretation, unnecessary inspections or cost-intensive maintenance activities. This paper focuses on best practices in order to perform highly repeatable and reproducible SFRA measurements.

KEYWORDS

IEC 60076-18, power transformer, reproducibility, SFRA, Sweep Frequency Response Analysis

SFRA has become a standard method to assess the integrity of power transformers

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Performing reliable and reproducible frequency response measurements on power transformers

1. Introduction

The Sweep Frequency Response Analysis (SFRA) method was introduced to verify the integrity of the active part of a power transformer. After manufacturing, power transformers are transported on site, often over long distances using different types of transportation, such as ship, train or truck. Both during transportation and loading from one vehicle to another, the transformer might be exposed to mechanical shocks. Such shocks can also be caused by earthquakes or mechanical impacts due to short-circuit forces after a failure. All these impacts can lead to a deformation or partial movement in the active part. Common diagnostic measurements such as transformer turns ratio, including exciting currents, short-circuit impedance at nominal frequency as well as frequency response of stray losses (FRSL), may have disadvantages regarding to their sensitivity to detect and prove mechanical deformations. For example, a buckling of a winding does not typically influence ratio or insulation resistance measurements and is hard to detect in a change of capacitance. Compared to them, the SFRA is the most sensitive method for reliable core and winding assessment [1]. This paper illustrates several best practices to perform SFRA measurements in order to ensure highly repeatable and reproducible test results.

2. Basics of the SFRA method

The SFRA method comprises a highly repeatable and reproducible frequency response measurement on a power transformer and the subsequent comparison with an existing fingerprint, also called a reference measurement [3], [4]. In principle, three methods are commonly used to assess the measured SFRA traces:

- Time-based (current SFRA results will be compared to previous results of the same unit)
- Construction-based (SFRA of one transformer will be compared to that of another of the same design)
- Phase-based (SFRA results of one phase will be compared to the other traces of the same unit)

The preferred method is the time-based comparison. However, the fingerprint or base-line measurement is, in the majority of cases, not available. Nevertheless, by a simple comparison of the SFRA plots of the phases or by a type-based comparison, a successful assessment of the results can be achieved. Even if a fingerprint of the transformer is available, the experience has demonstrated that the comparison has to be carried out carefully because in some cases the deviations observed are not related to deformations, but to measurements under different conditions or measurement mistakes [8]. For overcoming these misleading factors, the comprehensive time-based comparison concept is proposed in this paper.

2.1 Frequency response measurement

The active part of a power transformer, consisting of the winding, core, insulation and connecting leads, forms a complex electrical network, as indicated in Figure 1. Such a network has unique characteristics which can be visualized by the frequency response: A frequency-variable sinusoidal low-voltage signal of, for example, 10 V, is applied to one terminal and the response (U2) is measured at another terminal, Fig. 2. In order to measure the amplitude, phase and frequency of the injected signal, a reference measurement channel (U1) is connected to the same injection point as the source [2]. The frequency response consists of amplitude, ratio and phase difference between both terminals.

The frequency response can be measured in different ways in order to gather more information for a sophisticated assessment. The most common approach is the open-circuit measurement. Thereby, the frequency response is measured between two terminals of the same voltage level, leaving all other terminals open. When shorting the terminals of the other voltage level (for example, the low-voltage winding when measuring the high-voltage windings), a short-circuit measurement is performed. A capacitive inter-winding measurement describes a test between two windings on the same core limb (for example, the high- and low-voltage winding), while all other terminals are open. An inductive inter-winding measurement is also performed between two windings on the same core limb, whereas the measurement clamps are mounted on each winding terminal and the other end of the winding is connected to ground.

Three methods are commonly used to assess the measured SFRA traces: a time-based, a construction-based and a phase-based method

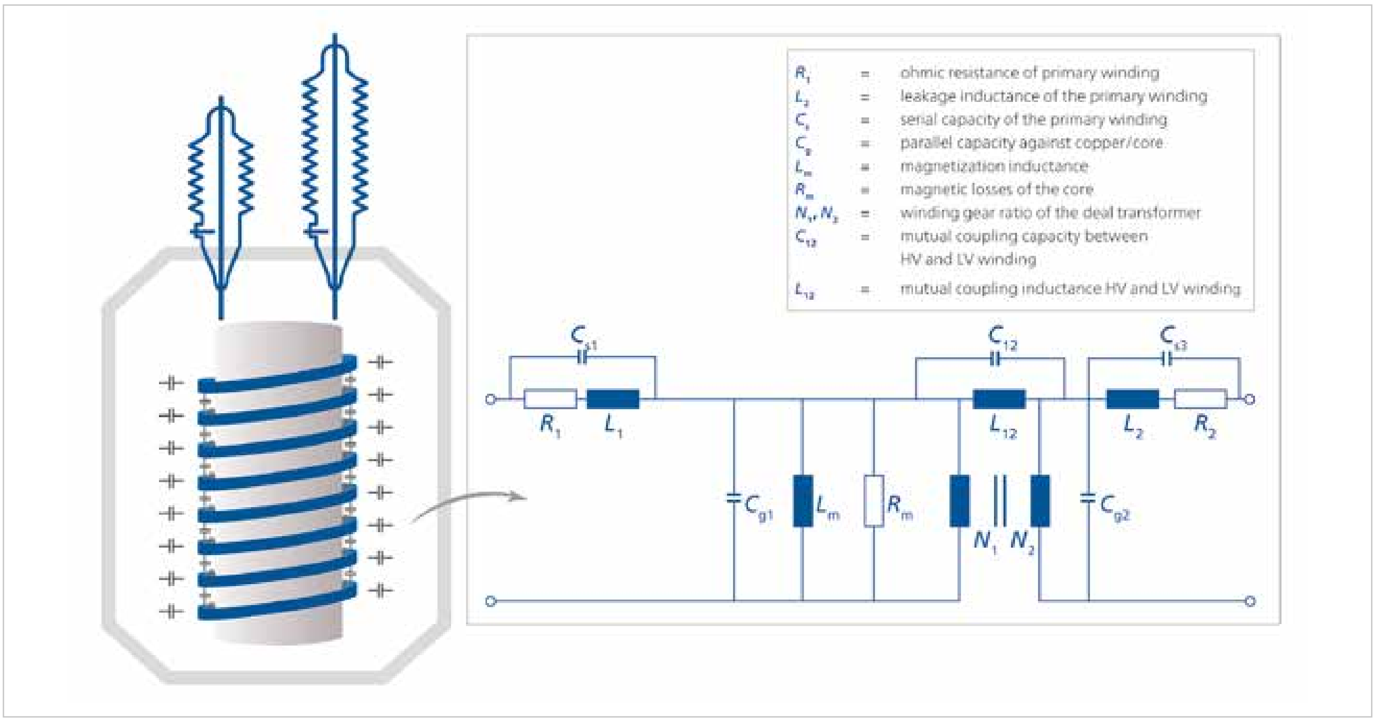

Figure 1. Simplified R-L-C equivalent circuit of a power transformer

2.2 Analysis methods for SFRA measurements

Depending on their main influences, different failure modes will be revealed stronger in different frequency ranges. As an example, core phenomena will influence the low-frequency region whereas connection issues will influence the very high-frequency range above 1 MHz [1]. Experience shows that setup issues, such as not following the shortest braid concept, can influence the frequency response even at 500 kHz. However, it is difficult to provide a general table which shows the relation between the frequency range and transformer characteristics as there are too many factors influencing the frequency range (e.g. MVA rating, winding type, voltage level, etc.). Basic references can be found within the CIGRE brochure. Different analysis tools can be used based on mathematical indices [5], or characteristic changes within the measured curves [6].

The connection technique is essential to achieving high degree of reproducibility of SFRA measurements

For every analysis, a fingerprint or baseline measurement is necessary. If available, a comparison should always be made to a previous measurement of the same transformer using the same configuration [7], a so-called time-based comparison. Such reference measurement can originate, for example, from commissioning tests or in-depth testing on site. Alternatively, if no reference measurement from this transformer is available, the frequency response can be compared to a sister asset. Sister assets typically have a very similar, but not identical, frequency response, as shown in Fig. 3. Therefore, small deviations are ac-

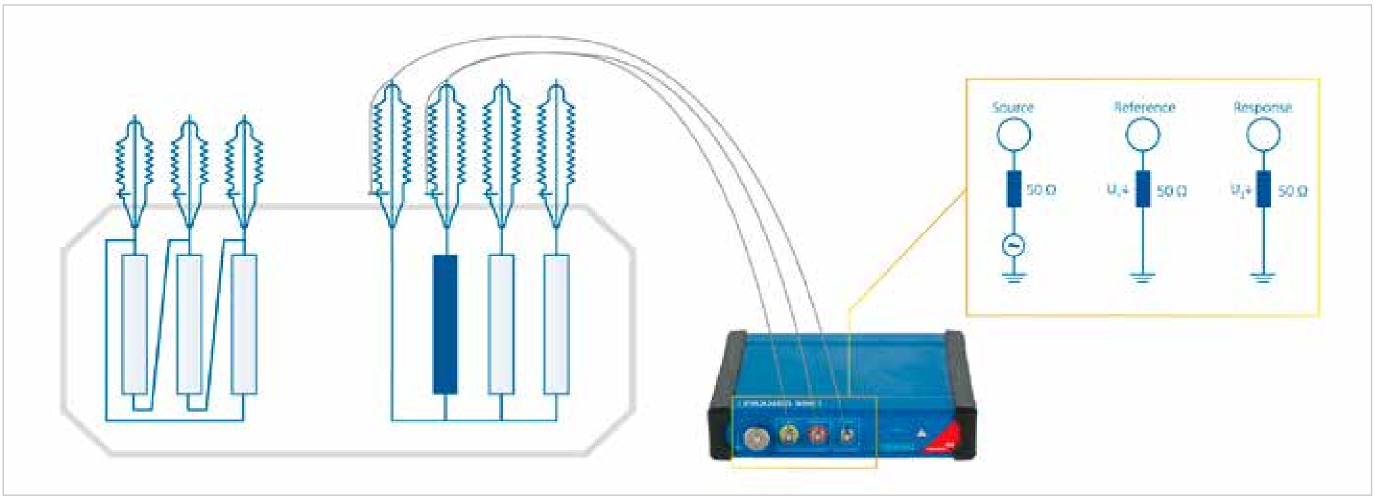

Figure 2. Typical setup of a sweep frequency response analysis

Figure 3. Frequency response measured in an open-circuit test on sister transformers (200 MVA, 230 kV interleaved disk winding)

ceptable and do not necessarily indicate a problem.

In cases where not even trace of a sister asset is available, phase-to-phase comparisons may be applied. A good comparison is only possible for a symmetrical design, which is not exactly given for common designs. Considering that even larger deviations can be caused by constructive differences between phases, phase-to-phase comparisons require the greatest amount of experience. Typically, the centre phase includes the most deviation, whereas the other two phases overlay with reasonable similarity. The main deviations between the centre phase and outer phases are expected at lower frequencies, which are mainly affected by the core due to the different flux paths.

3. Importance of the connection technique

The SFRA is a very sensitive method used to detect even the smallest changes within the electrical network of a power transformer. The advantage of being highly sensitive can sometimes be a disadvantage in terms of repeatability and noise sensitivity. Therefore, the connection technique is essential to achieve a high degree of reproducibility, especially in the high-frequency range above 500 kHz [1], [9].

The IEC 60076-18 standard describes the recommended procedure for a proper and reproducible measurement setup in detail, Fig. 5. It is recommended to use double-shielded coaxial cables which are connected to the bushing terminal. From here, a connection to the flange or tank should be installed on a low inductive ground, preferably using a flat, wide aluminum braid instead of a simple wire. As explained in [10], braids have a large surface, a low inductance, and the mesh reduces the considerable skin-effect above 80 kHz. As a consequence, the braid structure provides a better conductivity for high frequencies, resulting in a more efficient noise suppression towards ground compared to the use of simple wires.

The length of the ground connection influences the frequency response. To achieve high reproducibility, it is suggested to use the shortest possible length by pulling the braid tightly along the body of the bushing as shown in Figure 6.

Besides the connection technique itself, it is important to establish a proper electrical contact between the terminal flange and the measurement clamp used, respectively. Cleaning the terminal and removing lacquer layers help reduce the contact resistance. Modern SFRA devices provide a ground-loop check to ensure proper connections with a low contact resistance to ground.

In accordance with the applicable standards, SFRA tests must be performed with the same transformer configuration

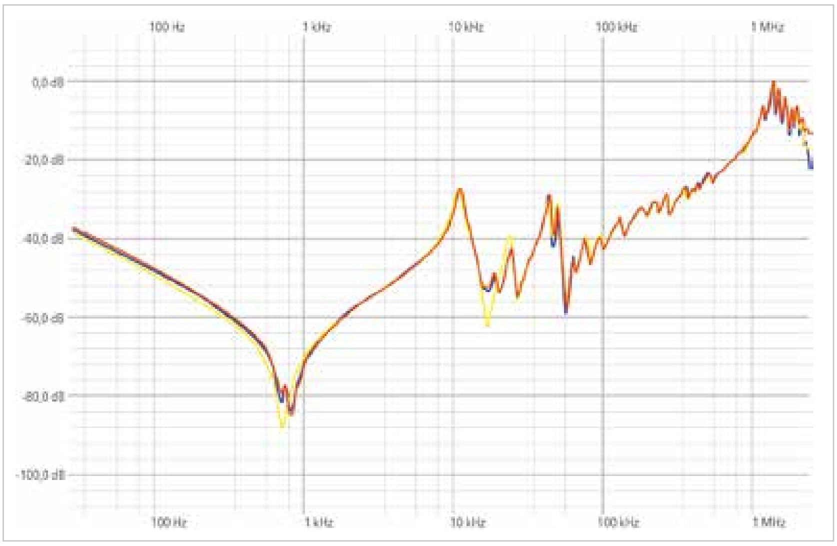

Figure 4. Comparison of the frequency response traces measured on three phases of the same transformer (200 MVA, 230 kV interleaved disk winding)

4. Influencing factors of the frequency response

As discussed above, it is essential for a comparative method such as SFRA to provide the highest confidence in excluding influencing factors related to the measurement setup or external factors, which will be described within the following chapter. For the sake of completeness, it is worth mentioning that for the described use-cases, the OMICRON FRANEO 800 SFRA test system was used and the end-to-end open circuit measurement was conducted on various assets.

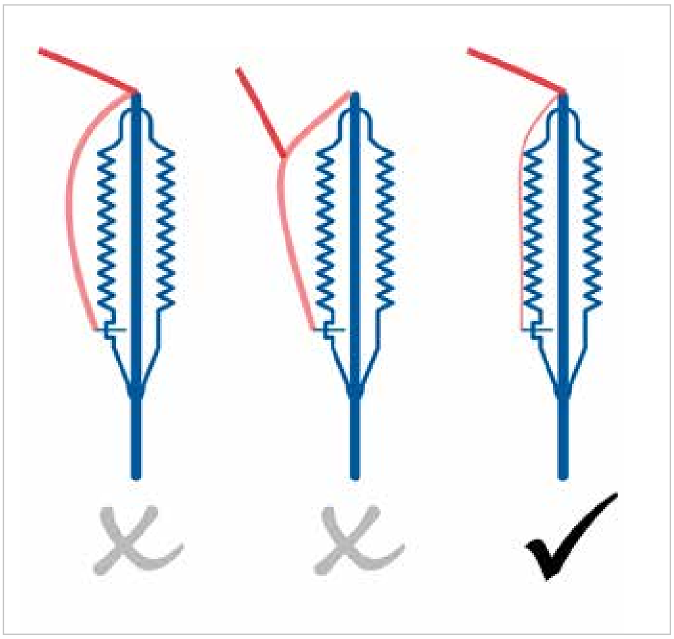

Figure 5. Schematic of the recommended setup according to IEC 60076-18

Figure 6. Example of shortest-braid connection concept: measurement cables (black) are connected to the bushing terminal and the grounding braid to the terminal and bushing flange

4.1 Factors on the measurement setup

4.1.1 Shorting and grounding of tertiary windings and separate neutral terminals

The measurement type "open-circuit" or "short-circuit" defines whether the terminals of the opposite voltage level have to be short-circuited or not. In other words, when measuring the high voltage side, it defines whether to short-circuit the low voltage terminals or not.

The measurement type does not provide information on how to handle separate neutral terminals or tertiary windings which significantly influence the measured frequency response. This includes floating, closed or grounded tertiary windings. Figure 7 shows the deviations between two open-circuit measurements made on the low-voltage windings with grounded and ungrounded tertiary winding. Various deviations, especially within the area of mutual coupling (interaction of the windings) on the measured frequency response can be observed. In general, the frequency response for the magnetization inductance and parallel capacitance remains unaffected. Therefore, it is suggested to leave all other terminals open and ungrounded, as recommended in the IEEE Standard C57.149 [3].

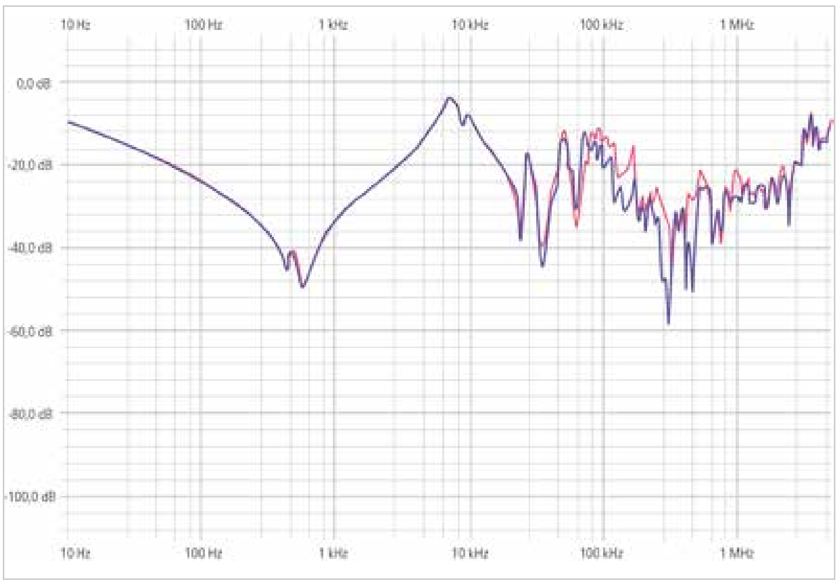

Figure 7. Influence of grounded (blue) and ungrounded (red) tertiary on measured LV open-circuit curves

4.1.2 Measurement direction

The measurement direction, which in the case of star-connected power transformers is from phase to neutral or neutral to phase, significantly influences the high-frequency behaviour as shown, for example, in Figure 8. If not specified differently, it is suggested to have the source and reference lead connected to the phase terminal and the response lead to the neutral terminal [3], [4].

4.1.3 Output voltage

In the low-frequency range, the frequency response is dominated by the core magnetization inductance and, therefore, depends on the output voltage, as shown in Figure 9. The residual curve is not affected by the output voltage as the transformer windings can be considered as a linear system, which, in principle, remains unaffected by the output voltage.

4.1.4 Grounding and measurement leads

Different procedures to connect the measurement and grounding leads are explained in IEC 60076-18 [4]. The most common way is to use specially-designed clamps connecting the double-shielded

Adapting the ground lead to ensure the shortest path to ground provides the highest degree of reproducibility

BNC-cable to the phase terminal, and to apply a braid wire for grounding the shield between the clamp and the bushing flange. As described in section 3, using a braid instead of a wire will significantly reduce the noise influence, especially around mains frequency. Furthermore, the length of the ground lead is essential for the low-frequency region, as shown in Figure 10. When using leads with a fixed length, the position of the lead influences the frequency response. Therefore, the concept of adapting the ground lead in order to ensure the shortest path to ground provides the highest degree of reproducibility.

4.1.5 Tap changer position and bushings

In accordance with the applicable standards, SFRA tests must be performed with the same transformer configuration, including bushings or tap changer position. Sometimes test bushings are used during factory acceptance tests and the final bushings are mounted on site. When comparing the frequency response measured at the factory with the one measured on site, deviations will occur most probably in the high-frequency range. Changing the tap changer position will cause continuous changes of the curve shape over a wide frequency range, as shown in Figure 11. It is suggested to perform measurements for each relevant phase on the lowest, highest and middle position of the tap changer, while switching continuously from the higher to the lower position [3], [4].

4.1.6 Contact between bushing terminal and ground lead

One of the most typical connection errors that occur is an unwanted contact of the ground lead with the bushing terminal. Such error influences the frequency response mainly on the higher frequencies, as shown in Figure 12. In order to avoid this short circuit, it is recommended to use an insulating cover for braids.

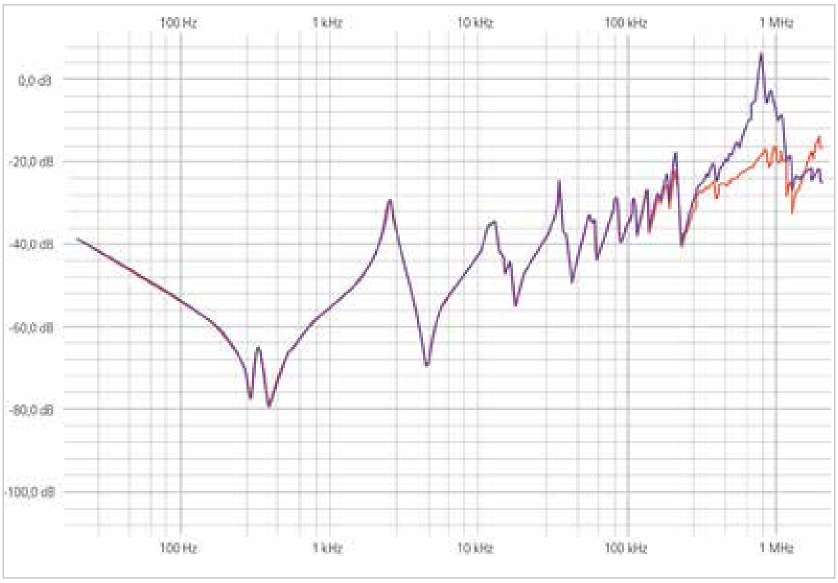

Figure 8. Influence of the measuring direction, source to phase (blue) vs. source to neutral (red)

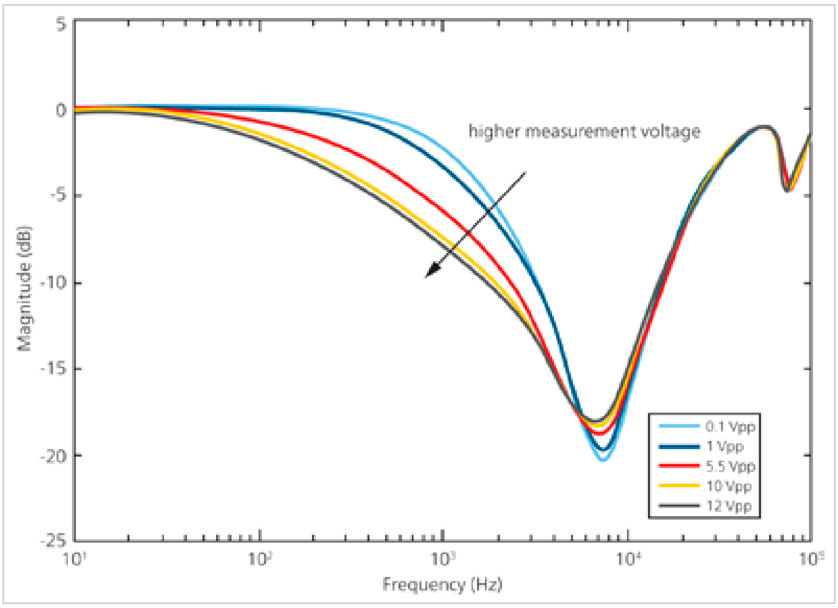

Figure 9. Effect of the selected output voltages; influence of different output voltages on magnetization inductance L_m

Figure 10. Influence of different connection techniques, the lowest noise influence and highest repeatability using a ground braid in the shortest path concept (blue), wire connection (green), and ground braid with a bigger loop (red)

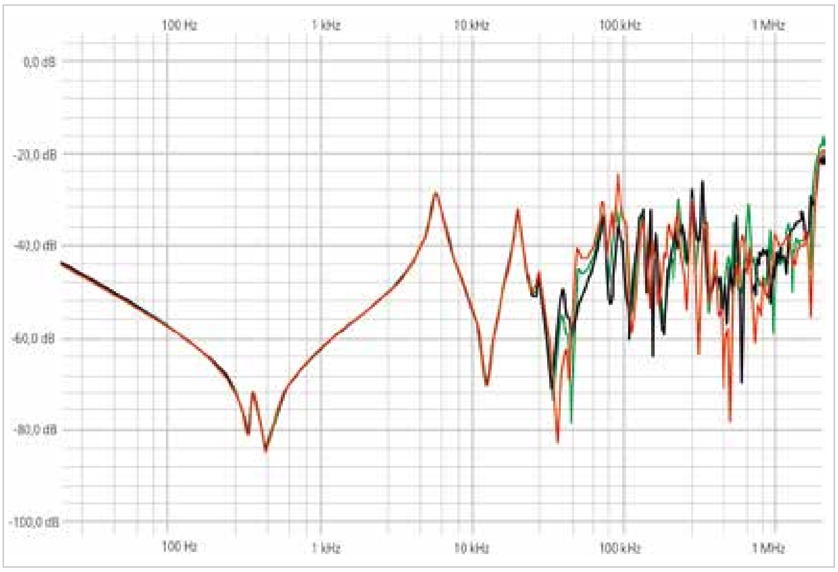

Figure 11. Influence of the tap changer position on the frequency response of a power transformer (tap 1 – red, tap 2 – green, tap 3 – black)

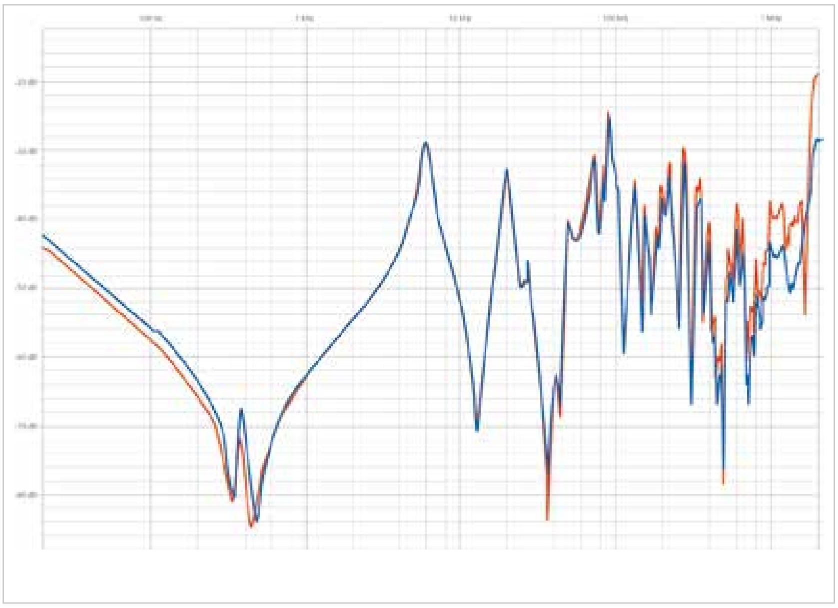

Figure 12. Frequency response measured on HV side in an open-circuit test; proper connected (red) and short circuit between terminal and ground at the reference (blue)

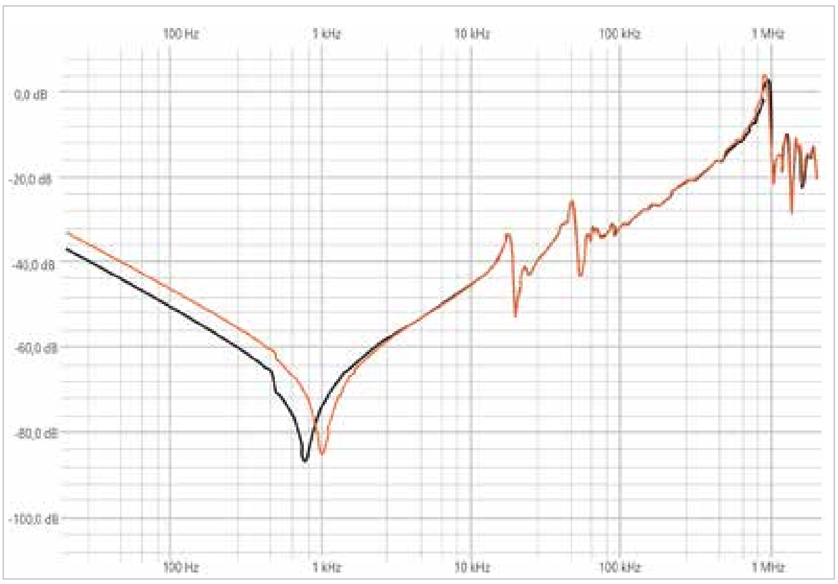

Figure 13. Frequency response of a power transformer measured in an open-circuit test before (red) and after (black) demagnetization

The use of ground braids instead of simple wires helps increase reproducibility

4.2 Other influencing factors

4.2.1 Residual magnetization

Residual magnetization is a frequently occurring phenomenon caused by previous measurements, such as a DC winding resistance measurement. This can be avoided by demagnetization before performing SFRA tests. The influence is evident, particularly in the very low-frequency range, as shown in Figure 13, where the core resonance is shifted to the right. Other parts of the SFRA trace remain unaffected by this phenomenon. Therefore, residual magnetism can be simply identified and usually does not influence further analysis.

4.2.2 Insulating fluid

A power transformer should always be measured with the same configuration as that it will have on site. This includes the insulation fluid, as it significantly influences the frequency response. When comparing the SFRA measurements of an unfilled and an oil-filled power transformer, as shown in Figure 14, a systematic shift of characteristic frequencies can be observed. This is caused by the different dielectrics (air/gas with $\varepsilon_{r,gas} = 1$ vs. oil with $\varepsilon_{r,oil} = 2.2$) and roughly corresponds to the theoretical value which can be calculated by the square root of the relative permittivity of mineral oil [11].

4.2.3 Temperature

Ambient environmental conditions such as temperature can influence the measured frequency responses. However, investigations have shown that thermal coefficients for shifting the resonance points with temperature are very small [12]. As a consequence, the shift can be neglected in the typical temperature range between 15 °C (59 °F) and 70 °C (185 °F).

Conclusions

This paper highlighted the importance of a suitable connection technique. The paper also discussed advantages of the technique suggested by IEC 60076-18 in comparison to other techniques. In addition to providing a high degree of reproducibility, the use of ground braids instead of simple wires helps to avoid the influence of the narrow-band noise around mains frequency and increases the reproducibility, especially in the high-frequency range above 500 kHz.

Influencing factors of the frequency response were listed and described, and examples of the curve shape change were given. This included their influence on the measurement setup, such as shorting or grounding of tertiary windings, measurement direction, output voltage, connection technique and tap changer position. Besides this, other effects were discussed, such as residual magnetization, the influence of insulation fluid or changes due to temperature and humidity.

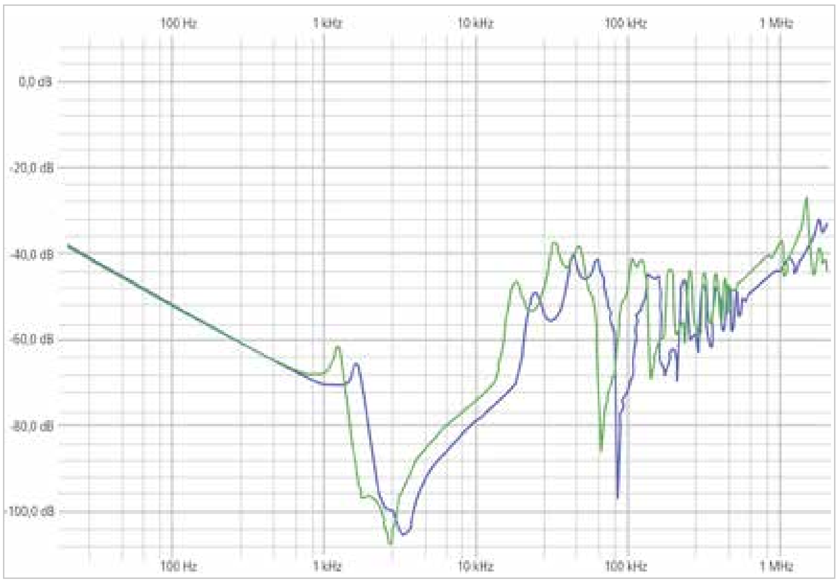

Figure 14. Measured HV traces of an oil-filled (green) and unfilled (blue) tank

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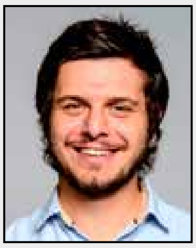
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