Electrical interferences in SFRA measurements – How to overcome undesirable effects

Michael Rädler, OMICRON electronics GmbH, Klaus/Austria
Stephanie Uhrig, OMICRON electronics GmbH, Klaus/Austria
Juan L. Velásquez Contreras, Hubert Göbel GmbH Böhnen/Germany

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Since the introduction of the IEC 60076-18 (Edition 1.0) standard in 2012, the Sweep Frequency Response Analysis (SFRA) method has become one of the most common electrical tests for power transformers. It provides comprehensive information about the mechanical and electrical integrity of the active part of power transformers. In contrast to traditional diagnostic methods, the SFRA is sensitive to external electrical interferences which may limit the comparability and can consequently lead to misinterpretation of the measurement results. This article discusses the theory of different noise sources and noise suppression techniques. Different case studies show the efficacy for measurements even in harsh conditions.

Keywords

Frequency Response Analysis, SFRA, Noise, Interpretation, Dynamic Range, IEC 60076-18, Mechanical Condition Assessment, Power Transformer, Electrical Condition Assessment, Broadband Noise, Narrowband Noise

Abstract

Power transformers are still some of the most costly and critical components in an electrical power network. Thus, the importance of a reliable condition assessment of these assets increases due to the aging of transformer fleets. The Sweep Frequency Response Analysis (SFRA) has become an important standard test and provides comprehensive information about the mechanical and electrical integrity of the active part of power transformers. Electrical as well as geometrical changes in the magnetic core, the winding assembly and the clamping structure, can be detected by a comparison of an actual measurement with a reference measurement. In contrast to traditional diagnostic methods, the SFRA is sensitive to external electrical interferences which may limit the comparability and can consequently lead to misinterpretation of the measurement results. For an optimum suppression of narrowband and broadband noise, software-based as well as hardware-based techniques can be utilized. This article discusses the theory of different noise sources and noise suppression techniques. Different case studies show the efficacy of measurements even in harsh conditions.

1 Introduction

At the latest since the IEC 60076-18 (Edition 1.0) standard was introduced in 2012, the acceptance on the market for the Sweep Frequency Response Analysis (SFRA) method has increased and it has become one of the most common electrical tests for power transformers. It is a non-invasive, low-voltage diagnostic test, delivering comprehensive information about the mechanical and electrical condition of the active part of power transformers. Shocks caused by transportation, seismic activity, mains power failures, etc. can cause problems in the windings, contacts or transformer core. It turns out that the SFRA is the most sensitive method to detect such mechanical and electrical defects.

In order to perform SFRA measurements, typically a low output voltage between 0.1 V and 10 V is used – sometimes even in harsh conditions. Thus, the results obtained can be distorted by the influence of noise. In these cases it can yield to unnecessary maintenance or repair actions, triggered by misinterpretations of the results. Allowing even non-experts to distinguish between trace deviations caused by mechanical or electrical problems, as well as noise, this article focuses on the influence of noise in SFRA measurements.

2 Sweep Frequency Response Analysis Method

The Frequency Response Analysis (FRA) method is classified into Impulse Frequency Response Analysis (IFRA) and Sweep Frequency Response Analysis (SFRA). In both methods the frequency response of a power transformer is compared to an existing reference measurement. The IFRA uses, as the name suggests, an impulse in time domain, whereas the SFRA evaluates a frequency sweep. As the IFRA is more prone to noise, SFRA has become state of the art and, therefore, this article just focuses on these techniques.

Power transformers can be seen as a complex electrical network of capacitances, inductances and resistors as shown in Figure 1. Each electrical network has its own unique frequency response. Thereby, deviations between the current and the reference measurement can indicate changes of internal components. These deviations can be directly related to different sections of the frequency range and they can be discerned from each other.

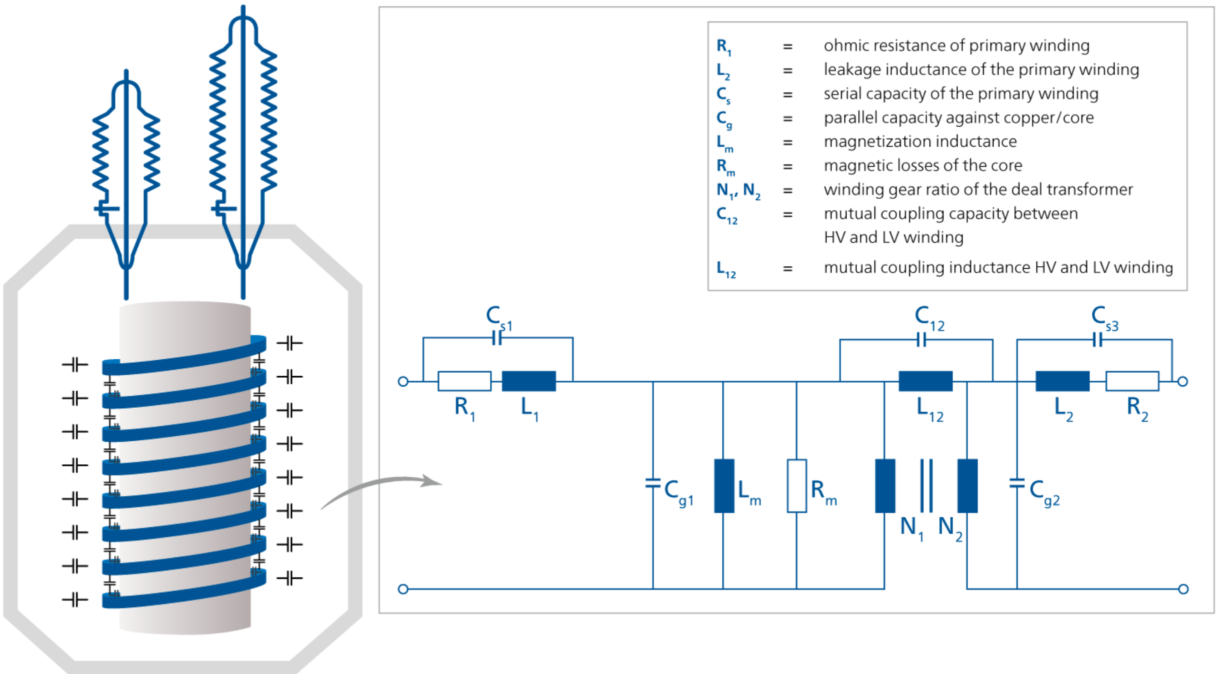

Figure 1: Simplified R-L-C equivalent circuit of a power transformer

For performing an SFRA measurement, a frequency-variable sinusoidal low-voltage signal between 0.1 V and 10 V is applied on one end of a winding as illustrated in Figure 2. In order to know exactly the amplitude, phase as well frequency of the injected signal, a reference measurement channel (U1) is connected to the same injection point. Simultaneously, the response signal at the other end of the winding is measured (U2). This subsequently allows calculation of the transfer function H(f) according to the equation (1). As SFRA is a direct measurement in frequency domain, no additional data processing is required.

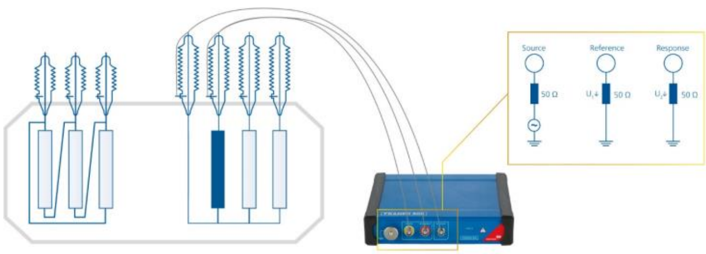

Figure 2: Typical setup of a transfer function measurement in frequency domain

The obtained measurement results are represented in the form of a Bode diagram where the magnitude k and phase φ are computed by two simple formula 2 and 3. In this sense, the transfer function H(f) is calculated using formula 1. The magnitude k, as measured by the SFRA equipment, is defined by formula 2. The phase φ, as measured by the SFRA equipment, is defined by using formula 3.

The SFRA is typically performed in a frequency range of 20 Hz up to 2 MHz and output voltages between 0.1 and 10 V are used. In this frequency range, the SFRA technique is the most reliable and efficient test in order to detect mechanical as well as some electrical failures of the active part of power transformers. The detected faults can be confirmed by further diagnostic measurements, such as leakage reactance, exciting current, or winding resistance measurements.

Using SFRA the following problems can be detected based on a comparative basis:

- Axial and radial winding deformation
- Displacements between high- and low-voltage windings
- Partial winding collapse
- Shorted or open turns
- Faulty grounding of core or screens
- Core movements
- Broken clamping structures
- Problematic internal connections

For healthy transformers, the measured trace matches the reference SFRA trace over the whole frequency range. Thereby, the reference trace could be a fingerprint from the same transformer which was obtained earlier or an SFRA trace from a sister transformer with the same specifications. A phase-based comparison requires more experience as deviations could be related to the transformers design, and not to mechanical damages. In case of failures caused by, for example, extraordinarily high mechanical forces, shocks due to transportation, seismic activities or mains power failures such as high short-circuit currents, the trace shows deviations in certain frequency ranges (Figure 3). As it is a comparative analysis, the noise must not significantly affect the magnitude and phase of the frequency response – this will be discussed in detail within the following sections.

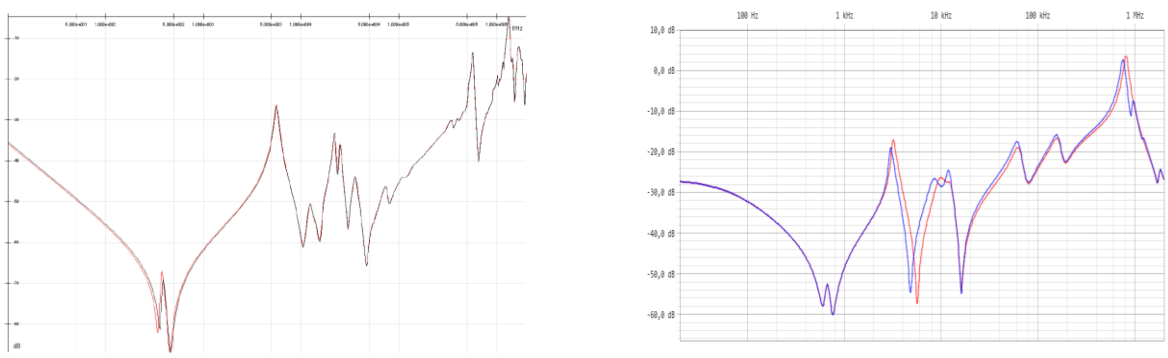

Figure 3: Typical frequency responses of power Transformers
left: healthy transformer, actual trace nearly identical to time based reference
right: Bulk movement, actual trace shows significant deviations to time based reference

Formula 1: $H(f) = \frac{U_2(f)}{U_1(f)} = \frac{50\,\Omega}{50\,\Omega + Z_{test}}$

Formula 2: $k = 20\log \frac{U_2}{U_1}$

Formula 3: $\varphi = \tan^{-1} \frac{\angle U_2}{\angle U_1}$

Formula 4: $L_M = \frac{N^2}{R_m}$

Formula 5: $R_m = \frac{\Theta}{\varphi} = \frac{N * I}{\frac{\mu * (N * I) * A}{l}} = \frac{l}{\mu * A}$

Formula 6: $\mu = \frac{B}{H}$

R_m = *magnetic reluctance*
L_m = *main inductance of the tranformer*
N = *number of turns*
l = *length*
A = *cross-sectional area refers to the geometry of the magnetic core*
B = *magnetic flux density*
H = *magnetic field strength*
μ = *magnetic permeability*

3 3 Sources of noise

Particularly in substation environments, there exists a variety of noise which can influence SFRA measurements. The sources of noise can be distinguished, in a simplified manner, into narrowband and broadband noise.

3.1 Narrowband noise

A typical narrowband noise is represented by the power frequency noise and its harmonics. The latter are a multiple of the power frequency, which is used within the overall electrical grid system.

In general, the narrowband noise affects the SFRA plots in the low frequency area between 30 Hz and 100 Hz. Above 300 Hz, the effects of such narrowband noise is very unusual. In substations with high harmonic pollutions some narrowband noise could also be observed. The effects of noise are significant from 3 Hz up to 100 Hz, whereas at harmonic frequencies the effects are slighter but still present. Fortunately, noise effects only occur during measurements in an environment with a high electromagnetic field strength how it typically can be found in substations with rated voltages above 380 kV.

The asset type respectively the size of the transformer windings is a crucial element for influencing the frequency response results: The signal attenuation increases with the inductance and, thus, the response signal becomes more sensitive to noise. Noise effects only take place in the very low frequency area where the linear magnetization inductance dominates the overall frequency response.

The interpretation of the mechanical condition of the active part of a power transformer is not influenced by the presence of narrowband noise at as the first resonance points typically appear above 130 Hz. In contrast, however, electrical failures of a power transformer such as short circuits between turns, open circuits or shorted core laminates can be identified by analyzing the low frequency area. As an example, Figure 4 illustrates the SFRA plots measured in the 500 kV windings of a power transformer where the above mentioned effects can be observed.

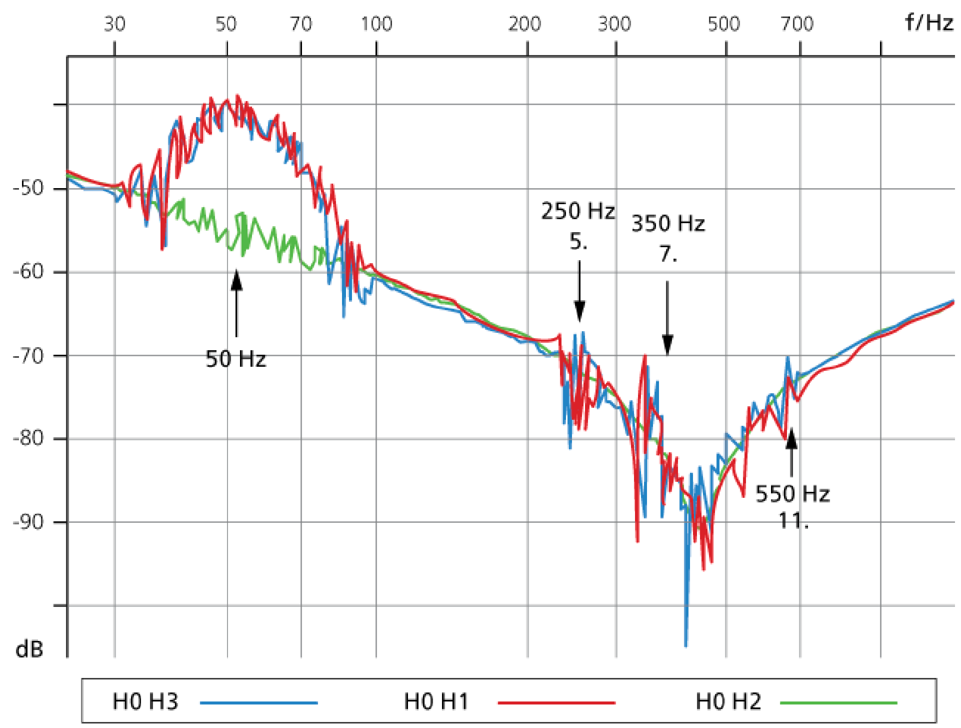

Figure 4: Sweep Frequency Response of three phases of a 500 kV windings, with narrowband noise at power frequency and its harmonics

3.2 Broadband noise

During SFRA measurements, there will always be a noise floor that affects the SFRA plots. This specific type of internal noise is classified as a broadband noise and is caused by the connected SFRA test device. The level of noise depends on the dynamic range of the SFRA test instrument being used.

Signal theory defines noise floor as the measure of the signal created from the sum of all the noise sources and unwanted signals within a measurement system. It is used as an indicator for the minimum strength of a signal to be measureable. The noise floor of an FRA instrument is defined by its dynamic range. The IEC 60076-18 standard defines as the dynamic range a minimum device specific requirement of -90 dB to +10 dB. Beside this fact and based on the gained experience over that last years it has an advantage to calculate the dynamic range as absolute value of the negative measurement range plus 20 dB. This is graphically illustrated in Figure 5.

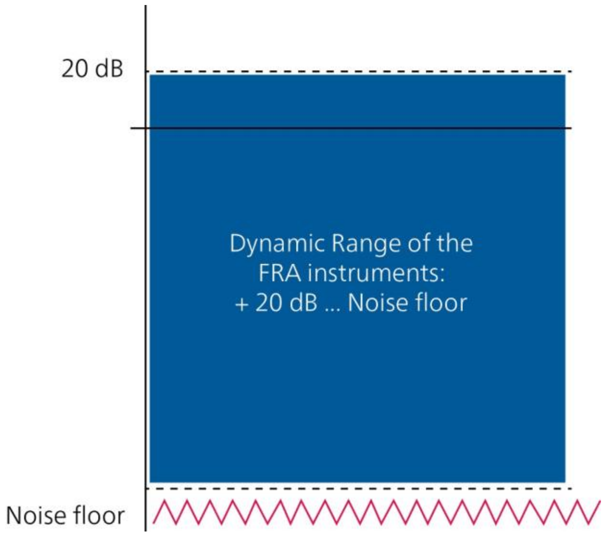

Figure 5: Illustration of noise floor and dynamic range

Compared to the effects due to narrowband noise, the effects due to the noise floor are assessed as highly critical. This type of noise is usually present in SFRA plots for power transformers with a high magnetization inductance, windings connected in a delta configuration or for capacitive interwinding measurements. Noise floor makes the assessment of the results very difficult as several resonance points, which are important asset related information, can be affected by this type of noise.

Figure 6 shows an example of the influence of noise floor: A power transformer with a delta winding was measured with an SFRA instrument with a noise floor of -80 dB. In this example it can be recognized that below -80 dB the frequency response is highly affected by the noise floor. This is caused by the limited dynamic range of the SFRA instrument being used. Therefore, it is recommended to select a SFRA test instrument with a dynamic range greater than 100 dB. Modern SFRA devices offer, for example, a dynamic range up to > 150 dB.

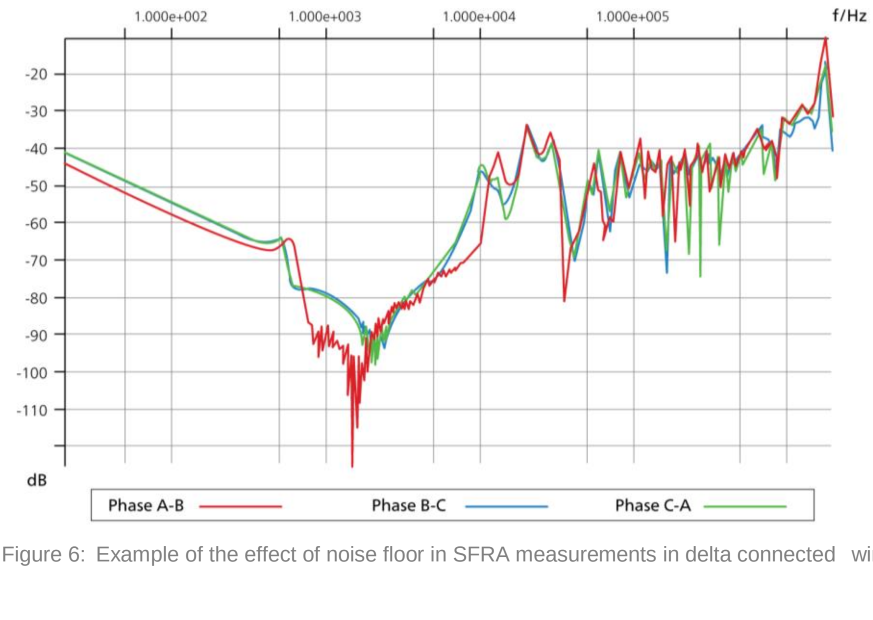

Figure 6: Example of the effect of noise floor in SFRA measurements in delta connected windings

4 Noise mitigation techniques

There are several methods which can be used in order to mitigate the influence of external disturbances on SFRA traces. These methods can be divided into two different groups: hardware-based techniques and software-based methods.

4.1 Hardware-based techniques

Zur Minimierung von Rauschsignalen bei Messungen bieten sich für SFRA-Systeme verschiedene hardwarebasierte Möglichkeiten an, wie bestimmte Anschlusstechniken, Eingangsfilter und eine anpassbare Ausgangsspannung.

4.1.1 Reliable connection technique

A proper connection technique can help to reduce the influence of external interferences. The IEC 60076-18 standard describes the recommended procedure for a proper and reproducible measurement setup in detail.

Ensuring the highest available signal-to-noise ratio, the standard recommends for SFRA measurements the usage of double shielded coaxial cables, which have to be grounded by wide, flat aluminium braids. This grounding concept provides a large surface area, the lowest inductance and is less sensitive to narrowband noise.

In order to eliminate any influence of the grounding system on the SFRA results, the grounding braids should always run tightly along the body of the bushing (shortest braid concept) as illustrated in Figure 7 and Figure 8. The used connection technique is essential ensuring a high degree of reproducibility, especially in the high frequency range, e.g. above 500 kHz.

Figure 7: Example of shortest braid connection concept

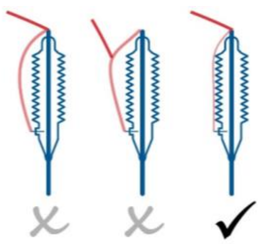

Figure 8: Recommended setup according to IEC 60076-18

Compared to a connection technique using simple cables, an aluminium braid can significantly reduce the influence of noise as visualized in Figure 9.

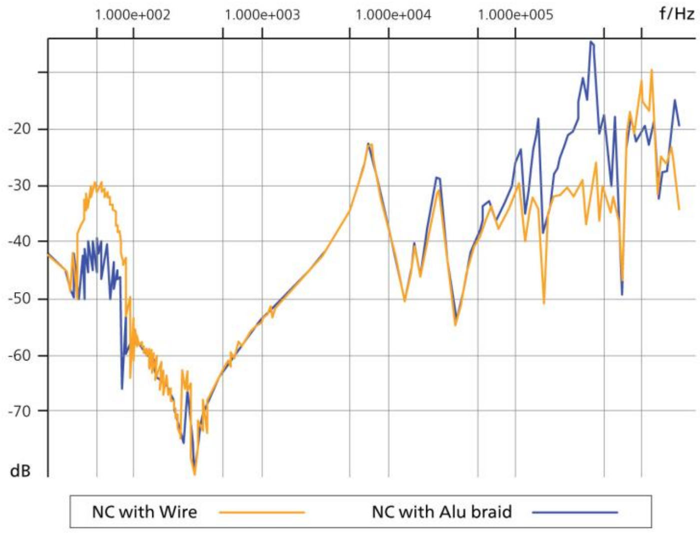

Figure 9: Effect of two different connection techniques, using a banana cable (4mm) and aluminium braid

4.1.2 Advanced input filters

Most SFRA test instruments are equipped with input filters which are capable of suppressing narrowband noise up to a certain level. These noise suppression capabilities can be controlled by adapting the bandwidth of the measurement. The setting of the bandwidth is always a compromise between noise suppression capabilities and the required measurement time. An optimal setting of the bandwidth can also be obtained by adapting the receiver bandwidth automatically as a function of the attenuation of the signal. The minimum measurement resolution bandwidth based on the IEC 60076-18 standard requires for measurements below 100 Hz a maximum bandwidth resolution of 10 Hz. For measurements above 100 Hz it should be less than 10 % of the measurement frequency or half of the interval between adjacent measuring frequencies. In order to decrease the overall measurement time without the compromise of distorted measurement traces, intelligent bandwidth algorithms are integrated in sophisticated SFRA instruments.

Such SFRA instruments select automatically the ideal bandwidth during measurements. First a broadband measurement is performed in order to identify the critical frequency areas. In the next step, only a narrowband measurement will be performed in the identified/distorted areas considering the main requirements given by the IEC. This concept is illustrated in a simplified manner in Figure 10. If a sample at the frequency “If” has to be measured, the SFRA device only measures signals whose frequencies are within the bandwidth range. Any perturbation by frequencies out of the bandwidth range will not be measured. Based on this approach, the overall noise suppression capabilities can be enhanced by simply reducing the receiver bandwidth.

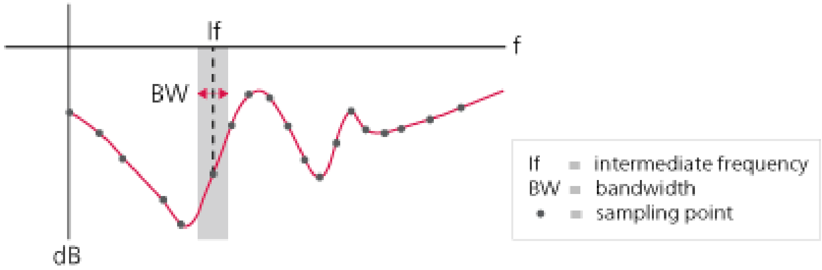

Figure 10: Illustration of the adaptive bandwidth concept

4.1.3 Adjustable output voltage

The transfer function H(f) measurement is independent from the output voltage level of an SFRA test instrument since a power transformer winding can be considered as a linear system. However, the output voltage is directly correlated to the signal-to-noise ratio. Especially at power frequency (50/60 Hz), a higher output voltage level can help to increase the interference immunity of narrowband power frequency noise.

Another consequence of the linear system is that, in the low frequency range, the frequency response is dominated by the core magnetization inductance and depends, therefore, on the voltage. This can be explained as the magnetization inductance is contingent upon the applied test-voltage and the turns of the windings. The simplified formulas 4, 5 and 6 describe this effect.

In general, the applied test voltage of the SFRA test equipment used will change the magnetic permeability µ according to the hysteresis curve of the selected core material. This causes a change of the magnetic reluctance, which will also change the core inductance. The following images, Figure 11, illustrate the influence of different output voltages and the associated changes of the SFRA plots (left) and the increased interference immunity of narrowband noise due to a higher output voltage (right).

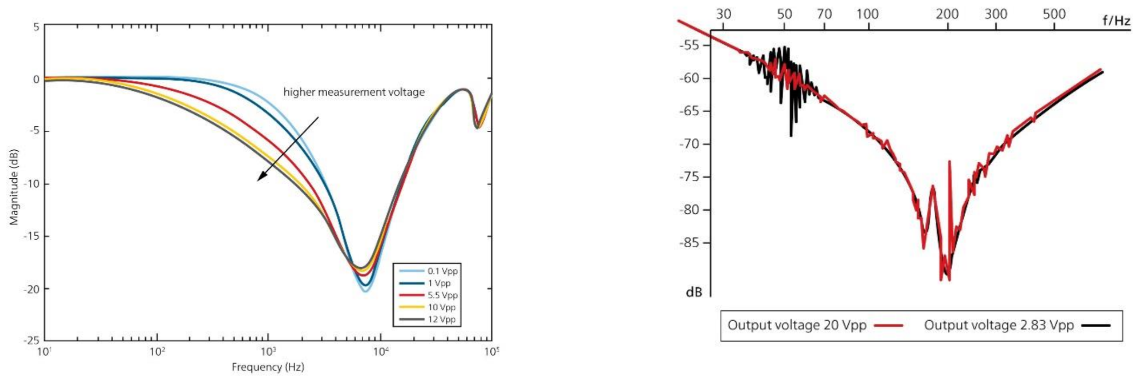

Figure 11. Effect of the selected output voltajes
left: influence of different output voltages on magnetization inductance Lm
right: influence on narrowband noise suppression capabilities by using different output voltages

4.2 Software-based methods

The software-based methods are mainly based on data post processing, including for example smoothing algorithms or averaging filters.

The software-based methods consist of filtering techniques which remove the noise of an already measured SFRA trace by means of signal processing methods. Other software-based methods are based on variance analysis. They are developed to detect and quantify the non-linear distortions and the disturbing noise within SFRA measurements.

Other methods such as the Wavelet transformation, which is mainly used for suppressing noise in time domain measurements, or Kalman filters are also applicable. In addition, there is also a variety of simple algorithms such as averaging filters, moving average filters, exponential weighted moving average filters, etc. which can all be used for reconstructing distorted SFRA measurement traces. Some SFRA instruments have signal processing tools already implemented as a part of the basic software package in order to improve the obtained measurement data. Figure 12 shows the reconstruction of a distorted measurement trace caused by narrowband noise, using an averaging filter.

Filter techniques help to increase the overall quality for the interpretation of the SFRA traces. Tools like this are mainly used by SFRA experts as resonances can be removed very easily, which in turn could lead to a wrong assessment of the asset condition. Moreover the original measurement traces, this means the traces without any signal processing, needs to be available as well.

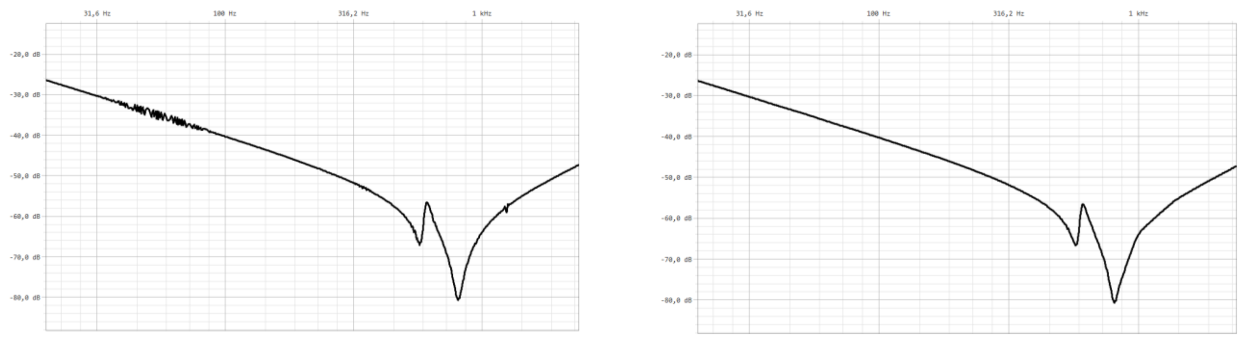

Figure 12. Comparison of the SFRA trace before (left) and after noise removal (right)

5 Case Studies

A SFRA measurement has been performed on a three-phase 70 MVA power transformer. The primary winding is rated with 240 kV and the secondary winding with 10.5 kVA. The main purpose of the SFRA measurement was to obtain a proper fingerprint for future diagnostic purposes, therefore, this specific case study does not focus on the overall mechanical condition assessment.

The measurement took place on site next to a live 240 kV overhead line. Two different SFRA instruments with different algorithms for the receiver bandwidth adaption were used in order to check their noise suppression capabilities (Figure 13). As already described within this article, narrowband and broadband noise can influence several resonance points, which may contain important asset related information. This makes the assessment of the obtained SFRA results sometimes very difficult, especially for users with less experience.

The SFRA traces of the phase U of the 240 kV winding shows that the SFRA trace obtained with the SFRA instrument 1 is influenced by the narrowband 50 Hz noise and its harmonics. Due to the static algorithms of the automatic bandwidth adaption the overall measurement (starting from 20 Hz up to 2 MHz) took 56 seconds. It can also be recognized that the second resonance point created by the parallel capacitance (Cg) and the magnetization inductance (Lm) is slightly distorted (left picture).

The second measurement was performed by using a more sophisticated SFRA instrument with improved hardware-based noise filter capabilities – in this article designated as SFRA Instrument 2. Due to the intelligent bandwidth adaption, at low frequencies the measurement traces are not influenced by any external noise effects.

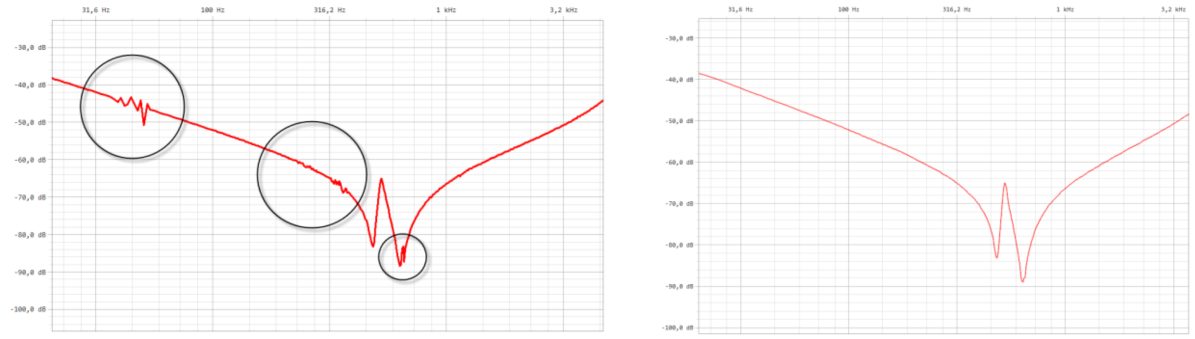

Figure 13: End-to-end open-circuit on HV winding performed with SFRA Instrument 1 (left) and SFRA Instrument 2 (right)

In particular, capacitive interwinding measurements can be severely influenced by the noise floor and the power frequency noise due to the lower signal-to-noise ratio. Thus, a higher dynamic range, higher output voltage and intelligent receiver bandwidth adaption help to improve the overall measurement results. The capacitive interwinding measurement results are illustrated in the Figure 14. The results from SFRA Instrument 1 show a heavy distortion by the narrowband noise. Compared to them the results from SFRA Instrument 2 show almost no distortions due to the intelligent receiver bandwidth adaption.

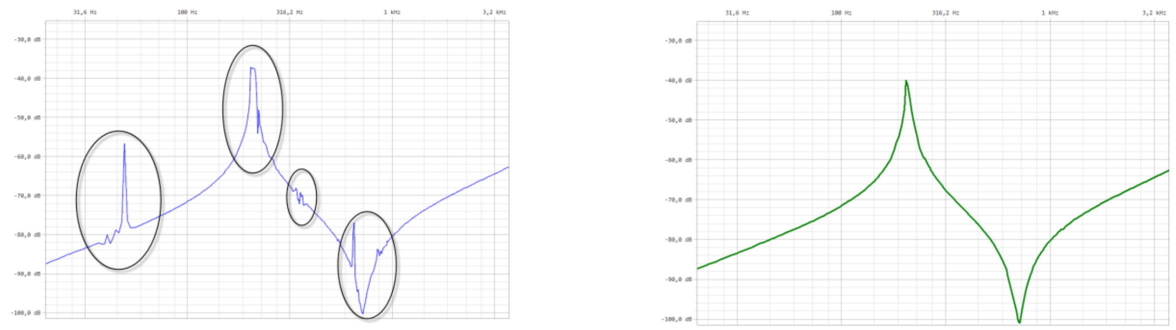

Figure 14: Capacitive interwinding on HV winding performed with SFRA Instrument 1 (left) and SFRA Instrument 2 (right)

An alternative approach to reduce the influence of narrowband power frequency noise is to perform an end-to-end short-circuit measurement, whereby the low-voltage side is shortened. Based on this method, the winding impedance will be isolated from the core properties especially around the power frequency. In simple terms, the transformers magnetization inductance Lm becomes inactive and only the leakage reactance will be measured within the low frequency area. The biggest disadvantage of this specific method is that the electrical condition information cannot be assessed any further and, therefore, this method should be performed in addition to the recommended end-to-end open-circuit measurement. As illustrated in the Figure 15, both measurement results show no distortions at the rated power frequency and its harmonics.

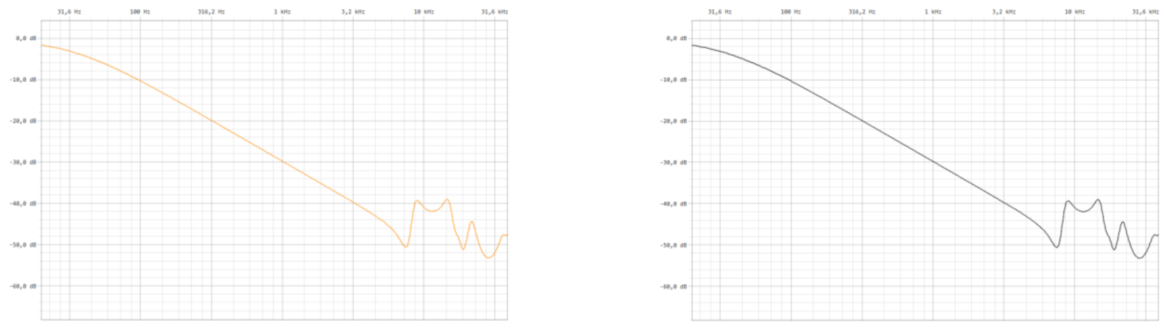

Figure 15: End-to-end short-circuit on HV winding performed with SFRA Instrument 1 (left) and SFRA Instrument 2 (right)

6 Summary

Noise coming from the environment in a substation might always influence SFRA measurements. It can be separated into narrowband and broadband noise. There are different possibilities for an efficient mitigation of noise influence, they can be distinguished in hardware-based techniques and software-based methods.

Especially the device-specific dynamic range severely influences the interpretation of the results. An adjustable output voltage and intelligent receiver bandwidth adaption are the most common techniques to improve the quality of the obtained SFRA traces. Software-based solutions with e.g. smoothing algorithms or averaging filters are independent from the applied hardware. Therefore, they can be used even after measurements have been executed just for result assessment.

In case of distorted measurement curves non-SFRA-experts can become uncertain how to assess the mechanical integrity of the power transformer. By utilizing a combination of the mentioned hardware- and software-based techniques, the resulting traces can be analyzed in most cases without significant influence of noise. The presented case studies show how the effects of low frequency noise can effectively be reduced by an intelligent receiver bandwidth adaption and increased output voltage. It should be kept in mind, that for a proper reproducibility of SFRA measurements in the low frequency range, it is recommended to perform the measurements at the same output voltage at which the reference measurement was performed.

As can be seen, modern SFRA test devices and an appropriate software can provide reliable SFRA measurement even in harsh conditions and help to improve the condition assessment of power transformer.

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Leads

At the latest since the IEC 60076-18 standard was introduced, the acceptance on the market for the Sweep Frequency Response Analysis (SFRA) method has increased and it has become one of the most common electrical tests for power transformers

The detected faults can be confirmed by further diagnostic measurements, such as leakage reactance, exciting current, or winding resistance measurements

In contrast, however, electrical failures of a power transformer such as short circuits between turns, open circuits or shorted core laminates can be identified by analyzing the low frequency area

There are several methods which can be used in order to mitigate the influence of external disturbances on the SFRA traces

Therefore, it is recommended to select a SFRA test instrument with a dynamic range greater than 100 dB. Modern SFRA devices offer, for example, a dynamic range up to > 150 dB.

In order to decrease the overall measurement time without the compromise of distorted measurement traces, intelligent bandwidth algorithms are integrated in sophisticated SFRA instruments

As can be seen, modern SFRA test devices and an appropriate software can provide reliable SFRA measurement even in harsh conditions and help to improve the condition assessment of power transformer

Authors

Michael Rädler is holding a Dipl. Ing. (FH) degree in industrial engineering from the University of Applied Science in Mittweida, Germany. After he graduated from the HTL (Federal Secondary College of Engineering) in Bregenz, Austria, in 2007, he started his professional career as an application engineer at OMICRON electronics, where he focused on power transformers. Since September 2013 he's been the product manager for OMICRON`s multifunctional primary test system for substation commissioning and maintenance (CPC100). He has published several papers about electrical measurements on power transformers and is member of the Cigre and works in the SFRA working group.

Stephanie Uhrig (née Raetzke) joined OMICRON electronics in 2010 as product manager and has since been responsible for various power transformer test systems. Currently her main focus is on frequency response analysis test systems (FRANEO 800). Stephanie studied electrical Engineering and Power Engineering and gained her Dipl.-Ing. degree at the Munich Technical University in 2003. She then worked for the Laboratory for High-Voltage Engineering of the university, where she obtained her PhD in 2009, focusing on materials for high-voltage engineering.

Juan L. Velásquez Contreras was born in Venezuela. He gained his BSc degree in Electrical Engineering from the UNEXPO (National Experimental Polytechnic University) in Venezuela in 2002. He then joined CVG Venalum in Venezuela, where he worked as a maintenance and project engineer for high-voltage assets. In 2006 Juan joined CITCEA (Center of Technological Innovation) in Spain. As a project engineer he worked on the implementation of condition-monitoring systems in power transformers. From 2008 until 2011 he worked as a product manager for diagnostic instruments at OMICRON electronics. In 2011 he completed his PhD in the area of Asset Management of Power Transformers at the Polytechnic University of Catalonia, in Barcelona, Spain. From 2011 until 2016 Juan worked as HVDC technology engineer at Amprion GmbH. In August 2016 he started to work as a development and service engineer at Hubert Göbel GmbH.

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