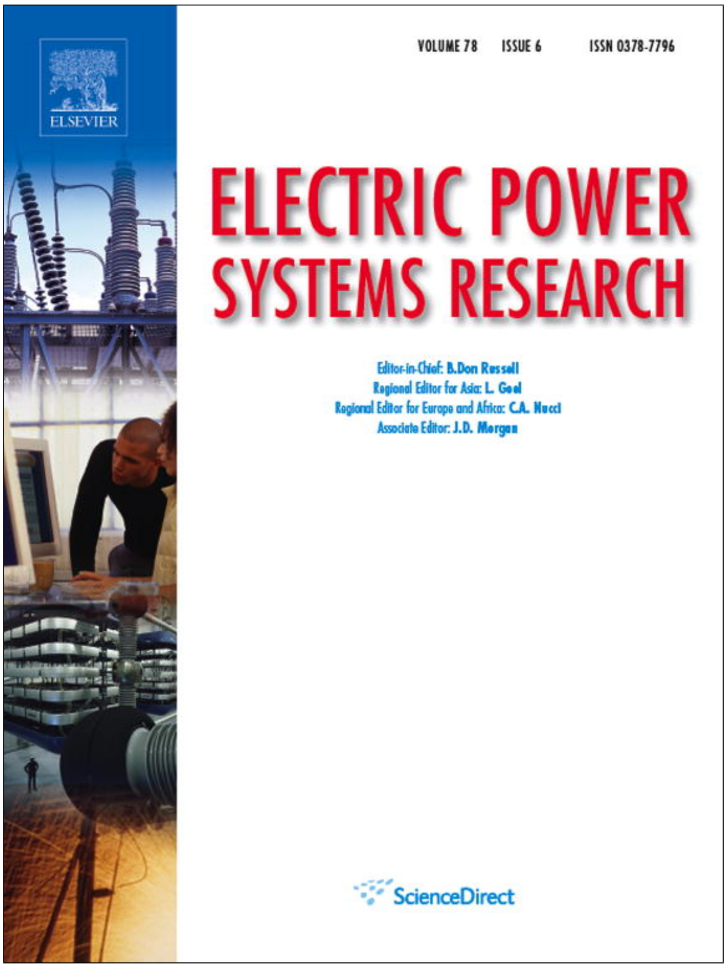

VOLUME 78 ISSUE 6 ISSN 0378-7796

ELECTRIC POWER
SYSTEMS RESEARCH

Editor-in-Chief: B.Don Russell
Regional Editor for Asia: L. Goel
Regional Editor for Europe and Africa: C.A. Nucci
Associate Editor: J.D. Morgan

ELSEVIER

ScienceDirect

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Electric Power Systems Research 78 (2008) 1119–1128
ELECTRIC POWER SYSTEMS RESEARCH
www.elsevier.com/locate/epsr

Short survey

Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers

J.R. Secue*, E. Mombello

Instituto de Energía Eléctrica (IEE), Universidad Nacional de San Juan, Av. Lib. Gral. San Martín 1109 Oeste, 5400 San Juan, Argentina

Received 18 November 2006; received in revised form 18 July 2007; accepted 4 August 2007
Available online 27 September 2007

Abstract

The sweep frequency response analysis (SFRA) is an analysis technique for detecting winding displacement and deformation (among other mechanical and electrical failures) on power and distribution transformers. Nowadays, there is an increasing interest in SFRA method because of its sensibility in detecting mechanical faults without opening the unit. SFRA as a diagnostic technique must integrate both the off-line measurements and the interpretation of the data in order to provide an assessment of the condition of the windings. However, guidelines for the measurement and record interpretation are not available. The evaluation is presently done by experts in the topic through the visual inspection or with the help of statistical parameters such as the correlation coefficient and the standard deviation. However, criteria like the limits of normal variation of the parameters, and the features observed in the records in the presence of a determined type of fault could not to coincide. Although, there are some proposals for making the interpretation more objective, neither of them integrate human expertise along with the different kind of parameters obtained from the evaluation of the records in a diagnostic model. This paper presents a survey on the alternatives in the measurement techniques and interpretation of SFRA measurements, describing some sources of uncertainty in applying this methodology.

Keywords: Transformer; Sweep frequency response analysis (SFRA); Winding displacement; Winding deformation

1. Introduction

A reliable detection of mechanical failures in power transformers due to winding displacement and deformations requires the implementation of a sensitive technique for the detection of this type of damage. Some of the diagnosis techniques used for this purpose are:

1. Measurement of short-circuit impedance (reactance) [1,2].
2. Vibro-acoustic method [3,4].
3. Frequency response analysis—FRA, obtained by two methods [4–47].
    a. Low-voltage impulse—LVI.
    b. Sweep frequency response analysis—SFRA.
4. Measurement of frequency response of stray losses—FRSL [5,6].

FRA technique is widely used because of its high sensitivity and is based on the concept that changes in the windings due to deformation and displacements cause a change in the impedances of the transformer and consequently a modification of its frequency response.

Frequency response analysis includes SFRA and LVI. Most of the literature about this topic indicates that the term FRA is understood as it was introduced by Dick and Erven [7]: "The FRA method uses a sweep generator to apply sinusoidal voltages at different frequencies to one terminal of a transformer winding. Amplitude and phase of signals obtained from selected terminals of the transformers are plotted directly as a function of frequency". This definition coincides with the current definition of SFRA method used by several authors, and is the one used in this paper.

The research works carried out in previous works [5,7–16] allows to establish the characteristics of LVI and SFRA and to determine some advantages that SFRA has over LVI as: higher signal to noise ratio, bigger repeatability and reproducibility and less requirements of measurement equipment.

This paper presents a review of the SFRA methodology. Section 2 focuses on the different aspects to be considered

---

* Corresponding author. Tel.: +54 2644226444; fax: +54 2644210299.
E-mail addresses: janneth.secue@gmail.com (J.R. Secue), mombello@iee.unsj.edu.ar (E. Mombello).

0378-7796/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2007.08.005

for the implementation of this metrology: frequency range and connection of the non-tested terminals. Section 3 presents a description of the SFRA's sensitivity, and several aspects related to the diagnosis. Several sources of uncertainty and inaccuracies influencing the results of the measurement and the subsequent diagnosis are showed in Section 4.

2. SFRA metrology

In order to analyze the SFRA metrology some general concepts of metrology must be given:

Measurand: Particular quantity subject to measurement.
Method of measurement: A logical sequence of operations, described generically, used in the performance of measurements and based in a principle of measurement or scientific base.
Measurement procedure: Set of operations, described specifically, used in the performance of measurements according to a given method.

2.1. SFRA measurand

There exist two possibilities of measurand in applying the SFRA method: Transfer Function (V_{out}/V_{in}) and Impedance (V_{in}/I_{out}). As explained in the literature [8], the transfer function obtained from voltage ratio V_{out}/V_{in} has no direct relation with the impedance measurement. The voltage ratio (V_{out}/V_{in}) is most frequently used as transfer function to be measured. The reasons for using impedance or voltage ratio transfer functions are not clearly established in the literature.

Reference [17] indicates that admittance measurement is usually less sensitive to small geometric changes than voltage ratio measurement. In [7,18] both types of measurement are made in order to obtain diagnosis criteria. In [7] these measurements are used also to calculate parameters of an equivalent circuit of the transformer winding.

The main characteristics of the SFRA measurand are twofold: frequency range and number of frequencies, which have been not clearly defined.

2.1.1. Frequency range

Table 1 contains a list of references reporting SFRA measurements. The third column indicates whether the measured magnitude was an impedance (*Z*) or a transfer function (*H*) and second column the frequency range, which varies from 10 Hz to 10 MHz.

2.1.2. Set of frequencies to be used during the test

The necessary time for performing an SFRA test (typically several minutes) is related to the bandwidth and number of spot frequencies, which are not universally defined. The number of spot frequencies used or recommended by the different authors is different. For example, 1000 spot frequencies are used in [7], 2000 in [8] and 3000 in [18].

Table 1
Frequency ranges used for SFRA measurements

Reference	Frequency	Measurement
[4,19]	100 Hz to 1 MHz	*Z*
[6,9]	Up to 2 MHz	*H*
[7][a]	1 kHz to 10 MHz	*H–Z*
[8,17]	20 Hz to 2 MHz	*H*
[11]	10 kHz to 1 MHz	*H*
[12]	10 Hz to 2 MHz	*H*
[13,20–22]	Up to 1 MHz	*H*
[14][b]	10 Hz to 1 MHz	*H*
[16]	5 Hz to 2 MHz	*H*
[18]	100 Hz to 3 MHz	*H–Z*
[23]	100 Hz to 1 MHz	*H*
[24]	Up to 10 MHz	*Z–H*
[25]	Up to 2 MHz	*Z–H*
[26,27]	50 Hz to 1 MHz	*H*
[28,29]	50 Hz to 200 KHz	*H*
[30]	10 Hz to 1 MHz	*H*
[31]	Up to 10 MHz	*H*
[32,33]	10 Hz to 10 MHz	*H*
[34,35]	Up to 200 kHz	*Z*
[36][c]	1 kHz to 1 MHz	*H*
[37]	1 kHz to 450 kHz	*H*
[38]	10 kHz to 3 MHz	*H*

[a] Measurements up to 10 MHz were carried out, but it is concluded that the upper limit of the useful frequency range is 1 MHz.
[b] It is mentioned that the upper limit of the reproducible range is probably at least 1 MHz.
[c] Several measurements have been performed in order to define the frequency range for the test, it has been established that the upper limit for the reproducible range is 1 MHz.

According [8], the relative spacing between adjacent spot frequencies must be always less than 2%.

2.2. SFRA measurement procedure

There are three important aspects involved in the measurement procedure: terminals connection of tested and non-tested terminals, types of measurement (transferred and non-transferred) and set of measurements to be performed.

2.2.1. Terminals connection

a. Non-tested terminals grounded through a damping resistor of 1 kΩ. In [7] a damping resistor of 1 kΩ is connected from each non-tested terminal of the transformer to the grounded tank. These resistors help to damp out secondary oscillations in non-excited windings and to minimize stray capacitance at the bushing terminals. Similarly in [36] resistors are connected to all tested and non-tested terminals.
b. All non-tested terminals open (floating). This configuration is used in [17,24,29,39,40]. In [29] non-tested terminals are left floating and the HV/LV neutral is grounded. Reference [39] states that earthing or short-circuiting non-tested terminals constrains the flux in the transformer to follow certain paths what results in the loss of potentially useful data.
c. Measurements using non-tested terminals short-circuited. Reference [21] indicates that short-circuiting the non-tested

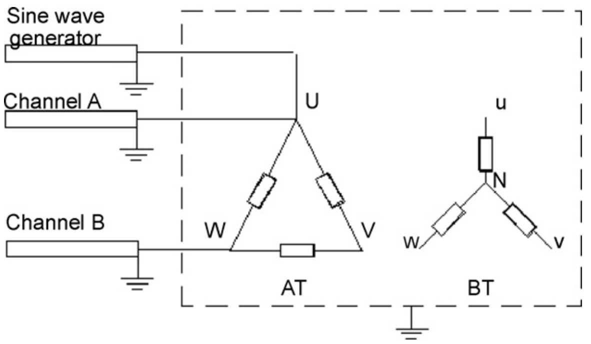

Fig. 1. Non-transferred measurement of a transfer function.

windings helps to remove the core effect at lower frequencies below 200 kHz. This effect is identified in [8] as the cause of the variation of the frequency response in the 2 kHz range, which becomes more noticeable when non-tested terminals are floating.

The authors of [4] perform tests using grounded (short-circuited) non-tested terminals as well as using open non-tested terminals in order to obtain complementary information from the measurements. In a similar way, in [41] measurements using ungrounded (short-circuited) non-tested terminals and open non-tested terminals are proposed, too.

2.2.2. *Types of measurement*

a. Non-transferred measurements: The terminals used in the test belong to the same voltage level (see Fig. 1).
b. Transferred measurements: The terminals used in the test belong to the different voltage levels (see Fig. 2).

These types of measurement can be performed either for the case of transfer function or impedance measurement. For example, in [18] the input voltage and the input current of the low-voltage winding are measured to estimate the input impedance; this is a non-transferred measurement of the impedance. On the other hand, the output voltage of the high-voltage winding is measured to estimate a transfer function. This is transferred measurement.

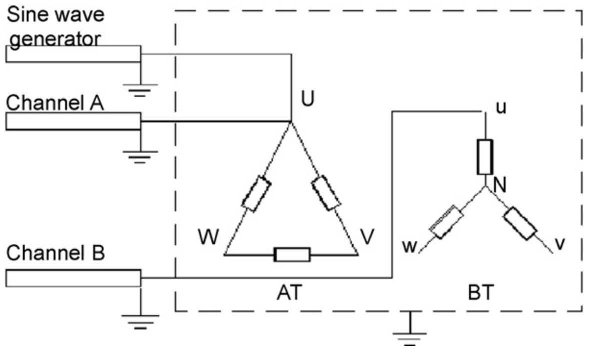

Fig. 2. Transferred measurement of a transfer function.

2.2.3. *Quantity of measurements (tests)*

The number of measurements to be performed depends on factors such as:

a. Set of tested terminals and connection form.
b. Set of non-tested terminals and connection form.
c. Type of measurement considered.

Comparing proposals [4,7,41] for a two-winding three-phase wye–wye connection transformer, it can be seen that the different proposals define the set of non-tested terminals and the number of tests to be carried out in a different way.

In reference [4] 15 tests are suggested, with both open and grounded (short-circuited) non-tested terminals:

a. Non-transferred measurements:
   - Measurements performed having each terminal of the HV windings as input and the respective neutral terminal as output. Similarly, also the terminals of the LV were used as inputs and the LV neutral terminal as output. All measurements performed using open non-tested terminals (HV and LV).
   - Measurements performed having each terminal of the HV windings as input and the respective neutral terminal as output, keeping HV non-tested terminals open and short-circuited LV terminals. Similarly, also the terminals of the LV winding were measured. These measurements characterize the HV/LV windings and the leakage impedances between primary and secondary winding.
b. Transferred measurements:
   - Measurements using the terminals to each phase of the HV winding and the corresponding terminals (same phase) of the LV winding, being non-tested terminals (HV and LV) open and neutral terminals grounded. These measurements describe the leakage impedances between primary and secondary winding.

Reference [41] reduces the number of tests from 15 tests to 12 since measurements between each LV terminal and LV neutral terminal keeping non-tested LV terminals open and non-tested HV terminals short-circuited are not proposed.

In reference [7] a set of 24 tests using grounded non-tested terminals is proposed. The test to be performed are:

a. Non-transferred measurements:
   - Measurements performed having each terminal of the HV windings as input and the respective neutral terminal as output. Similarly, also the terminals of the LV were used as inputs and the LV neutral terminal as output.
   - Supplementary measurements using both HV and LV neutral terminals.
   - Supplementary measurements inverting the role input –output of each pair of terminals.
b. Transferred measurements:
   - Measurements using the terminals to each phase of the HV winding and the corresponding terminals (same phase)

of the LV winding, for highlighting capacitive coupling between HV and LV windings.

These quantities do not include additional tests for different tap positions.

3. Fault diagnosis using SFRA

The sensitivity of SFRA has been extensively tested in several works [4,7,8,14,16,18,20,22–24,27,28,30–34,36–43,45] by means of faults simulations in laboratory and of real cases studies of transformers in service. Several types of faults can be detected by SFRA, such as winding movements, winding deformation, unclamped screws at the ends of a winding (loss of clamping pressure), inter-turn faults, loosening of connecting leads of HV and LV windings to the bushings, poor tank grounding, multiple core grounding, among others.

There is linguistic agreement between some experts [8,14,24,31], that major faults (caused by large movements of the core or windings) are identified in the low frequency range whereas minor faults (interturn faults, connection leads and small displacements) are identified in the high frequency range. However, there is no agreement regarding the frequency range to be used during the tests.

A drawback of SFRA as diagnostic tool is that there are no standard procedures to analyze and interpret the measurement records yet. The diagnosis task is performed by experts through the visual inspection of the records or with the help of some statistical and mathematical parameters. The analysis depends on factors as the type of recordings used for the comparison, the features extracted from the frequency response, etc. These factors are described below.

3.1. Type of recordings

SFRA method is based on the analysis of frequency response recordings taken during the lifetime of the transformer. There are two possibilities:

a. *Analysis of recordings taken on windings having reference recordings.* It is assumed that a set of historical records representing a healthy state of the transformer is available.
b. *Analysis without reference recordings.* If there are not historical recordings of the transformer there are two possibilities:
    - Analysis using recordings which belong to different phases of the same transformer. Due to the asymmetries inherent in the transformer design, there are differences between phases that must be considered. It has been reported in [15] that normal difference inter-phase are not comparable with the difference present in the case of significant winding displacements or deformations. This analysis has the advantage that the measurements are made under the same conditions.
    - Analysis using recordings of twin transformers. The comparison is made on the basis of recordings from a twin transformer, either a new transformer with the same characteristics or an old one in good condition. This is the most difficult alternative, because it is not easy to find transformers of the same constructive characteristics, whose operation conditions has been similar.

3.2. Features extracted from the frequency response

When reference recordings exist, the following features are analyzed [39]:

- Changes in the shape of the curve.
- Appearance of new resonant frequencies or disappearance of existing ones.
- Large shifts in existing resonant frequencies.

In order to establish the differences between recordings some parameters have been defined, namely: correlation coefficient (CC), standard deviation (S.D.) and maximum absolute difference (DABS). An analysis of the sensibility for detecting faults of CC and S.D. for different frequency ranges is done in [42,43]. The conclusion was that CC is a useful statistical parameter, while S.D. is an unreliable comparison parameter.

In [18] the disadvantages of CC and S.D. are analyzed. The authors of [18] state that CC is not sensitive for detecting changes in the frequency response characterized by a similar shape but having a constant difference in magnitude, and that an undesirable overestimation of the parameter S.D. takes place when the order of magnitude of the two responses analyzed differs not as a consequence of any fault but as a consequence of the slight shift of a peak, which is normal in this type of measurement. Other parameters such as: sum of squares error (SSE), sum squared ratio error (SSRE), sum square max–min error (SSMMRE), and absolute sum of logarithmic error (ASLE) were proposed by the authors in order to correct these undesirable characteristics of the CC and S.D. However, most of them, excepting ASLE, have undesirable numerical disadvantages. ASLE was presented as the most reliable parameter which was designed to make the fully log-scaled comparison in the magnitude frequency response; its application considers a previous process of interpolation proposed by the authors. The normal range of variation for these parameters has not been set yet.

On the other hand, some proposals have been made in order for the interpretation of SFRA measurements to be more objective:

Ryder's proposal [39]. This includes the calculation of CC by ranges of frequencies, relative change in first resonant frequency, relative chance in minimum low frequency amplitude and relative change in number of high frequency resonances. The criteria to be applied to determine whether a particular behavior constitutes a normal variation or not is not included as a part of the method.

Frequency response modeling using an equivalent circuit [19,27,28,30]. These models consider the behavior of the core and windings as a function of the frequency. In [19] the equivalent circuit uses sections having different topology, representing a particular bandwidth defined on the basis of

Table 2
Characteristics of the proposals for the interpretation of SFRA measurements

Proposal	Advantages	Disadvantages
Ryder's [39]	-The diagnostic is made using several parameters, which are integrated and codified, allowing a more reliable diagnosis. - A diagnosis table is proposed, several failures are identified depending of the specific code.	-The methodology for assessing what is a normal variation for the parameters is not an integral part of the method. -It is possible that a particular code corresponds to more than one fault. -A particular code could not match any fault type in the diagnosis table, e.g. in the following cases: two separate faults are present, an unusual fault no considered is present or there are measurement problems. -The phase response is not considered.
FR modeling using an equivalent circuit having a predefined topology [27],[28],[30]	- Takes account of both magnitude and phase frequency responses. - Takes account of the behavior of the core and windings as a function of the frequency. - Since the topology of the circuits is predefined, the analysis is just made by comparing the parameters of both equivalent circuits one by one. - A diagnosis table indicating the possible relationship between the transformer parameters and the type of fault is proposed.	- Since the topology of the models are predefined, these usually not fit the FR because they are limited to low order functions. - An analysis of parameter variations in the range in which they are considered as normal due to changes in the measurement system or usual differences between phases of the same transformer has not been made.
FR modeling using an equivalent circuit with topology not previously predefined [19]	- Takes account of both magnitude and phase frequency responses. - Takes account of the behavior of the core and windings as a function of the frequency. - The equivalent circuit topology is specific for each case, making possible a correct fit of the FR.	- An analysis of the sensitivity of the parameters for different kind of failures has not been made. - An analysis of parameter variations in the range in which they are considered as normal due to changes in the measurement system or usual differences between phases of the same transformer has not been made. - When a fault is present, resonance frequencies can appear or disappear. In these cases the topology of models are different. How the comparison should be made in such cases has not been defined. - A diagnosis table defining relations between the model parameters and possible faults is not proposed.
Mathematical models [26],[29]	- Takes account of both magnitude and phase frequency responses. -The functions are not limited to any specify order, it allows a correct fit of the measurement.	- The use of the model parameters for diagnosis purposes has not been clearly defined at the time of publication of the paper, since it will require further investigation.
ANN [22],[25],[34]	- Allows detecting the state of the windings, i.e. normal or abnormal condition.	-The proposed method requires the simulation of faults in a test transformer and its applicability is limited to transformers like the test transformers, i.e. twin units.

resonant or antiresonant frequencies. The complete model size depends on the quantity of the resonant and antiresonant points which are identified in each particular case. In [27,28,30] the initial equivalent circuit is simplified to three circuits for low, medium and high frequency. In [27] the equivalent transfer functions have low order (second and third), which do not fit the frequency response measured; the parameters of the functions are obtained using the *invfreqs* MATLAB command (Signal Processing Toolbox). In these proposals the variations of the parameters of these circuits are used for comparison purposes. The function *invfreqs* finds a continuous-time transfer function that corresponds to a given complex frequency response. From a laboratory analysis standpoint, *invfreqs* is useful in converting magnitude and phase data into transfer functions [48].

Modeling of transformers based on the internal geometry and material properties [32,37,38,40,44–47]. These models are a theoretical approach based on numerical simulation, their importance is related with the possibility of evaluating the sensitivity of the method for different kinds of faults.

Mathematical models. In these proposals the frequency response is modeled as a rational function with real coefficients. In [25] the rational function is solved through the already mentioned MATLAB function *invfreqs*. In [26,29] the problem of finding the polynomial coefficients is solved using *invfreqs* and non-iterative frequency-domain subspace-based identification algorithms. The parameters of the rational model are proposed for comparison purposes, but their sensibility to different kind of faults is not reported.

Artificial neural network (ANN) for fault diagnosis [22,25,34]. The use of ANNs for failure identification is proposed in these research works. These ANNs are trained by simulating faults in a specific test transformer. In [22] the CC and SD are calculated for low, medium, high frequency ranges and also for whole frequency range; then they are used as inputs of the ANN. The output is a number, 0 indicates a normal state of the windings, and 1 indicates abnormal state. The procedure is similar in [34] but only the CC is used as inputs of the ANN and the output is a number, if the output value exceeds a limit (the unity) then the diagnosis is a fault in the transformer windings. In [25] several networks are trained using the absolute frequency from poles and zeros, natural frequency, and damping coefficient as inputs; this ANN is able to identify and classify the type of fault.

Table 2 summarizes the main characteristics of the proposals.

4. Uncertainty and inaccuracies using SFRA

In practice there are several sources of uncertainty and inaccuracies that can influence the measurement results.

A linear single-input single-output system can be formally characterized by means of its impulse response $h(t)$ or by its frequency response, $H(\mathrm{j}\omega)$. The frequency response is a representation of the system's response to sinusoidal inputs at varying frequencies. The response of a linear system to a sinusoidal input is a sinusoid having the same frequency but a different magnitude and phase. The frequency response is defined as the magnitude and phase differences of the used transfer function.

It means that in order to perform a frequency response analysis in transformers there are two factors that must be taken into account:

- The analysis must be performed using a frequency range in which the system can be assumed to be linear.
- Not only the magnitude but also the phase response should be analyzed.

The first factor is associated with the effects of the iron core nonlinearity, which depends on the frequency range. The authors of [10] propose to perform the measurements at frequencies greater than 1 kHz for which it is supposed that the transformer behaves linearly and the iron core does not play a significant role. In [8] the effect of the core becomes significant for frequencies lower than 2 kHz; in [8,21] it is stated that the effects of the core are reduced if non-tested windings are short-circuited. In [46,47] the nonlinear effects of the core has been assumed to be negligible above 10 kHz, it is considered that the penetration depth of the magnetic field decreases with an increase of frequency. However, in [49] it was shown that there is a considerable inductance above 1 MHz. So the interaction between core and windings exists in the whole frequency range, even at higher frequencies.

The second factor refers to the fact that the phase response must be taken into account.

Table 3
Parameters used for frequency response analysis

$$\mathrm{ASLE}(x, y) = \frac{\sum_{i=1}^{N} \left| 20\log_{10} y_i - 20\log_{10} x_i \right|}{N} \qquad (1)$$

$$\mathrm{DABS}(x, y) = \frac{\sum_{i=1}^{N} |y_i - x_i|}{N} \qquad (2)$$

$$\mathrm{CC}(x, y) = \frac{\sum_{i=1}^{N} x_i y_i}{\sqrt{\sum_{i=1}^{N} x_i^2 \sum_{i=1}^{N} y_i^2}} \qquad (3)$$

$$\mathrm{MM} = \frac{\sum_{i=1}^{N} \min(x_i, y_i)}{\sum_{i=1}^{N} \max(x_i, y_i)} \qquad (4)$$

Except for CC, x_i and y_i are the ith elements of the frequency responses to be compared. N is the number of samples

$$\text{For CC:} \quad x_i = x_n - \mu_x \qquad (5)$$

$$\text{and} \quad y_i = y_n - \mu_y \qquad (6)$$

where μ_x and μ_y are the arithmetic average for $\{x_n\}, \{y_n\}_{n=1,\ldots,N}$

Usually, it is only considered the magnitude response for the diagnosis, if the phase response is used, then it must be correctly represented. When the phase is shown from −180 to +180° ($-\pi, \pi$ rad) there are some jumps when the angle exceeds one of the limits. This wrapped phase may be corrected by certain algorithms that unwrap the phase, as the *unwrap* function (MATLAB's Signal Processing Toolbox).

Another kind of error of the frequency response measurement is the presence of outliers in the records. These normally affect the magnitude and the phase and cause distortions in any statistical test based on sample means and variances; for example the parameter SSE is very sensitive to outliers. The detection of outliers in the measured frequency response is possible through visual inspection or techniques for discrete signals which use forward differences. Outliers can be suppressed by means of an interpolation process as proposed in [18], which considers the non-equidistance of the used spot frequencies (logarithmically distributed).

5. Case study showing the sensitivity of the mathematical and statistical parameters

As an example, the parameters DABS, CC and MM (Min–Max relation) are calculated to show their sensitivity to variations in the frequency response and how they could be used for diagnostic purposes. Table 3 shows the corresponding mathematical expressions of these parameters. The parameter DABS has the same form as ASLE excepting the factor $20\log_{10}$ and both parameters give the same results if the input data for

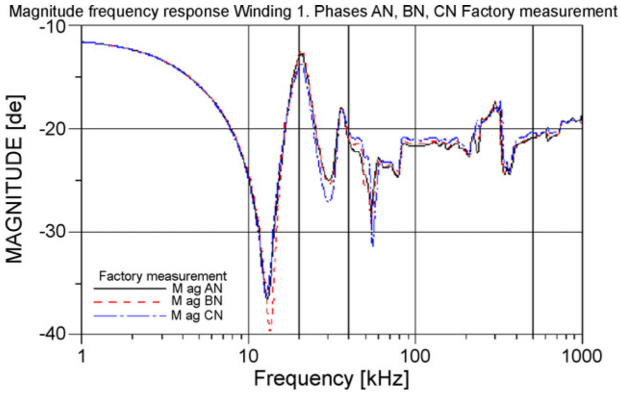

Fig. 3. Transfer function amplitude.

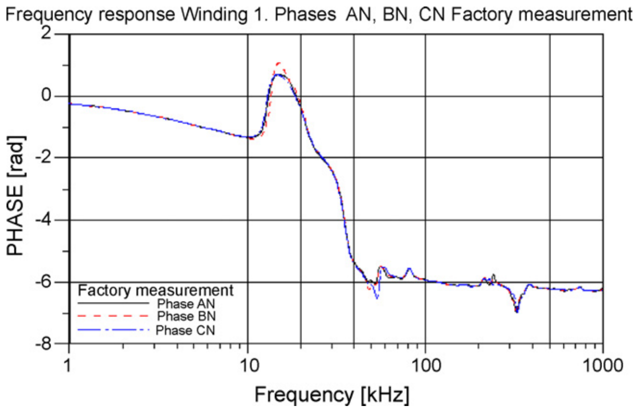

Fig. 4. Transfer function phase.

DABS is given in decibels for the magnitude response. Min–Max (MM) allows comparing the similarity of a data set. The parameter CC is sensible to resonance frequency displacements and to differences in the amplitude provided that they are not constant.

In analyzing similarity by means of CC, MM and DABS, the highest possible similarity level is CC = 1, MM = 1 or DABS = 0.

The tests carried out on a three-phase transformer (132 /69/13.86 kV–60/60/50 MVA wye–wye–delta) at factory were used to evaluate the sensitivity of the parameters. The transfer function was measured using an HP 4192A Impedance/Transfer Function Analyzer. The measurements were made at 1000 logarithmically spaced spot frequencies in a frequency range from 1 kHz up to 1 MHz. The analysis was performed using records belonging to different phases of the primary winding. To evaluate the parameters, the measurements were processed in order to suppress outliers and to correct wrapped phase. Figs. 3 and 4 show the amplitude and phase response, respectively.

Table 4 shows the values of the different parameters applied to magnitude and phase response for defined frequency ranges, which were selected in order to highlight the sensitivity of the parameters as a consequence of variations between phases.

Analysis of the results:

- Range 1: 1–10 kHz

  The parameters DABS and Min–Max are sensitive to slight differences in amplitude between the responses, and CC to the similarity in the shape of the responses, magnitude and phase.
- Range 2: 10–20 kHz

  The parameter DABS assesses the differences in amplitude between phases as a result of slight shifts in the resonant frequency at 13 kHz corresponding to phase B with respect to the other phases. The parameters CC and Min–Max also

Table 4
Parameters evaluated for a primary winding

Frequency range (Hz)	Phases	Magnitude response			Phase response		
		DABS	CC	Min–Max	DABS	CC	Min–Max
1 kHz to 10 kHz	AN-BN	2.1E−02	1.000	0.999	1.0E−03	1.000	0.999
	BN-CN	8.6E−02	1.000	0.994	2.7E−03	1.000	0.996
	CN-AN	6.5E−02	1.000	0.996	1.7E−03	1.000	0.998
10 kHz to 20 kHz	AN-BN	1.2E+00	0.980	0.955	1.7E−01	0.979	0.803
	BN-CN	1.7E+00	0.962	0.937	2.4E−01	0.958	0.737
	CN-AN	7.0E−01	0.995	0.973	7.4E−02	0.994	0.897
20 kHz to 40 kHz	AN-BN	2.5E−01	0.999	0.988	2.9E−02	1.000	0.989
	BN-CN	1.2E+00	0.981	0.944	3.7E−02	1.000	0.987
	CN-AN	1.2E+00	0.980	0.942	3.9E−02	1.000	0.986
40 kHz to 100 kHz	AN-BN	4.2E−01	0.977	0.982	3.8E−02	0.943	0.993
	BN-CN	8.9E−01	0.833	0.962	6.3E−02	0.770	0.989
	CN-AN	1.2E+00	0.786	0.951	8.6E−02	0.677	0.985
100 kHz to 500 kHz	AN-BN	2.2E−01	0.982	0.989	2.1E−02	0.986	0.997
	BN-CN	4.6E−01	0.922	0.978	3.1E−02	0.939	0.995
	CN-AN	5.8E−01	0.919	0.973	3.4E−02	0.937	0.994
500 kHz to 1 MHz	AN-BN	1.1E−01	0.983	0.994	1.2E−02	0.913	0.998
	BN-CN	1.5E−01	0.969	0.993	1.5E−02	0.825	0.998
	CN-AN	2.3E−01	0.936	0.989	2.1E−02	0.625	0.997

Table 5
Characteristic of the parameters CC, MM, DABS

	No sensitivity to	Sensitivity to
CC	Changes in the shape of the responses characterized by a constant difference in the amplitude	Changes to the shape of the curve as a consequence of: • The creation of new resonant frequencies or the elimination of existing resonant frequencies • Shifts in existing resonant frequencies • Non-constant amplitude differences
MM	Changes in the shape of the responses, which do not involve changes in amplitude	Changes of the shape especially related to amplitude variations in the responses as a consequence of: • The creation of new resonant frequencies or the elimination of existing resonant frequencies • Shifts in existing resonant frequencies • Changes in which the responses may be similar in shape but have a constant difference in amplitude
DABS	Changes in the measurements which do not involve changes in amplitude	Changes of the amplitude in the curves as a consequence of: • The creation of new resonant frequencies or the elimination of existing resonant frequencies • Shifts in existing resonant frequencies • Non-constant amplitude differences

identify the shift at this resonant frequency (reduced values compared with 1).

- Range 3: 20–40 kHz

  The vertical variations for the phases A and B with respect to the phase C observed in the magnitude response are identified by DABS. The slight shifts of the resonant frequencies, which are not easily visualized, and the non-constant vertical changes between the responses are identified by CC and Min–Max. The parameter Min–Max quantifies the amplitude variations better than CC.

  In this case the phase response has no detectable variations and CC indicates that the shapes are similar for the three responses, and the values of DABS and Min–Max lead to conclude that there are no important variations in amplitude.

- Range 4: 40–100 kHz

  The differences between the magnitude response of phase C with respect to those of phases A and B, which evidence not only shifts but non-constant variation of the amplitude, are identified for all parameters. However, a higher sensitivity of the CC can be appreciated. If the diagnosis be based on the analysis of CC, these low values could be interpreted as a bad condition for the phase C, but at the same time the values of Min–Max for magnitude and phase responses indicate that the differences are even smaller than those of the preceding range. The CC is highly sensitive to shape variations and Min–Max quantifies amplitude variations better, hence these parameters complement each other.

- Ranges 5 and 6: 1000–500 kHz/500 kHz to 1 MHz

  As in the previous range, CC is sensitive to the presence of some local minima and maxima, their displacements and slight non-constant amplitude differences. DABS and Min–Max evidence that the amplitude differences are not significant.

Table 5 summarizes the characteristics observed in the parameters.

The analysis using several parameters is most reliable since it is possible to confirm or weaken the diagnosis. As it has been shown in this example, the use of only one parameter could lead to an overestimation or underestimation of specific and isolated variations present in the frequency response. Besides, if the sensitivity of several parameters is integrated, it is possible to construct an automatic diagnostic system. For example, if an axial displacement causes only amplitude changes in the transfer function (TF) in a specify frequency range as described in [38], DABS and Min–Max will vary and if the differences are not uniform (which is the most possible situation) CC will be considerably sensitive to this change as well, allowing to confirm the diagnosis. In order to identify the type of fault, a certain knowledge of the corresponding typical values of the used diagnostic parameters is necessary.

The use of statistical or other parameters obtained from the frequency response model as a rational function (poles, zeros, residues, etc.) in applying SFRA methodology entails the processing of measured data. The parameters of the rational function obtained from the frequency response must be found by means of a fitting process. A very efficient and new method for doing this is Vector Fitting [50], a robust and public domain software whose approach is given in the form of partial fractions. The method presents satisfactory numerical stability in the case of high order approximations and wide frequency ranges, which is necessary since the frequency response of power transformers normally has several resonance frequencies in the frequency range from 1 kHz to 1 MHz.

A diagnostic technique based on multiple parameters of different kind (e.g., CC, ASLE, poles and residues) in order to take advantage of the different sensitivity of each parameter in the identification of features characterizing specific faults, which also takes the uncertainty, the imprecision and the experts' knowledge into account has not been proposed yet.

6. Conclusions

Nowadays, there is great interest in SFRA because of its sensitivity in detecting mechanical failures without opening the unit. If SFRA is to be used as a diagnostic technique, it must integrate the off-line measurements and the interpretation of the data in order to provide assessment to the mechanical condition of the windings and core.

The survey presented above shows that there are no guidelines for the measurement and although there are several proposals for the interpretation of the recordings, neither of them integrate human expertise and represent it by means of an expert system which require a knowledge structure.

The following characteristics must be taken into account in order to obtain a suitable diagnostic tool based on SFRA:

- The complex nature of the frequency response. Magnitude and phase responses must be taken into account for the analysis.
- There are several physical interactions present during the measurement, such as the interactions between windings, core and tank, depend on the type of winding excited, secondary winding type, terminal configuration, non-tested terminals connection, etc. An equivalent circuit could integrate all these physical phenomenon, but it requires the information of geometrical and physical properties of the materials which is not easily available.
- The measurements are affected by certain errors, thus any result is only an approximation or estimation of the real value of the measurand. Consequently, the parameters calculated from the measurements are also affected by errors.
- A diagnostic methodology which makes use of parameters of different kind, e.g., statistical and those obtained from rational functions, had not been yet proposed. In order to integrate all parameters, it is necessary to consider that those coming from rational functions contain amplitude and phase information. On the contrary, in the case of statistical parameters it is necessary to calculate them separately, that is, one for magnitude and another one for phase response.
- The knowledge of the experts in the topic is valuable but it has not been integrated in a systematic way. This knowledge can be illustrated, for example, by the fact that there is a linguistic agreement between some experts with regard to the relation between the severity of the fault and the frequency range analyzed.

All these factors indicate that the diagnosis based on SFRA is not straightforward, however, fuzzy causal diagnosis can be applied in order to obtain a diagnostic methodology. The consistency fuzzy approach and abduction fuzzy approach described in [51] could be adopted for the solution due to its effectiveness for dealing with several sources of uncertainty, such as those described for SFRA and those obtained in the process of feature extraction, i.e., the characteristic parameters. Furthermore, the experts' knowledge can be integrated with this approach.

Acknowledgement

The co-author J.R. Secue would like to thank the German Academic Exchange Service (DAAD) for the financial support of this work.

References

[1] C. Bengtsson, Status and trends in transformer monitoring, Power Deliv., IEEE Trans. 11 (3) (1996) 1379–1384.

[2] D.K. Xu, J.H. Huang, Y.M. Li, On-line monitoring of winding deformation of power transformer, in: Electrical Insulating Materials, 2001 (ISEIM 2001). Proceedings of 2001 International Symposium on 19–22 November, 2001, pp. 853–856.

[3] C. Bartoletti, M. Desiderio, D. Di Carlo, G. Fazio, F. Muzi, G. Sacerdoti, F. Salvatori, Vibro-acoustic techniques to diagnose power transformers, Power Deliv. IEEE Trans. 19 (1) (2004) 221–229.

[4] G. Csépes, I. Kispál, Case stories of FRA results used to detect the winding movement and geometric changes in power transformers (Hungarian experience), Cigre SC A2, June 2003 Merida Colloquium.

[5] M. Wang, A.J. Vandermaar, K.D. Srivastava, Review of condition assessment of power transformers in service., Electr. Insulation Mag. IEEE 18 (6) (2002) 12–25.

[6] P. Picher, C. Rajotte, Comparison of FRA and FRSL Measurements for the Detection of Transformer Winding Displacement, Institut de recherche d'Hydro, Québec, Canada, Cigre SC A2, June 2003, Merida Colloquium.

[7] E.P. Dick, C.C. Erven, Transformer diagnostic testing by frequency response analysis, IEEE Trans. Power Apparatus Syst. PAS-97 (November/December (6)) (1978) 2144–2153.

[8] C. Sweetser, T. McGrail, Sweep frequency response analysis transformer applications. A Technical Paper from Doble Engineering, January 2003.

[9] J.A. Lapworth, P.N. Jarman, I.R. Funnell, Condition assessment techniques for large power transformers, in: Reliability of Transmission and Distribution Equipment, Second International Conference, Conference publication No. 406, IEE, 29–31 March, 1995.

[10] P.T.M. Vaessen, E. Hanique, A new frequency response analysis method for power transformers, Power Deliv. IEEE Trans. 7 (1) (1992) 384–391.

[11] L. Xiaowei, S. Qiang, Test research on power transformer winding deformation by FRA method electrical insulating materials (ISEIM 2001), in: IEEE Proceedings of 2001 International Symposium, 19–22 November, 2001, pp. 837–840.

[12] S. Tenbohlen, D. Uhde, J. Poittevin, Enhanced diagnosis of power transformers using on- and off-line methods: results, examples and future trends. CIGRE Session 2000, paper 12-204. Available on http://www.uni-stuttgart.de/ieh/forschung/veroeffentlichungen/2000_CIGRE_paper_12-204.pdf.

[13] R. Ocón, A. Cancino, T. Asiain, Evaluación del método de respuesta en frecuencia (FRA) en la detección de deformaciones mecánicas en un devanado experimental. CIGRE - México 3er. Congreso Bienal y Expo Industrial 18–20 Junio, Irapuato Guanajuato, 2003.

[14] S.A. Ryder, Diagnosing transformer faults using frequency response analysis, Electr. Insulation Mag. IEEE 19 (2) (2003) 16–22.

[15] L. Coffeen, J. Hildreth, A new objective method for transformer frequency response analysis to determine winding deformation without the use of historical data [the objective winding asymmetry method], in: Proc. IEEE Spring Transformers Committe Meeting, Vancouver, BC, Canada, 2002.

[16] S. Tenbohlen, S.A. Ryder, Making frequency response analysis measurements: a comparison of the swept frequency and low voltage impulse methods, in: XIIIth International Symposium on High Voltage Engineering, Netherlands, 2003.

[17] M. Hässig, R. Bräunlich, R. Gysi, J. Alff, V. Der Houhanessian, W.S. Zaengl, On-site applications of advanced diagnosis methods for quality assessment of insulation of power transformers. In Electrical Insulation and Dielectric Phenomena, IEEE 2001 Annual Report Conference on 14–17 October 2001, pp. 441–447.

[18] K. Jong-Wook, P. ByungKoo, J. Seung, K. Sang Woo, P. PooGyeon, Fault diagnosis of a power transformer using an improved frequency-response analysis, Power Deliv. IEEE Trans. 20 (1) (2005) 169–178.

[19] J. Pleite, E. Olias, A. Barrado, A. Lazaro, J. Vazquez, Transformer modeling for FRA techniques, in: Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES, vol. 1, 6–10 October, 2002, pp. 317–321.

[20] R. Ocón, R. Malewski, A. Cancino, Frequency response analysis-transformer manufacturer perspective, Cigre SC A2, June 2003 Merida Colloquium.

[21] H. Fridman, Assessment of mechanical/thermal condition on two transformers, Cigre SC A2, June 2003, Merida Colloquium.

[22] D.K. Xu, C.Z. Fu, Y.M. Li, Application of artificial neural network to the detection of the transformer winding deformation, in: High Voltage Engineering, Eleventh International Symposium on (Conf. Publ. No. 467), vol. 5, August, 1999, pp. 220–223.

[23] B. Bak-Jensen, J. Bak-Jensen, L. Mikkelsen, Detection of faults and ageing phenomena in transformers by transfer functions, IEEE Trans. Power Deliv. 10 (1) (1995) 308–314.

[24] S. Birlasekaran, F. Fetherston, Off/on-line FRA condition monitoring technique for power transformer, IEEE Power Eng. Rev. Lett. (September) (1999).

[25] S. Birlasekaran, Y. Xingzhou, F. Fetherstone, R. Abell, R. Middleton, Diagnosis and identification of transformer faults from frequency response data, in: Power Engineering Society Winter Meeting, vol. 3, IEEE, 23–27 January, 2000, pp. 2251–2256.

[26] H. Akcay, S.M. Islam, B. Ninness, Identification of power transformer models from frequency response data: a case study, Signal Process. 68 (1998) 307–315.

[27] S.M. Islam, K.M. Coates, G. Ledwich, Identification of high frequency transformer equivalent circuit using Matlab from frequency domain data, in: Industry Applications Conference. Thirty-Second IAS Annual Meeting, IAS '97, Conference Record IEEE, vol. 1, 5–9 October, 1997, pp. 357–364.

[28] M. Stace, S.M. Islam, Condition monitoring of power transformers in the Australian State of New South Wales using transfer function measurements, in: Proceedings of the 5th International Conference. Properties and Applications of Dielectric Materials, vol. 1, 25–30 May, 1997, pp. 248–251.

[29] H. Akcay, S.M. Islam, B. Ninness, Subspace-based identification of power transformer models from frequency response data, Instrum. Measur. IEEE Trans. 48 (3) (1999) 700–704.

[30] S.M. Islam, Detection of shorted turns and winding movements in large power transformers using frequency response analysis, in: Power Engineering Society Winter Meeting, vol. 3, IEEE, 23–27 January, 2000, pp. 2233–2238.

[31] P.M. Jarman, Transformer winding movement and fault detection, Assessment of degradation within Transformer Insulation Systems, IEE Colloquium on, 6 December 1991, 8/1-8/2.

[32] J. Jayasinghe, Z.D. Wang, P.N. Jarman, A.W. Darwin, Investigations on sensitivity of FRA technique in diagnosis of transformer winding deformations, in: Electrical Insulation, 2004. Conference Record of the 2004 IEEE International Symposium, 19–22 September, 2004, pp. 496–499.

[33] P.M. Nirgude, B. Gunasekaran, B. A.D. Rajkumar, B.P. Singh, Frequency response analysis approach for condition monitoring of transformer. Electrical Insulation and Dielectric Phenomena, CEIDP '04, 2004 Annual Report Conference on 17–20 October, 2004, pp. 186–189.

[34] J. Zhijian, L. Jingtao, Z. Zishu, Diagnosis of transformer winding deformation on the basis of artificial neural network, in: Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials, vol. 1, 21–26 June, 2000, pp. 173–176.

[35] J. Zhijian, Z. Minglin, Z. Zishu, Fault location of transformer winding deformation using frequency response analysis Electrical Insulating Materials (ISEIM 2001), in: Proceedings of 2001 International Symposium, 19–22 November, 2001, pp. 841–844.

[36] I. Merlo, Determinación de pautas y criterios para la elaboración de diagnósticos de fallas en transformadores de distribución basándose en ensayos de análisis de respuesta en frecuencia (FRA), Degree Dissertation, Dept. Elec. Eng. Univ. San Juan Argentina, 2003.

[37] Y. Guillot, O. Moreau, D. Vo-quoc, FRA diagnostic method: simulation applied to sensitivity analysis and criteria derivation for mechanical shifting, in: Proc. of the 12th Int. Symp.on High-Voltage Engineering (ISH2001), Bangalore, India, 20–24 August, IV, No. 6-2,2001.

[38] E. Bjerkan, H.K. Høidalen, O. Moreau, FRA sensitivity analysis using high frequency modeling of power transformers based on the finite element method, in: Proceedings of the XIVth International Symposium on High Voltage Engineering, Tsinghua University, Beijing, China, 25–29 August, 2005.

[39] S.A. Ryder, A new method for diagnosing transformer faults using frequency response analysis, Cigre SC A2, June 2003 Merida, México, Colloquium.

[40] O. Moreau, Y. Guillot, B. Barre, FRA diagnosis method: simulation applied to feasibility study and efficiency improvement, in: Power Engineering Society 1999 Winter Meeting, vol. 2, IEEE, 31 January–4 February, 1999, pp. 1059–1064.

[41] C. Sweetser, T. Mcgrail, Winding frequency response analysis using the sweep frequency response analysis (SFRA) method, IEEE SFRA Specification, Doble Submission Version 1.0 March 2003, Available on http://www.doble.com/products/SFRA_Center/content/ieee/draftieeefra.pdf.

[42] S.A. Ryder, Transformer diagnosis using frequency response analysis: results from fault simulations, in: Power Engineering Society Summer Meeting, vol. 1, IEEE, 21–25 July, 2002, pp. 399–404.

[43] S.A. Ryder, Methods for comparing frequency response analysis measurements, in: Electrical Insulation. Conference Record of the 2002, IEEE International Symposium, 7–10 April, 2002, pp. 187–190.

[44] N. Al-Khayat, L. Haydock, Swept frequency response tests for condition monitoring of power transformers, in: Electrical Electronics Insulation Conference, 1995, and Electrical Manufacturing & coil Winding Conference. Proceedings, 18–21 September, 1995, pp. 45–47.

[45] K. Herszterg, H. Martins, S. Carneiro, Analytical approach of frequency response through a mathematical model of transformer windings, in: Proceedings of the XIVth International Symposium on High Voltage Engineering, Tsinghua University, Beijing, China, 25–29 August,2005.

[46] E. Rahimpour, J. Christian, K. Feser, H. Mohseni, Transfer function method to diagnose axial displacement and radial deformation of transformer windings, Power Deliv. IEEE Trans. 18 (2) (2003) 493–505.

[47] M. Florkowski, J. Furga, Detection of Winding Faults in Electrical Machines using the Frequency Response Analysis Method, Institute of Physics Publishing Measurement Science and Technology, 2004.

[48] User's Guide Version 7 on Signal Processing Toolbox Matlab.

[49] E. Bjerkan, H.K. Høidalen, O. Moreau, Importance of a proper iron core representation in high frequency power transformer models, in: Proc. of the 14th Int. Symp. on High-Voltage Engineering (ISH2005), Beijing, China, August 25–29, 2005.

[50] B. Gustavsen, A. Semlyen, Rational approximation of frequency domain responses by vector fitting, Power Deliv. IEEE Trans. 14 (3) (1999) 1052–1061.

[51] D. Dubois, M. Grabisch, O. Mouzon, H. Prade, A possibilistic framework for single-fault causal diagnosis under uncertainty, General Syst. 30 (2) (2001).