

Aspects of the Practical Application of Sweep Frequency Response Analysis (SFRA) on Power Transformers

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SUMMARY

Sweep Frequency Response Analysis (SFRA) has turned out to be a powerful and sensitive method to evaluate the mechanical integrity of core, windings and clamping structures within power transformers by measuring their electrical transfer functions over a wide frequency range. The contribution summarizes various aspects of the practical application of SFRA. After a short introduction of SFRA basics a survey of existing standards and guides on FRA is given. The different sources of reference data and their significance are discussed using examples. Uncertainties are shown and tips for dealing with them are presented. The choice of test types is discussed for measurements without existing reference data. Information about the handling of test data is mentioned. A summary of guidelines derived from a large number of successful measurements is given to put the reader in a position to achieve a good degree of repeatability, too. Finally the application of SFRA for the evaluation of transportation is described and an example for the successful detection of shipment damage is given.

KEYWORDS

- 1 SWEEP FREQUENCY RESPONSE ANALYSIS (SFRA) – STANDARDS – ASSESSMENT – REPEATABILITY – TRANSFORMER TRANSPORTATION – SHIPMENT DAMAGE – SISTER TRANSFORMERS – MEASUREMENT MISTAKES**

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1 INTRODUCTION

The deregulation of the electric power market involves increasing of economic pressure which requires a reduction in servicing and decreasing maintenance costs. On the other hand, we face aged and aging transformer fleets operating with increasing loads [1] all over the globe. Therefore, the diagnosis of this apparatus becomes more relevant in general but especially for strategically important or particularly risky transformers. In the last few years a fast-paced technical development regarding various aspects of measurements, data acquisition and analysis has taken place across the world. Sweep Frequency Response Analysis (SFRA) has turned out to be a powerful, non-destructive and sensitive method to evaluate the mechanical integrity of core, windings and clamping structures within power transformers by measuring the electrical transfer functions over a wide frequency range. This is usually done by injecting a low voltage signal of variable frequency into one terminal of a transformer's winding and measuring the response signal on another terminal (see fig. 1). This is performed on all accessible windings following according guidelines. The comparison of input and output signals generates a frequency response which can be compared to reference data (see chapter 3).

The core-and-winding-assembly of power transformers can be seen as a complex electrical network of resistances, self-inductances, ground capacitances, coupling inductances and series capacitances as schematically shown in figure 2. The frequency response of such a network is unique and, therefore, it can be considered as a fingerprint.

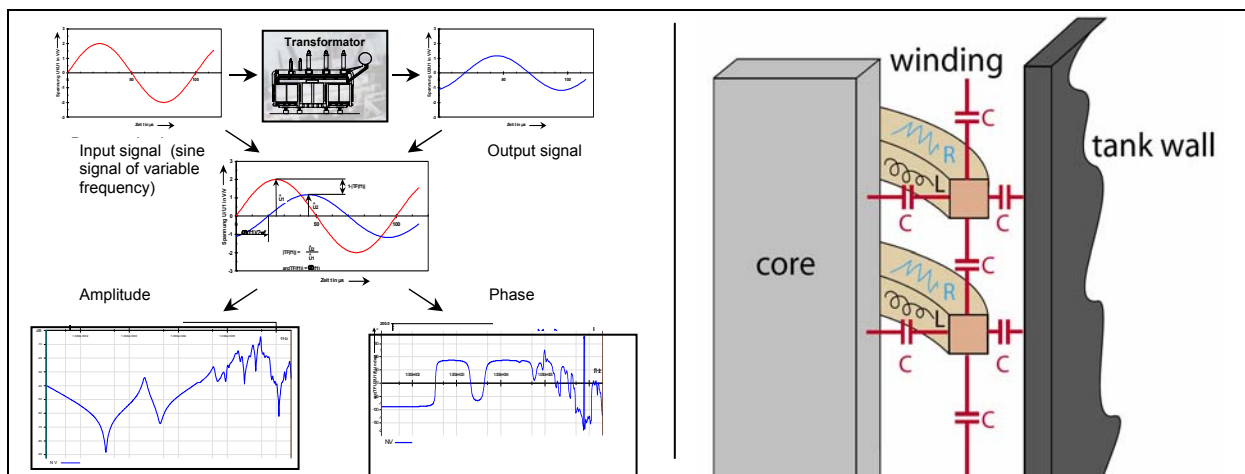


Figure 1: Principle operation of SFRA (left) and simplified network behavior of a transformer's active part (right)

Geometrical changes within and between the elements of the network cause deviations in its frequency response. Differences between an FRA fingerprint and the result of an actual measurement are an indication of positional or electrical variations of the internal components. Different failure modes affect different parts of the frequency range and can usually be discerned from each other. Practical experiences as well as scientific investigations show that currently no other diagnostic test method can deliver such a wide range of reliable information about the mechanical status of a transformer's active part.

2 STANDARDS AND GUIDELINES

The first mandatory standard in the world was established on 2005-06-01 in China. This standard, named DL 911/2004, only refers to SFRA measurements, suggesting that IFRA (Impulse- FRA) measurements are uncommon in China. It covers subjects including the test principle, requirements for testing instruments, testing methods and the analysis of the results. The standard mentions open circuit end-to-end measurements only (see also fig. 12) and for the sense of measurements on star connected windings the standard requires the injection of the signal into the neutral terminal and a measurement

of the response at the phase terminal. The standard evaluates a frequency range between 1 kHz and 1 MHz and is unique in that it gives a mathematical rule about how to judge test results based on a calculation of co-variances [2].

In the following, two examples are given to show the application of this assessment. First, the outer HV phases of a 36-year-old transformer (40 MVA) after a refurbishment are compared (fig. 2, left). Both traces show good congruity which is in alignment with the known condition of the windings. The assessment according to the Chinese standard confirms this evaluation (green). The second example on the right shows HV winding test results (middle phase) of two 63-MVA sister transformers. One transformer has failed a dielectric test. The reason for this turned out to be shorted turns, which are clearly visible on an SFRA measurement and confirmed by the Chinese assessment (red - indicating a severe problem).

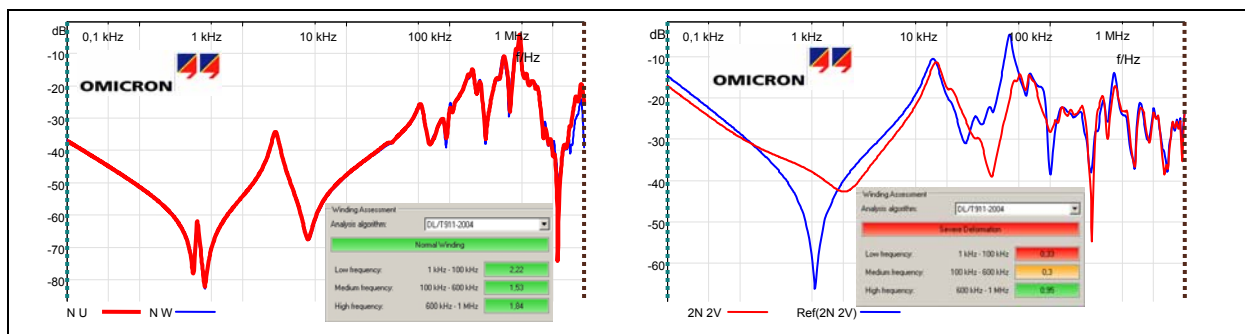


Figure 2: Assessment tool confirms healthy condition(left) ; Failure clearly identified by the assessment tool (right)

In 2002 the IEEE established a Task Force (TF) concerned with FRA and followed it up with a Working Group (WG) founded in 2004. The scope of this WG, termed PC 57.149, is the creation of a guide for the application and interpretation of FRA for oil immersed transformers. As with the Chinese Standard, the IEEE will recommend a three lead test system for “source”, “reference” and “measurement”. This is in accordance with common scientific knowledge and is supported by all SFRA test instrument manufacturers. The IEEE draft guide proposes additional tests to those recommended by DL 911/2004. The IEEE draft guide also gives assistance by providing a mathematically-based trace assessment with cross-correlation coefficients, although it should be noted that it is not planned to recommend limiting values as are found in DL 911/2004. The IEEE guide to FRA testing of power transformers may be published at the end of 2010 and will be a step forward for existing and prospective users of this technique. More information about this work can be found on the transformers committee homepage:

<http://www.transformerscommittee.org/>

The Cigré Study Committee (SC) A2 – Transformers - decided in 2003 to establish a Working Group on the application of FRA to power transformers. This WG A2/26 with the title “Mechanical Condition Assessment of Transformer Windings using Frequency Response Analysis (FRA)” started its work in 2004 and ended with the publication of Cigré report No 342 in April 2008. During this period, besides regular meetings the WG organized two FRA test workshops. During these workshops a large number of practical investigations were performed yielding a better understanding of the differences in FRA practices. The connection technique (cabling practice) turned out to be an influencing factor of utmost importance. Therefore it has been recommended to standardize the cabling practice to take advantage of the demonstrated sensitivity of this high-frequency measurement. The resulting brochure [3] is a valuable source of information and a helpful guide for the practical application of FRA. More information about this work is available at the Cigré A2 homepage:

<http://www.cigre-a2.org/>

Finally, the IEC plans to establish a working group in 2009 to develop a standard for FRA testing until 2011.

3 PRACTICAL ASPECTS OF SFRA TESTING

SFRA is a comparative measurement method. This means results of an actual test – usually a set of curves (mainly the amplitude in dB's over the frequency) representing all windings of a transformer as separate as possible – are compared to reference or baseline data. Three methods are commonly used to assess the measured traces:

- Time-based (current FRA results will be compared to previous results of the same unit)
- Type-based (FRA of one transformer will be compared to another of the same design)
- Phase comparison (FRA results of one phase will be compared to the results of the other phases of the same transformer)

Thus, the first step before a measurement is to answer the question: Is reference data available? If FRA measurements have been performed on this transformer in the past, the results of the measurements should be uploaded into the software of the available FRA instrument and shall be analyzed prior to the planned test. During this, one should check the existing data for consistency and correct documentation. A key factor of the documentation is the way the connections have been carried out. From a practical point of view it has turned out to be best practice to store photographs of the connection details together with the measurement data. This is significant help to achieve the highest possible degree of repeatability while reproducing the same arrangement for the measurement.

If the data is of reliable quality their analysis allows the tester to get an idea of the "expected results" which is vital for avoiding measurement mistakes. For the planned test the same measurements under the same conditions (e.g. tap changer position) have to be foreseen. According to the reason of the actual test additional measurements might be recommendable because different types of SFRA measurements are best-suited for different investigations. These decisions shall clearly be made before the start of the measurements since time pressure usually is one of the most common circumstances during transformer tests. Figure 3 shows an example of a time-based comparison on an 8 MVA-transformer (always HV phase 3). The black curve has been measured in 04/2006 the red curve in 5/2007 while the blue curve dates from 11/2008.

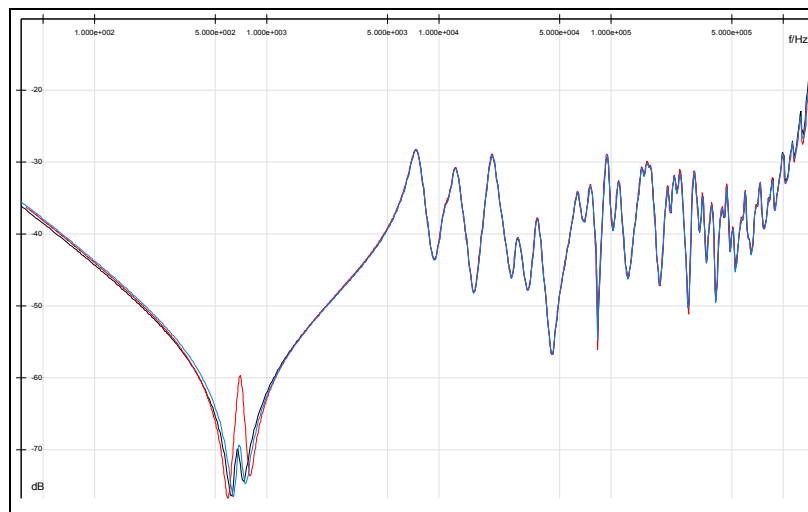


Figure 3: Time-based comparison: Three tests of the same phase between April 2006 and November 2008

The core region below a view kHz shows deviations due to different stages of core remanence which is natural. For the frequencies between 1 kHz and 1,5 MHz the tests have good congruity which is an indication for an unchanged geometry inside the transformer and thus the healthy status of the tested winding, considering the first test was performed on the phase being in healthy status, too. This has been the case for this transformer.

If no historical data of the concerning transformer is available, the use of SFRA data from type-equal ("sister-") transformers is common and mostly useful. The handling of the data is generally the same as described for the time-based comparison. However, minor deviations between curves of sister transformers can normally not be excluded. Figures 4 present an example of a successful type-based comparison of two 30-MVA transformers. Overlaying the data of the HV windings it is obvious that the related curves (same colors for each phase) correspond very well. Considering that it is most unlikely to have two transformers with exactly the same kind of mechanical failure, the good congruity of the results is a good indication for the healthy status of both units.

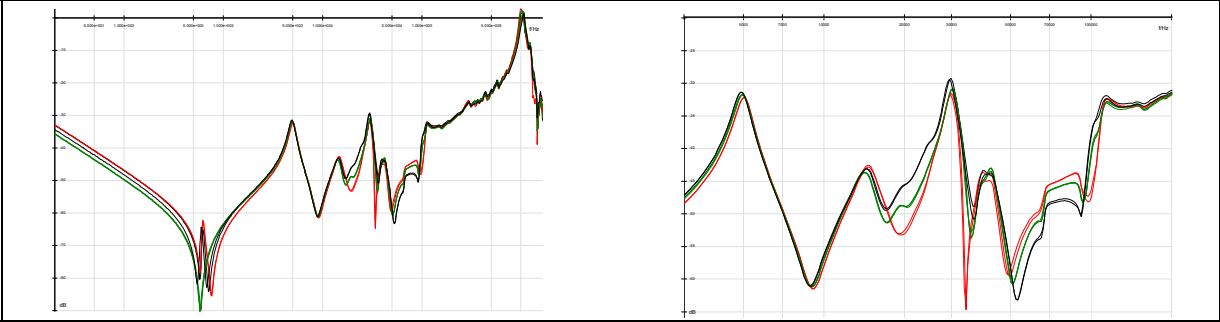


Figure 4: Type-based comparison: HV phases of two sister units showing good congruity (left), right zoomed 3 kHz – 200 kHz

However, it is important to recognize that equally specified transformers not in every case show exactly the same frequency responses. An example for different SFRA results (20 Hz – 2 MHz) on identically specified 60-MVA single phase generator step-up transformers is given in figure 5. Despite the fact that all units were in good shape the SFRA results are not in alignment. The left part of the figure shows a zoomed region of incongruity in a frequency range from 5 kHz to 550 kHz. Obviously the windings design has been changed during the manufacturing process of this batch of transformers. This assumption has been confirmed by the manufacturer.

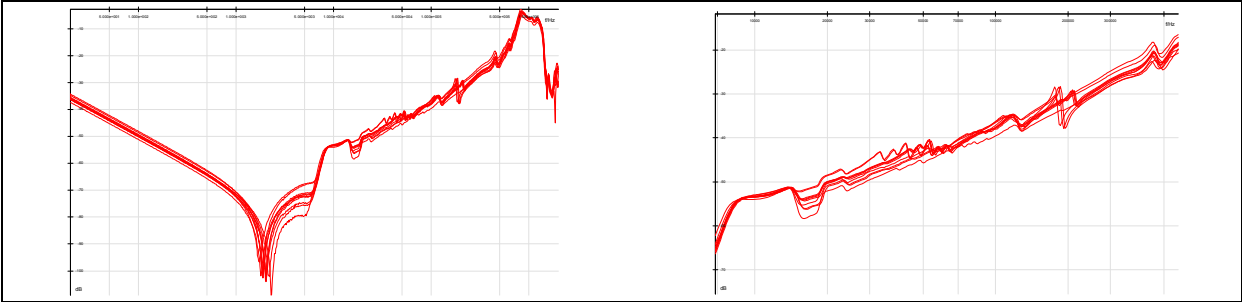


Figure 5: Type-based comparison: HV winding responses of 10 single phase sister transformers showing non-congruent results

The case above shows that a mismatch of SFRA results during a type-based comparison means not necessarily that one or both of the transformers are damaged. In such cases it is recommendable to use more than one reference test if available or to consult the transformers manufacturer.

If no reference data is available the set of tests shall be planned according international guides and with respect to the objectives of the test (fingerprint, failure investigation, transportation assessment etc.). The most common measurement is the end-to-end test with all untested terminals left floating. These curves contain the most informational content about the core and the winding and are therefore the most important and most common type of tests. The left part of figure 6 shows this measurement principle schematically. In this case the signal source and the reference measurement channel are connected to the neutral terminal while the response measurement channel is connected to one of the star connected phases. It is also possible to use the opposite direction (signal injection in the phase and

measurement on the neutral) but both directions should not be mixed. On the right, figure 6 shows the end-to-end test with a short circuit connection of the corresponding windings. This removes the core influence (magnetizing inductance) and is characterized by the leakage instead. For higher frequencies, representing information about the winding structure itself, both end-to-end test types give the same results. It is common practice not to include the LV neutral into the short-circuit connection.

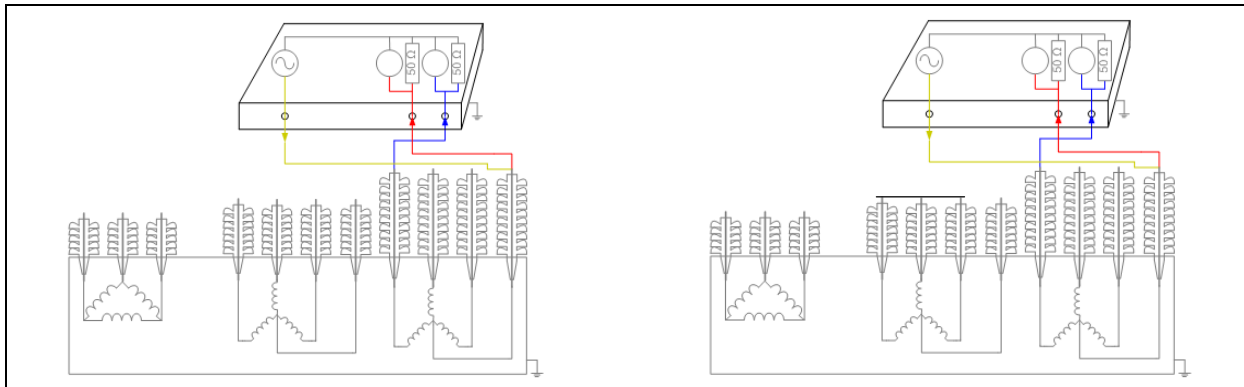


Figure 6: Principle of end-to-end tests

Other tests can be the capacitive inter-winding test (fig. 7), or the not that common inductive inter-winding test. Capacitive inter-winding measurements seem to be promising due to their high sensitivity in the detection of radial deformations. The inductive inter-winding test is complementary to the turns-ratio test (TTR) in the low frequency range. Anyway, the selection of the type of tests to be performed is also a matter of the available testing time. For the definition of the sweep settings it has been proven that a frequency range between 20 Hz and 2 MHz is usually sufficient. With respect to the further use of the actual data as references for future measurements it must be mentioned again that exact documentation is essential for SFRA measurements.

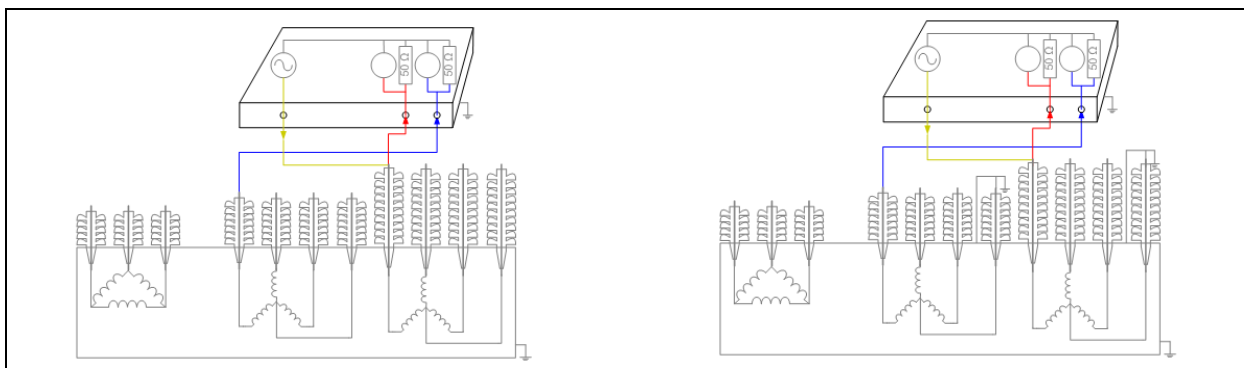


Figure 7: Principle of inter-winding tests – left capacitive, right inductive

Without reference data it is common practice to compare the phases of a transformer against each other. For three-phase transformers it must be noted that the middle limb usually differs from the outer phases in the core region (up to a view kHz) as well as in higher frequency regions which are related to the winding structure under test. As an example figure 8 shows the HV winding responses of a 350-MVA GSU. It is visible that the middle phase (green curve) deviates slightly from the other phases (black and red). Despite this it is obvious that the resonances and anti-resonances are in good alignment which is a good indication of the healthy status of the windings. According to the authors experience app. 60% of all SFRA tests can be assessed just based on phase comparisons. But it must be noted that also healthy windings may not correlate well, according to their winding design. In such cases further investigation (e.g. type-based comparison) is required. It can be estimated that app. 90 % of all SFRA measurements can be evaluated without fingerprint data of the tested object being

available. In right part of figure 8 an example of a newly build 63-MVA transformer is given. The HV windings show different winding responses despite being verifiable in sound condition. More often than for HV windings this kind of effect is to be observed on LV or tertiary windings.

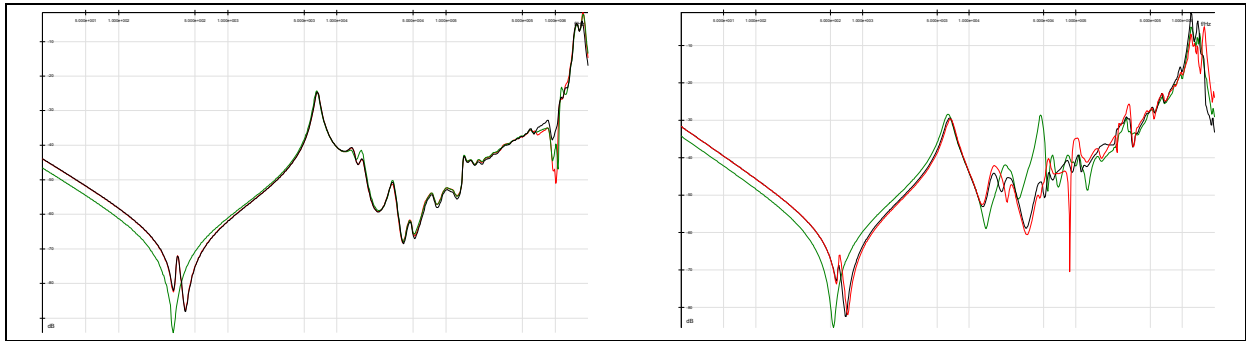


Figure 8: Phase comparison of HV windings in healthy state with good alignment (left) and with non-corresponding results (right)

4 RULES TO ACHIEVE REPEATABILITY

Finally a summary of guidelines derived from a large number of successful measurements is given to put the reader in a position to achieve a good degree of repeatability, too. This is of need because all types of assessments explained in chapter 3 are based on the ability to exactly reproduce the measurement results under same conditions. Without this it is often very critical or even impossible to distinguish between measurement mistakes and real damage inside the tested transformer.

- All connections from the transformer except the tank ground and auxiliary connections shall be removed.
- The contacts of the bushings shall be cleaned and the connection clamps have to be tightened firmly to assure reliable electrical contact.
- Three shielded high frequency cables (usually coaxial cables) of exactly same length should be used.
- It must be assured that the ground extensions of the measuring cable shields do not have electrical contact with the terminal contacts.
- Ground extension of the test leads must be of low inductance (broad braids with large surface, made of a large number of small wires to reduce the skin effect at higher frequencies).
- Ground extension to the base of the bushing (reference potential is the transformer tank) shall be as short as possible and with the smallest achievable loop.
- It is very important to ensure reliable contact between ground extension and tank. A lot of measurement mistakes are related to this point.
- Detailed information about the test set-up should be stored together with the test data. This will help to reproduce the measurements for future tests. Detailed photographs are recommended.
- Every test result should immediately be checked for plausibility and compared to expectations and available references. A very noisy curve is almost an indication for poor grounding. Figure 9 gives two typical examples for this phenomenon. It is important to recognize measurement mistakes on-site and to repeat the questionable test after finishing the required corrections.

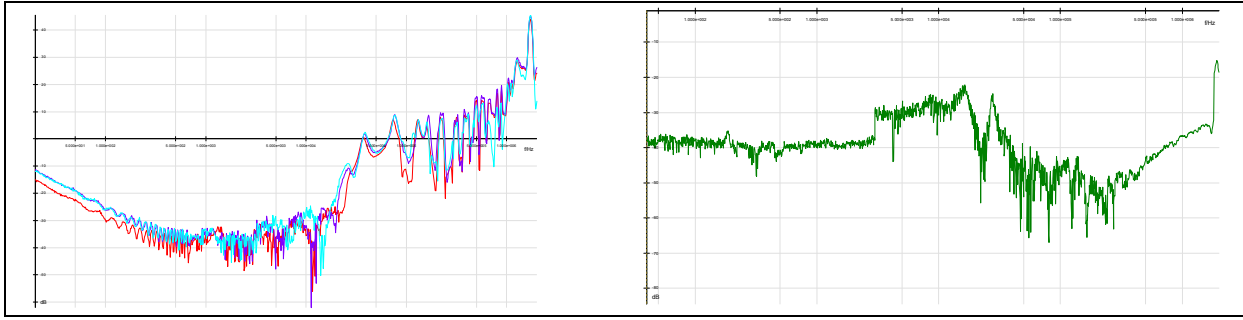


Figure 9: Typical examples of measurement mistakes

5 APPLICATION OF SFRA DURING TRANSFORMER TRANSPORTATION

The evaluation of transformers transportation is an increasingly popular application of the SFRA method. This is reasonable due to the ability of SFRA to provide in-depth information about the core, the windings and the clamping structures, as well with one set of tests. All these parts are susceptible to transportation damage.

As for all other applications of SFRA, performing the test under the same conditions is important to get reliable results. Therefore the initial test shall be performed on the transformer in its transport configuration. Usually the transformer will be equipped with bushing cover plates or transport bushings, which is strongly recommendable to facilitate testing, and without oil (depending on size and restrictions). Thus it is obvious that normal baseline data from factory or on-site fingerprint tests can not be used for this purpose because the results will differ from each other. On the other hand it must be noted that transportation test results usually can not be used as baseline data for future tests in operational condition. The first transportation evaluating test shall be performed as end-to-end open circuit measurement with all other terminals floating. Short circuit measurements are not able to display the core area. The test shall be performed using logarithmic measurement point setting since linear scaling may not sufficiently cover the lowest frequency region related to the magnetic core which is especially vulnerable for transport damage.

After the initial test before the start of the transportation, rechecking tests can be performed at any time during transit. It is important to note that the SFRA test should be the last electrical test prior to transportation and the first test after arrival. Other tests in between, especially DC tests (e.g. winding resistance test) may change the core magnetization status and hinder a reliable evaluation of the core integrity. The status of core remanence should be noted in the test documentation. The same is valid for tap changer position and the oil level or even its absence. If the test has been performed shortly after draining the oil this fact should be noted too, because of the effects of residual oil within the insulation. A re-test on-site without oil may lead to inconclusive results since the residual oil may be dropped out during the transport which may lead to changes in the capacitance and therefore slightly shifted SFRA curves.

In addition it is important that the transportation configuration of the transformer is well documented and available to other testing personnel who have to perform the repeating measurements. It might be necessary to identify and record more than one transportation configuration since the transformer may undergo several legs of transport like truck, ship, railroad, crane off-loading etc. Any of these transportation legs can exert undue physical shock to the transformer. Testing before and after transport legs that have different legal custodies is prudent. After the receipt of the transformer at its final destination one last test in transportation configuration should be performed to evaluate the transportation. If this test confirms healthy status another SFRA test with the transformer assembled and oil-filled as required for insulation resistance testing should be performed to be used as baseline or fingerprint data for future testing. In all cases it is recommended to photograph the connections between FRA device and the bushings.

In the following example SFRA tests has been performed on a batch of transformers after their transportation from Europe to Africa. Impact recorder readings were suspicious. Additionally bumping marks were found. Figure 10 shows two example pictures of a suspect unit. No SFRA tests had been performed prior shipment but fortunately type-based and phase comparisons were possible.



Figure 10: Bumping marks indicating possible damage of this transformer after its shipment

The measurement on the left of figure 11 displays the core region of the suspect transformer in the frequency range 100 Hz – 50 kHz. Contrasting on the right a sister unit with the core in healthy condition is shown in the same frequency range. The remanence information has been available from the manufacturer. The cores were demagnetized and therefore all equal-type transformers should show the same behavior in the core region below 5 kHz. Obviously the transformer on the right has a perfect match of the outer phases (red and blue). The deviation of the middle phase (green) is as expected. The curves on the left are different - the outer phases have a poor congruity. The most unlikely shape shows the curve of phase 3 in blue.

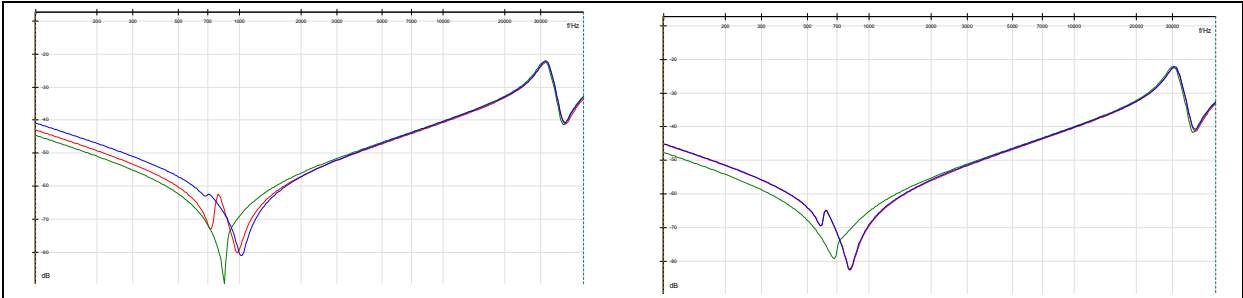


Figure 11: Type-based comparison of the suspect transformer (left) with an equal unit (right)

Based on the result above and the impact recorder readings it has been decided to open the transformer for visual inspection. The findings confirmed the assessment of the SFRA results. The limb 3 was displaced to the right. The according clamping rod was found bent and the upper wooden clamping frame was partly ruptured. The clamping pressure was significantly reduced on the affected phase. Finally the transformer has been shipped back to the manufacturer for repair.

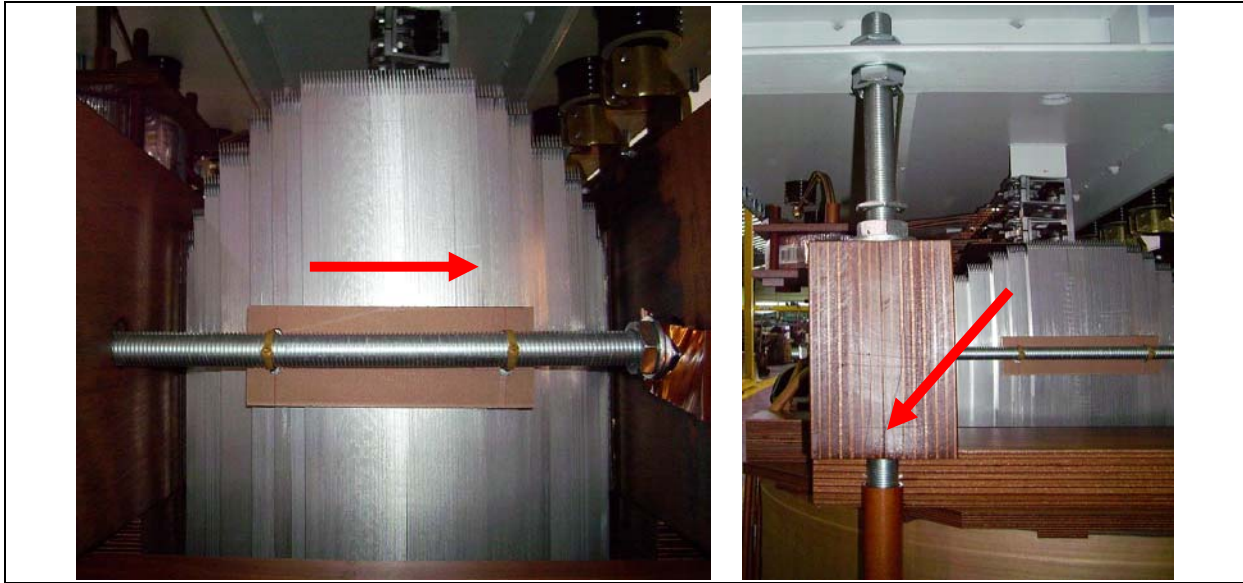


Figure 12: Displaced limb of phase 3 (left), bent clamping rod and ruptured clamping frame (see arrow) on the right

6 CONCLUSIONS

The SFRA is a powerful method for the detection and diagnosis of defects in the active part of power transformers. It can deliver valuable information about the mechanical as well as the electrical condition of core, windings, internal connections and contacts. No other single test method for the condition assessment of power transformers can deliver such a diversity of information. Therefore the SFRA is an increasingly popular test. The value of fingerprint data is more and more recognized by users all over the world. Comparing the time and the frequency domain FRA test methods it seems to be obvious that SFRA, measuring directly in frequency domain, prevailed. Reproducibility is the key for a successful application of SFRA. Therefore highest accurateness is essential when establishing the connections. Due to the work of Cigré WG A2/26 consensus about the effective and reliable application of this method has been achieved. The authors wish to thank all members of this WG for their work.

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