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New SFRA measurement interpretation methodology for the diagnosis of power transformers

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Abstract The analysis of the frequency response by the Sweep Frequency Response Analysis method (SFRA) is a diagnosis technique that can detect displacements, deformations and other mechanical and electrical failures in power and distribution transformers. One of the main disadvantages of the method is the lack of an international agreement regarding the methodology for measurement analysis, which is usually done by experts in the field, who normally make the diagnosis with the aid of statistical parameters such as correlation coefficient and standard deviation, or parameters derived from modeling the frequency response as a complex transfer function, represented by poles and zeros, or poles and residues. This paper presents a new methodology for SFRA measurement analysis, which makes use of the properties of various types of parameters and expert knowledge through the application of fuzzy causal diagnosis.

Keywords Power transformers · Frequency response analysis · Fuzzy causal diagnosis.

List of abbreviations

AAE	Average absolute error
ADV	Percentage deviation in the areas under the frequency response magnitude curves
ADMR	Absolute difference of the magnitude of the residues
AMMRR	Average min–max rate of the magnitude of the residues
ARA	Ratio between the areas under the frequency response magnitude curves
ANC	Absolute normal condition
CC	Correlation coefficient
CNS	Consistency index
DMSP	Diagnosis based on measurements on the same phases
DMDP	Diagnosis based on measurements on different phases
DMSPDP	Diagnosis based on measurements on both the same and different phases
FAC	Failure condition (includes TFC and NTFC)
FCD	Fuzzy causal diagnosis
FF1	Relative change of the first characteristic frequency
MF1	Relative change in the magnitude of the first characteristic frequency
MM	Min–max ratio
MNC	Modified normal condition
NC	Normal condition (includes ANC and MNCs)
NTFC	Not typified failure condition
Pcrt	Average percentage of the total amount of coincident maxima and minima
PcrtN	Absolute change of the total number of maxima and minima over the entire frequency range
SD	Standard deviation
SFRA	Sweep frequency response analysis
TFC	Typified failure condition

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1 Introduction

The sweep frequency response analysis (SFRA) method involves measuring transfer functions in the transformer windings when applied a sinusoidal voltage in a wide frequency range and comparing afterwards present and reference measurements. This analysis could be performed by the use of reference measurements performed on the same transformer phase (diagnosis based on measurements on the same transformer phase—DMSP), or measurements on another transformer having the same design, or comparing measurements from different phases of a three-phase transformer (diagnosis comparing measurements on different phases—DMDP). However, the relationship between failures and changes in the frequency response is not clearly known.

Although the method was introduced by Dick and Erven [1] in 1978, the SFRA measurement fundamental concepts and procedures are neither clear nor general, and the lack of an internationally recognized procedure for analysis of the measurements represents a significant disadvantage of the method. The analysis is currently carried out by experts in the field through visual inspection or using mathematical and statistical parameters, which could lead to incorrect diagnosis if used on a non-systematic way. Research works [2] and [3] provide a review of the metrology and diagnostics related to SFRA. The SFRA method as a diagnostic technique has to integrate off-line measurement and measurement interpretation to provide an accurate transformer condition assessment.

This paper proposes a new methodology for measurement interpretation through an automated diagnostic system based on the principles of Fuzzy causal diagnosis (FCD) [4,5]. This new methodology takes into account (1) the uncertainty inherent in any type of measurement and the one arisen from the calculation of the parameter that describe the characteristics observed in the measurements; (2) the integration of different types of parameters: mathematical, statistical and rational approximation obtained from the measured complex frequency response; and (3) the inclusion of the knowledge given in the form of natural language by experts in the field, for example, to qualitatively describe the characteristics that can be seen in the measurements not only in the case of particular type of fault but also in the cases of normal behavior. Section 2 discusses some commonly used parameters in SFRA analysis, identifying some individual advantages and disadvantages of their implementation and introducing other useful parameters for diagnosis. Section 3 describes the general diagnostic strategy. Section 4 describes the normal and abnormal behavior models proposed for SFRA diagnosis and how to relate one to each other. Section 5 presents application examples and finally, Sect. 6 compiles the main conclusions of this work. An introduction to the application of FCD to SFRA measurement interpretation can be found in the “Appendix”.

2 Parameters used for SFRA diagnostics

For the development of an automatic diagnostic tool, it is desirable that the information contained in the measurements is described by means of several parameters whose deviations from reference values make failure detection possible. The use of multiple parameters simultaneously makes the diagnosis more reliable and robust.

The parameters considered for the characterization of the measurements are classified into four types depending on their nature and the information they are able to analyze, as indicated below.

2.1 Type 1 parameters

They are suitable for the analysis of critical points (maxima and minima of the frequency response magnitude), allowing the behavior investigation of the resonance and antiresonance frequencies, also known as characteristic frequencies. Ryder [6] proposes the variation in the number of resonance frequencies as a diagnostic criterion for SFRA, suggesting for it the following parameters:

- Relative change of the first resonance frequency.
- Relative change in the magnitude of the first resonance frequency (below 10 kHz).
- Relative change in the number of resonance frequencies in the high frequency range (100 kHz–1 MHz). These parameters have been adopted and others have been introduced with identical aim, i.e., the analysis of the characteristic frequencies. They are shown in Table 1.

The parameters FF_2 and MF_2 are also introduced as in the case of FF_1 and MF_1, but considering the values of the second characteristic frequency. Additionally, for the frequency set $f_{R1R2} = f_{R1} \cup f_{R2}$ which includes the critical points (maximum and minimum) identified in both measurements (note that a critical point identified in R_1 may not be in R_2 and vice versa), the following parameters are defined:

$N_{T1T2\mathrm{out}}$: Number of spot frequencies in set f_{R1R2} for which the absolute difference of magnitude and phase between both measurements exceed pre-established limits for diagnosis. Through the study of no-failure cases the values 0.7 dB and 0.1 rad. for, respectively, magnitude and phase were determined and they are considered as suitable limits.

2.2 Type 2 parameters

Type 2 parameters are statistical and mathematical parameters. Their application involves the use of magnitude and phase of the frequency response and the subdivision in frequency ranges. Four frequency ranges have been defined: Range 1 (1 kHz–10 kHz), Range 2 (10 kHz–100 kHz), Range 3 (100 kHz–500 kHz) and Range 4 (500 kHz–1 MHz).

Table 1 Type 1 parameters

Relative change of the first characteristic frequency	Relative change in the magnitude of the first characteristic frequency	Absolute change of the total number of maxima and minima over the entire frequency range
$\mathrm{FF}_1 = \frac{f_{11}}{f_{12}}$ (1)	$\mathrm{MF}_1 = \frac{M_{f11}}{M_{f12}}$ (2)	$PcrtN = \mathrm{abs}(N_{T1} - N_{T2})$ (3)
Average percentage of the total amount of coincident maxima and minima		
$Pcrt = \frac{P_{friN_{T1}}+P_{friN_{T2}}}{2}$ (4)	$P_{friN_{T1}} = \frac{fri}{N_{T1}} * 100$ (5)	$P_{friN_{T2}} = \frac{fri}{N_{T2}} * 100$ (6)

R_1 andR_2 reference and present frequency response measurements, respectively, f_{11} first characteristic frequency in R_1, f_{12} first characteristic frequency in R_2, M_{f11} magnitude of the first characteristic frequency in R_1, M_{f12} magnitude of the first characteristic frequency in R_2, N_{T1} total number of maxima and minima in R_1, N_{T2} total number of maxima and minima in R_2, fri coincident maxima and minima in R_1 and R_2

Table 2 Type 2 parameters

Correlation coefficient		Min–max ratio	Average absolute error
$\mathrm{CC}(x, y) = \frac{\sum_{i=1}^{N} X_i Y_i}{\sqrt{\sum_{i=1}^{N} X_i^2 \sum_{i=1}^{N} Y_i^2}}$ (7)	$X_i = x_i - \mu_x$ (8) $Y_i = y_i - \mu_y$ (9) μ_x and μ_y are the arithmetic average for$\{x_i\}$, $\{\mathrm{y}_i\}_{\mathrm{i=1..N.}}$	$\mathrm{MM} = \frac{\sum_{i=1}^{N} \min(\lvert x_i\rvert, \lvert y_i\rvert)}{\sum_{i=1}^{N} \max(\lvert x_i\rvert, \lvert y_i\rvert)}$ (10)	$\mathrm{AAE}(x, y) = \frac{\sum_{i=1}^{N} \lvert y_i - x_i\rvert}{N}$ (11)

The values x_i and y_i are the i-th elements of the frequency responses to be compared. N is the number of samples. In analyzing similarity by means of CC, MM and AAE, the highest possible similarity level is CC = 1, MM = 1 or AAE = 0

Table 3 Type 3 parameters

Absolute difference of the magnitude of the residues	Average Min–Max rate of the magnitude of the residues
$\mathrm{ADMR}(M_1(s), M_2(s))_{\mathrm{SR}} = \frac{\sum_{i=1}^{N_{\mathrm{SR}}} \lvert R_i(M_1(s)) - R_i(M_2(s))\rvert}{N_{\mathrm{SR}}}$ (12)	$\mathrm{AMMRR}(M_1(s), M_2(s))_{\mathrm{SR}} = \frac{\sum_{i=1}^{N_{\mathrm{SR}}} \frac{\min(R_i(M_1(s)), R_i(M_2(s)))}{\max(R_i(M_1(s)), R_i(M_2(s)))}}{N_{\mathrm{SR}}}$ (13)

$M_1(s)$ is the function that fits the first measurement, $M_2(s)$is the function that fits the second measurement, *SR* is the frequency range identifier, N_{SR} is the number of residues belonging to the frequency range SR, andR_i is the magnitude of the i-th residue belonging to the frequency range SR

Parameters such as the correlation coefficient (CC) and Standard Deviation (SD), among others, have been analyzed and used for analysis of the measurements [6,7]. From a sensitivity analysis of different parameters [8], the parameters listed in Table 2 were selected on the assumption that its application is useful when used in a complementary manner, combined with each other or with other parameters of different types.

2.3 Type 3 parameters

Type 3 parameters are the poles and residues of the complex frequency response. These parameters are obtained from the function $M_x(s)$ that best fits the frequency response measurement in the frequency domain. The identification of $M_x(s)$ was carried out using the Vector Fitting algorithm [9,10]. Once the residues have been obtained and sorted by frequency range, the calculation of the parameters listed in Table 3 is carried out.

2.4 Type 4 parameters

These parameters are surface ratios and deviations. Purkait [11] proposed parameters involving the ratio between the areas under the frequency response magnitude curves (ARA) and the percentage deviation in the areas under the frequency response magnitude curves (ADV) to detect insulation faults. These parameters are sensitive to deviations of the amplitude of the frequency response and, therefore, are useful for SFRA diagnosis. Table 4 shows the mathematical expressions used to calculate these parameters.

Table 4 Type 4 parameters

Ratio between the areas under the frequency response magnitude curves (ARA)	Percentage deviation in the areas under the frequency response magnitude curves (ADV)
$\mathrm{ARA}= \frac{\int \lvert M_1(s)\rvert ds}{\int \lvert M_2(s)\rvert ds}$ (14)	$\mathrm{ADV}= \frac{\lvert\int \lvert M_1(s)\rvert ds - \int \lvert M_2(s)\rvert ds\rvert}{\int \lvert M_1(s)\rvert ds} 100$ (15)

$\lvert M_1(s)\rvert$ is the magnitude of the frequency response of the first measurement; $\lvert \mathrm{M}_2(\mathrm{s})\rvert$ is the magnitude of the frequency response of the second measurement

3 Diagnostic strategy

In using SFRA technique, it is desirable that reference measurements (fingertips) should be available, but lamentably it is not often the case. The consequence is that two diagnostic strategies are necessary: the first one is only focused on cases for which reference measurements are available

(Diagnostic Strategy A), and the second one is exclusively based on the comparison of records from different phases from the present measurements (Diagnostic Strategy B). These strategies make use of the following diagnostic procedures:

Diagnosis from Measurements on the Same Phase (DMSP) Reference measurements are available, which represent the normal condition of the transformer, so the diagnosis can be made from measurements performed on the same phase at different times.

Diagnosis from Measurements on Different Phases (DMDP) There are no reference measurements and, therefore, the diagnosis must be made from measurements on the phases of the same transformer.

Diagnostic strategy B only uses DMDP, whereas diagnostic strategy A uses either DMSP or both DMSP and DMDP for the case that the diagnosis from DMSP leads to an abnormal condition, and DMDP is used to verify that DMSP is correct.

Both DMDP and DMSP consist of two models, a normal behavior model (NBM) and an abnormal behavior model (ABM), so that there exist four behavior models. The normal behavior model is used first to check whether a normal condition is met; otherwise, the abnormal behavior model is used to classify the fault. Figure 1 depicts a simplified scheme of the diagnostic strategy.

It is to be noted in this flow chart that the final decision for strategy A takes the results of both DMDP and DMSP into account.

4 Models for normal and abnormal behavior

These models have been developed on the basis of Fuzzy Causal Diagnosis (see "Appendix").

4.1 Normal behavior models

The normal behavior model aims to

1. detect inconsistencies between observations and the symptoms describing the normal condition and
2. detect deficiencies in the measurements. The identification of this type of cases speaks about the robustness of the diagnostic system since it avoids them to be classified as an abnormal condition.

The following types of variations are included in the normal behavior model:

a. Changes due to interference and changes in the measurement system related to the grounding system and the resistance of the coaxial cable shieldings.
b. Slight variations caused by the measurement system, specifically due to stray parameters of test leads, and the magnetization condition of the iron core (when the transformer is put out of service to perform the measurements).
c. Design and construction variations between phases (i.e. DMDP).

In order to meet these two objectives, two types of condition are defined in the normal behavior model: Absolute Normal Condition (ANC) and Modified Normal Conditions (MNCs).

The assumption in the case of ANC is that the observations must be consistent with the possibility distributions representing the normal values of the attributes over the entire frequency range.

The MNCs introduce possible variations in the measurements due to the causes mentioned above, which are modeled by modified possibility distributions derived from the ones representing the normal values. The MNCs are able to diagnose the normal condition of the windings and also the low

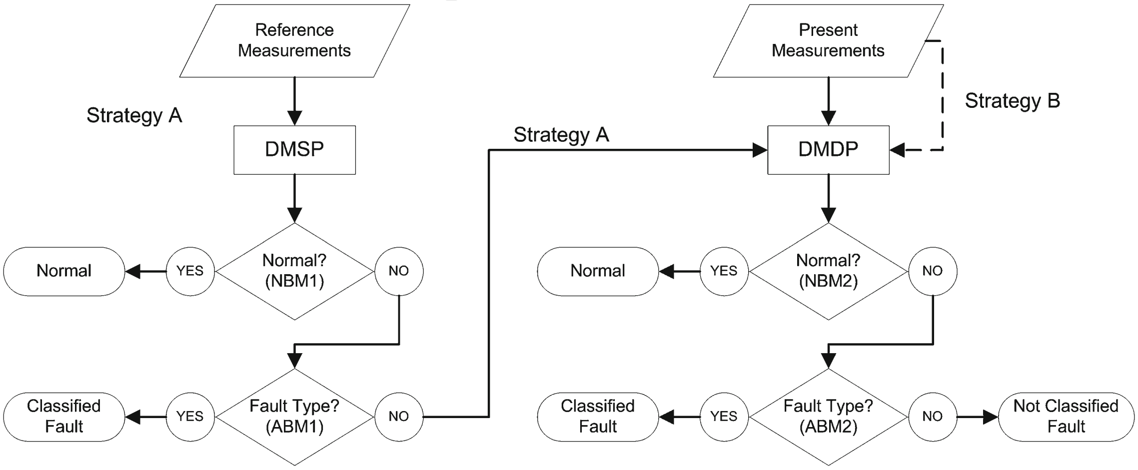

Fig. 1 Simplified diagnostic stragegy flow chart

reproducibility in the tests, in the case of DMSP. For DMDP these modified conditions indicate either external interference or that the differences between phases are considerable. The methodology used for the formulation of the different conditions included in the normal behavior model is presented next.

4.1.1 *Absolute normal condition-ANC*

Two ANCs must be formulated, one for DMSP and another one for DMDP. The ANC is defined for each type of diagnosis and differs only in the limits of the possibility distributions, which are stricter for DMSP than for DMDP.

In formulating the ANC each frequency range is evaluated in detail by examining type 2 parameters AAE, MM and CC, and type 4 parameters ARA and ADV. Subsequently type 1 parameters Pcrt and PcrtN are evaluated, which involve the entire frequency range. The ANC is defined by the following *requirements*:

Req1. ($\mathbf{AAE_{R1}}$ is *normal*) **AND** ($\mathbf{CC_{R1}}$ is *normal*) **AND** ($\mathbf{MM_{R1}}$ is *normal*)**AND** ($\mathbf{ARA_{R1}}$ is *normal*) **AND** ($\mathbf{ADV_{R1}}$ is *normal*)
Req2. ($\mathbf{AAE_{R2}}$ is *normal*) **AND** ($\mathbf{CC_{R2}}$ is *normal*) **AND** ($\mathbf{MM_{R2}}$ is *normal*) **AND** ($\mathbf{ARA_{R2}}$ is *normal*) **AND** ($\mathbf{ADV_{R2}}$ is *normal*)
Req3. ($\mathbf{AAE_{R3}}$ is *normal*) **AND** ($\mathbf{CC_{R3}}$ is *normal*) **AND** ($\mathbf{MM_{R3}}$ is *normal*) **AND** ($\mathbf{ARA_{R3}}$ is *normal*) **AND** ($\mathbf{ADV_{R3}}$ is *normal*)
Req4. ($\mathbf{AAE_{R4}}$ is *normal*) **AND** ($\mathbf{CC_{R4}}$ is *normal*) **AND** ($\mathbf{MM_{R4}}$ is *normal*) **AND** ($\mathbf{ARA_{R4}}$ is *normal*) **AND** ($\mathbf{ADV_{R4}}$ is *normal*)
Req5. ($\mathbf{Pcrt_{T}}$ is *normal*)
Req6. ($\mathbf{PcrtN_{T}}$ is *normal*),

(16)

where Req1, Req2, Req3 and Req4 are the requirements for frequency ranges 1, 2, 3 and 4, respectively, and Req5 and Req6 for the entire frequency range; **AND** represents the aggregation operator Soft-AND.

Bold words, e.g. $\mathbf{AAE_{R1}}$, correspond to the observations, while the word "*normal*" refers to the concept of fuzzy symptom. Values in parentheses represent consistency indices of the parameters with the corresponding condition.

The detailed evaluation by frequency ranges, i.e. requirements 1 to 4, is done by estimating the consistency between the observations, described by the parameters AAE, MM, CC, ARA and ADV, with their corresponding normal condition attributes. The consistency index aggregation is achieved through the aggregation operator Soft-AND (S-AND), since it allows to enhance the robustness and sensitivity typical of a diagnostic system [12]. This operator is an operator in between the AND operator and the generalized mean operator as indicated in expression (17):

$$S-\mathrm{AND}(x_1,\ldots,x_n) = 1-\left[\frac{\sum_{i=1,n}(1-x_i)^p}{n}\right]^{1/p} \quad p\in[1,\infty) \tag{17}$$

After performing a sensitivity analysis it has been found that the factor $p = 5$ gives a good sensitivity and robustness performance in the measurement evaluation.

The aggregation of the six requirements is made by means of the following expression:

$$(w_1,\mathrm{Req1})\oplus(w_2,\mathrm{Req2})\oplus(w_3,\mathrm{Req3}) \oplus(w_4,\mathrm{Req4})\oplus(w_5,\mathrm{Req5})\oplus(w_6,\mathrm{Req6})\,, \tag{18}$$

where

$w_1,\ldots,w_6$: weight assigned to each requirement.
$w_1,\ldots,w_4=1;\ w_5,w_6=0.9$

$\oplus$ is the weighted Soft-AND aggregation operator whose expression is given by the Eq. (19)

$$(x,w_x)\oplus(y,w_y) = 1-\left[\frac{w_x^p\,(1-x)^p+w_y^p\,(1-y)^p}{w_x^p+w_y^p}\right]^{1/p} \quad p\in[1,\infty) \tag{19}$$

Weighting factors are considered in the final evaluation, since requirements 5 and 6, which are related to Pcrt and PcrtN, typically have less information than requirements 1, 2, 3 and 4, which assess in detail each frequency range and take several parameters into account.

4.1.2 *Modified normal conditions*

The MNC identification is achieved evaluating the consistency and relevance indices of the observations in certain frequency ranges using the attributes described by the normal condition, and the consistency and relevance using attributes other than those defined for the normal condition in other frequency ranges. This methodology is also used to identify the type of fault. As an example, the description of MNC1 is presented below.

MNC1 (same phase and different phases) This condition includes slight variations in the measurements as a result of changes in the measurement system or the core magnetization, which arise in the first frequency range. The identification of this condition is possible by the analysis of the consistency of the observations with the normal condition attributes for the frequency ranges 2, 3 and 4, and of the consistency of the observations of range 1 with the attributes of the *slightly modified* condition (increased or reduced) in this range. The requirements defining this condition are

Req1. ($\mathbf{AAE}_{\mathbf{R1}}$ is *slightly increased*) OR ($\mathbf{MM}_{\mathbf{R1}}$ is *slightly reduced*)OR ($\mathbf{ARA}_{\mathbf{R1}}$ is *slightly modified**) OR ($\mathbf{ADV}_{\mathbf{R1}}$ is *slightly increased*)
Req2. (**Pcrt** is *normal*) AND (**PcrtN** is *normal*)
Req3. ($\mathbf{AAE}_{\mathbf{T-R1}}$ is *normal*) AND ($\mathbf{CC}_{\mathbf{T}}$ is *normal*) AND ($\mathbf{MM}_{\mathbf{T-R1}}$ is *normal*)
Req4. ($\mathbf{ARA}_{\mathbf{T-R1}}$ is *normal*) AND ($\mathbf{ADV}_{\mathbf{T-R1}}$ is *normal*)
*for this parameter *modified* can be *increased* or *reduced* (20)

The mathematical description of the MNCs and also of fault conditions is achieved by linking the requirements through the operators OR (max) and AND (min) as indicated in the description of the MNC1. In this case the aim is to achieve a good sensitivity to deviations from the normal value of the parameters within range 1 and also that the parameters calculated for the other frequency ranges to be consistent with the possibility distributions describing the normal condition. The aggregation factor of the requirements for all modified conditions is $p = 5$ and the weights of the requirements are $w_1 = 1,\ w_2 = 1,\ w_3 = 0.95$ and $w_4 = 0.95$.

4.2 Abnormal behavior model

The abnormal behavior model is made up of conditions that describe short-circuit, deformation and displacement failures. In this case, the main characteristics observed to identify the type of failure are

1. The behavior of the first characteristic frequencies.
2. The appearance and disappearance of characteristic frequencies.
3. Major displacements of characteristic frequencies and
4. Absolute value variations in the frequency response. As an example, the description for the deformation condition is given next.

4.2.1 Mechanical fault: winding deformation

The findings presented in the report "SFRA and Hoop Buckling" [13] and other documented failure cases [14–17] have been used for the definition of this fault. The evidence shows that this type of failure involves significant deviations in the parameters calculated for the faulted phase regarding sound phases in the range of low and medium frequency, up to approximately 500 kHz. Such changes include displacement of characteristic frequencies and major changes in amplitude. For the identification of the severe deformation failure the attributes of conditions different from normal are analyzed, especially in the frequency ranges 2 and 3. If the observations are consistent with the attributes of the modified conditions (other than normal) in range 2 and also with the normal condition attributes in range 3, this case is identified as a severe deformation failure. If the observations are consistent with the attributes of the modified conditions in ranges 2 and 3, the condition will also be considered as a severe deformation failure.

The following expressions describe the severe deformation condition, whose effects are observed in ranges 2 and 3:

Req1. (**Pcrt** is *slightly reduced*)OR(**Nout** is *equal to or greater than increased*)
Req2. ($\mathbf{AAE}_{\mathbf{R1}}$ is *equal to or less than slightly increased*) AND ($\mathbf{CC}_{\mathbf{R1}}$ is *equal to or greater than slightly reduced*) AND ($\mathbf{MM}_{\mathbf{R1}}$is *equal to or greater than slightly reduced*)
Req3. ($\mathbf{AAE}_{\mathbf{R2}}$ is *equal to or greater than increased*) OR ($\mathbf{CC}_{\mathbf{R2}}$ is *equal to or less than reduced*) OR ($\mathbf{MM}_{\mathbf{R2}}$ is *equal to or less than slightly reduced*) OR ($\mathbf{ADV}_{\mathbf{R2}}$ is *equal to or greater than increased*)
Req4. ($\mathbf{Rres}_{\mathbf{R2}}$ is *equal to or less than reduced*) OR ($\mathbf{ARA}_{\mathbf{R2}}$ is *equal to or less than reduced/* is *equal to or greater than increased*)
Req5. ($\mathbf{AAE}_{\mathbf{R3}}$ is *equal to or greater than increased*) OR ($\mathbf{CC}_{\mathbf{R3}}$ is *equal to or less than reduced*) OR ($\mathbf{MM}_{\mathbf{R3}}$ is *equal to or less than slightly reduced*) OR ($\mathbf{ADV}_{\mathbf{R3}}$ is *equal to or greater than increased*)
Req6. ($\mathbf{Rres}_{\mathbf{R3}}$ is *equal to or less than reduced*) OR ($\mathbf{ARA}_{\mathbf{R3}}$ is *equal to or less than reduced/* is *equal to or greater than increased*) (21)

The aggregation factor of the requirements for all modified conditions is $p = 5$ and the weights of the requirements are $w_1 = 1,\ w_2 = 0.95,\ w_3 = 1,\ w_4 = 1,\ w_5 = 1$ y $w_6 = 1$.

4.3 Linking the models

This section describes how the models of normal and abnormal behavior are to be linked.

First, the diagnosis based on measurements on different phases (DMDP) is described and afterwards the diagnosis based on measurements on the same phase *and* on different phases (DMSPDP).

4.3.1 *Diagnosis based on measurements on different phases*

In this case the measurements are processed first by the normal behavior model. In the event that these are consistent with this model, the final diagnosis will be a normal condition of the windings. Otherwise, the measurements are processed by the abnormal behavior model, which checks if it is about a typified fault or not. The corresponding algorithm for the assessment of the winding condition consists of four steps.

Step 1 Individual evaluation of each measurement pair j (for each phase $j = 1,2,3$) using the normal behavior model.

The following definitions are given:

CNS_{ANC}(j): Consistency between observations of the measurement pair j and the ANC.

CNS_{MNCS}(j): Consistency between observations of the measurement pair j and the MNC S.

S represents the MNC having the highest consistency with the observations. In addition to the absolute normal condition, 27 different MNCs have been defined for DMDP based on the analysis of actual cases representing slight deviations in different frequency ranges.

The measurements on different phases are classified by the normal behavior model on the basis of the corresponding consistency values according to the diagram depicted in Fig. 2.

Step 2 Evaluation of the three measurement pairs and eventually by the abnormal behavior model if any abnormality is detected. Two scenarios are possible:

a. If a normal condition (absolute or modified) is diagnosed for all measurement pairs, the general diagnosis for all windings is normal condition.

b. If for one or more measurement pairs there is no consistency with a normal condition (absolute or modified), it follows that they do not represent the normal condition of the windings. Consequently, for each measurement pair the diagnosis is obtained from the abnormal behavior model.

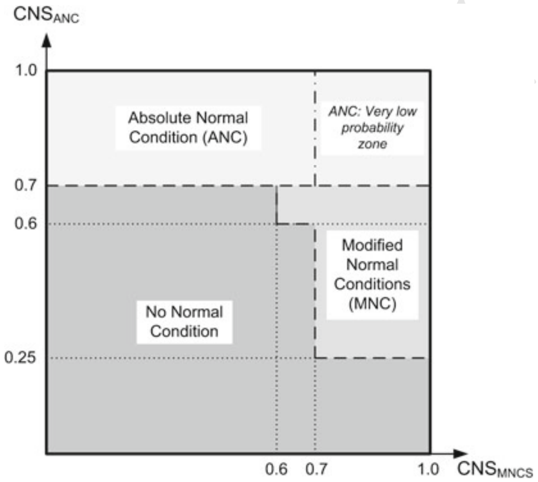

Fig. 2 Consistency values for classification of measurements on different phases according to the normal behavior model

The consistency index between the measurement pair j and the failure condition having the greater consistency and relevance with it is named CNS_{FAC} (j). Regarding the abnormal behavior model, if $\text{CNS}_{\text{FAC}} > 0.6$, it is assumed that the failure has been classified; otherwise it is assumed that the diagnosis is *not typified failure*. The different fault conditions included in the abnormal behavior model can be found in Table 5.

Step 3 Final diagnosis and identification of the faulted phase(s) if any.

The final diagnosis depends on the results of steps 1 and 2.

As an example, assume the case of SFRA diagnosis for star-connected windings, where each measurement provides information of an individual phase, as shown in Table 6.

A possible consistency analysis result is

$j = 1$ (U1N1-V1N1): condition compatible with absolute normal condition $\text{CNS}_{\text{ANC-Ph1}} = 0.8$.

$j = 2$ (V1N1-W1N1): condition compatible with abnormal condition with Id = 1 (short circuit); $\text{CNS}_{\text{FAC-Ph2}} = 0.7$.

$j = 3$ (W1N1-U1N1): condition compatible with abnormal condition with Id = 1 (short circuit); $\text{CNS}_{\text{FAC-Ph3}} = 0.7$.

It is, therefore, possible that the phases associated to the measurement pair ($j = 1$), U and V, are in normal condition.

Table 5 Different conditions of the abnormal behavior model

Id	Description
1	Short circuit fault without important mechanical damage due to deformation and displacement
2	Short circuit fault with possible mechanical change, detected in frequency range 2
3	Short circuit fault with possible mechanical change, detected in frequency range 3
4	Short circuit fault with important mechanical change, detected in frequency ranges 2 and 3
5	Deformation failure detected in frequency range 2. High severity
6	Deformation failure detected in frequency range 3. Moderate severity
7	Deformation failure detected in frequency range 2, 3. High severity
8	Displacement failure detected in frequency range 3, 4. High severity

Table 6 Nomenclature for measurements on star-connected windings

Winding	Measurement	Voltage applied between	Voltage measured at	Corresp. phase
Primary star direct	U1N1[a]	U1-ground	U1-ground / N1-ground	U
	V1N1	V1-ground	V1-ground / N1-ground	V
	W1N1	W1-ground	W1-ground / N1-ground	W

[a] The number indicates the winding on which the measurements are performed

Table 7 Diagnoses from SFRA measurements performed on the same or on different phases

Diagnosis description	DRDP
Normal condition	NC
Undefined condition: Contradiction situation, the phase labeled as normal behaves similar to the other two phases, whereas the phases labeled as abnormal behave differently to each other.	UC*
Abnormal condition—typified fault	TFC
Abnormal condition—not typified fault	NTFC

NC normal condition, *UD* undefined condition, *TFC* typified fault condition, *NTFC* not typified fault condition
* Not for measurements on the same phases

The other two measurement pairs ($j = 2$ and $j = 3$) are consistent with the short circuit fault condition, since the two measurement pairs are related to phase W and consequently it possibly has a short circuit failure.

Table 7 summarizes the possible diagnosis when examining measurements on different phases.

Step 4 Assessing the quality of measurements

The normal behavior model gives a linguistic estimation for the test conditions and whether significant design and construction variations between the phases exist. This information will be useful for future diagnosis based on present measurements.

MNCs are slightly different from the absolute normal condition in one or more frequency ranges, and the deviations could be slight or moderate. To linguistically describe the uniformity of the measurements the following linguistic terms have been used: *very high, high, slightly high, slightly low, low, very low*.

4.3.2 Diagnosis based on measurements on the same phases and on different phases

The main assumption for this type of diagnosis is the availability of reference measurements which describe the normal condition of the transformer. The diagnosis is first based on measurements on the same phases and then the results are checked using the diagnosis based on measurements on different phases.

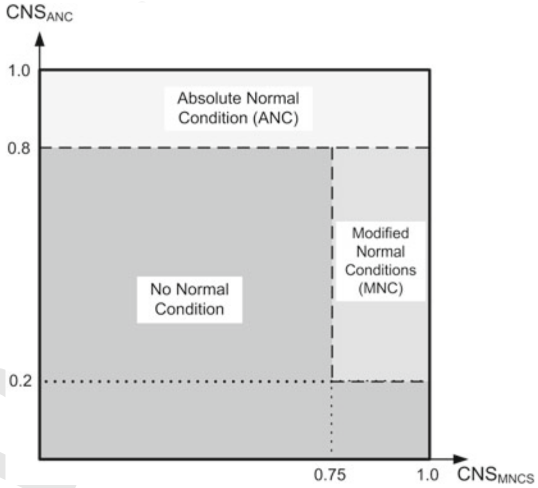

Fig. 3 Consistency values for classification of measurements on the same phases according to the normal behavior model

The algorithm for assessing the condition of the windings have five steps: the first four steps are based on measurements on the same phases and are similar to those presented for diagnosis based on measurements on different phases. The fifth step, which is the linkage with the diagnosis based on measurements on different phases, gives the possibility to detect any abnormality. The mentioned steps are described below.

Step 1 Individual evaluation of each measurement pair performed on the same phases by the normal behavior model (DMSP). At this step criteria are defined to decide whether each pair of measurements is consistent or not with the conditions defined in the normal behavior model.

For DMSP the normal behavior model is made up the absolute normal condition and 11 MNCs based on real cases representing typified slight variations in different frequency ranges.

The measurements on the same phases are classified by the normal behavior model on the basis of the corresponding consistency values according to the diagram depicted in Fig. 3.

Step 2 Measurement evaluation using the abnormal behavior model based for measurements on the same phases if any abnormality is observed. As for the case of measurements on different phases, the three pairs of measurements are processed. Two situations may arise:

a. If all measurement pairs are consistent with the normal condition, the general diagnosis for the windings will be normal condition. In this case an analysis using measurements on different phases is not performed.
b. If one or more measurement pairs on the same phases are not consistent with any condition of the normal behavior model, an evaluation by the abnormal behavior model is required. This situation can be the consequence of the following scenarios:

- The test conditions during the reference and the present measurements differ considerably, i.e. there is a very poor reproducibility between measurements on the same phases.
- The measurements evidence a fault. If the consistency index of the failure condition has the greatest consistency with the measurements $CNS_{TFC} \geq 0.7$, the associated windings are assumed to have such failure condition and the failure has been *typified*. If the consistency index is $CNS_{TFC} < 0.7$ the result of the diagnosis is *not typified failure*.

Step 3 Final diagnosis based on measurements on the same phases (DMSP).

The possible diagnosis result is the same as in the case of measurements on different phases (see Table 7), except for UC that does not exist in this case.

Step 4 Quality assessment of the measurements on the same phases.

In this paragraph the term quality is referred to the existence of high reproducibility in the measurements. This means that the test conditions during reference and present measurements are very similar, leading to almost no observable differences in the records. To linguistically describe the uniformity of the measurements on the same phases, the following linguistic terms have been used: *very high, high, slightly high, slightly low, low and very low*. It should be noted that this step is only done when the result of the previous step is normal condition.

Step 5 Supplementary analysis based on measurements on different phases (DMDP).

As already mentioned, there are three possible diagnoses when examining measurements on the same phases: NC, TFC and NTFC (see Table 7). If a faulted condition (typified or not) is diagnosed, the next step is to evaluate the measurements using the model based on measurements on different phases. From this last analysis it can be inferred either that the observed abnormalities between measurements on the same phases are due to poor test reproducibility, and to avoid giving a wrong failure diagnosis or to confirm the presence of a failure, thus making more reliable the final diagnosis. Two cases are possible:

Case 1: The result of DMSP is typified fault (TFC)

In this case a diagnosis is made based on records of different phases using the present records in order to confirm the presence of failure. Table 8 describes the possible DMSPDP results.

The starting point for this case is a typified faulted condition of the windings determined using measurements on the same phases. Although it is not expected that the evaluation of measurements on different phases results in a normal condition of the windings, this situation has been included in the case DMDP = NC. In this contradictory case the first diagnosis given by DMSP is accepted, since a greater amount of information has been considered to give this diagnosis, i.e. both present and reference measurements. Moreover, the consistency with the typified abnormal condition is greater than 0.7. Similarly, DMSP is accepted as final diagnosis for the case DMDP = UC. The cases DMDP = TFC and DMDP = NTFC confirm the presence of a failure; the difference is the ability of DMDP to typify the failure.

Case 2: The result of DMSP is not-typified fault (NTFC)

The starting point for this case is a not-typified faulted condition of the windings determined using measurements on the same phases. A diagnosis based on the measurements on different phases using the reference records is made first and then the same is done using the present records.

In this case there may be significant differences between the measurements on the same phases as a result of poor test reproducibility, a condition that could be inferred when the

Table 8 Diagnosis grid based on measurements on the same phases and on different phases DMSPDP

		DMSP		
		NC	TFC	NTFC
DMDP (present measurements*)	NC	NC(1)	TFC(2)	NC(5)
	UC	NC(1)	TFC(3)	NTFC(3)
	TFC	NC(1)	TFC(4)	NTFC(4)
	NTFC	NC(1)	TFC(4)	NTFC(4)

* Note: DMDF is performed on the present measurements except for the case labeled (5) in which it is also performed on the reference measurements

(1) Normal condition, given by DMSP. DMDP is NOT performed. Strictly speaking, this is not a DMSPDP case, but a DMSP case and was only included for the sake of completeness

(2) Abnormal condition, according to DMSP

(3) DMDP = UC, the phase labeled as normal is similar to the other two, while the abnormal phases differ from each other. Abnormal condition, according to DMSP

(4) The abnormal condition is confirmed

(5) Normal condition. The differences observed between the measurements on the same phases are due to very low test reproducibility

separate diagnoses of measurements on the same phase and those on different phases lead to a normal condition of the windings [Table 8, cell labeled (5)].

Except for the case labeled (5) in Table 8, where DMDP(reference) = DMDP(present) = NC, only DMDP (present) is used. Since the diagnosis based on measurements on the same phases (DMSP) is not conclusive, DMDP(present) is accepted in the case that DMDP = NC and as in the case before a low test reproducibility is assumed for measurements on the same phases. For the case DMDP = UC, the conclusion is that there is an abnormality in the windings, even though it could not be typified. The cases DMDP = TFC or DMDP = NTFC confirm the presence of a failure and the only difference is the ability of DMDP to typify the failure in each case.

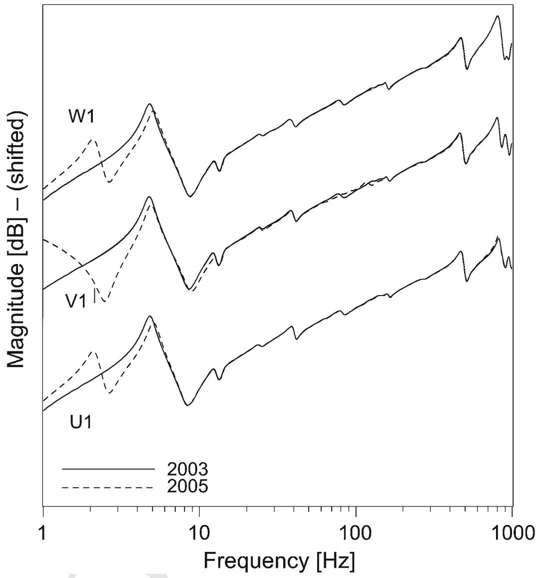

Fig. 4 Measurements on the same phases. Primary windings

5 Diagnostic procedure validation

5.1 Application example 1—diagnosis based on measurements made on both the same and different phases- DMSPDP

In the following the condition of the primary and secondary windings of a 230/138/13.8 kV 150 MVA YYD transformer is investigated. Reference measurements (A) made in 2003 and new measurements (B) made in 2005 are available. The first set of data was obtained at factory, and the second was obtained at substation.

A. Primary windings

Figure 4 shows the measured magnitude frequency response on the same phases for the primary windings. The different diagnosis steps for this case are described below.

Step 1 Individual evaluation of each measurement pair on the same phases.

As noted in Sect. 4.3 the measurements are first checked for consistency with the ANC. For the three phases the consistency index is $0.2 < \text{CNS}_{\text{ANC}} < 0.8$; therefore, an analysis of consistency and relevance with the MNCs is performed. This analysis indicates that the MNC 6 is the condition that best explains the measurements on phase U1. The measurements on phase V1 are more consistent with MNC 2 and the measurements on phase W1 are more consistent with modified normal condition 7. Table 9 summarizes the results of the normal behavior model for the measurements on the same phases.

Since the MNCs have a very low value, the conclusion of this step is that there is a failure, and the diagnosis procedure leads to step 2.

Step 2 Measurement evaluation using the abnormal behavior model based for measurements on the same phases.

The three pairs of measurements are processed with the abnormal behavior model. Table 10 summarizes the results with the abnormal behavior model.

Step 3 Final diagnosis based on measurements on the same phases (DMSP).

The diagnosis result based on measurements on the same phases indicates short circuit fault.

Step 4 Assessing the measurement quality

Because of the measurements are not consistent with the normal behavior model this step is skipped.

Step 5 Supplementary analysis based on measurements on different phases (DMDP).

Since a typified fault condition was diagnosed by the DMSP, the next step is to evaluate the measurements using the model based on measurements on different phases. In this case a diagnosis is made based on records of different phases using the present records in order to confirm the presence of failure. Figure 5 shows the present measured magnitude frequency response on different phases (2005).

The measurements are evaluated with the normal behavior model based on measurements in different phases. An abnormal condition is detected for the measurements pairs U1–V1 and V1–W1. The measurements pair W1–U1 is consistent with MNC 27 with a value of 0.75; this state identifies low variations in the measurements system observable in range 1, 2 and low interference in range 3 and 4. For the abnormal conditions an analysis with the abnormal behavior model is performed for the measurements pairs classified as “not normal” by the NBM indicating that a short circuit fault is the condition that best explains the measurements. Table 11 summarizes the results based on measurements on different phases (DMDP).

Table 9 Diagnosis summary using the normal behavior model. Primary windings

Measurement pair	Phase	ANC consistency index	MNC having the highest consistency	
			Condition Id.	Consistency index
U1N1(A)/U1N1(B)	U1	0.31	6.Variations due measurement system observable in range 1 and Low interference in range 4	0.18
V1N1(A)/V1N1(B)	V1	0.28	2. Variations due measurement system observable in range 1 and range 2	0.14
W1N1(A)/W1N1(B)	W1	0.31	**7**. Variations due measurement system observable in range 1 and medium interference in range 4	0.18

Table 10 Diagnosis summary using the abnormal behavior model. Primary windings

Measurement pair	Phase	Abnormal condition having the highest consistency	
		Condition Id.	Consistency index
U1N1(A)/U1N1(B)	U1	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00
V1N1(A)/V1N1(B)	V1	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00
W1N1(A)/W1N1(B)	W1	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00

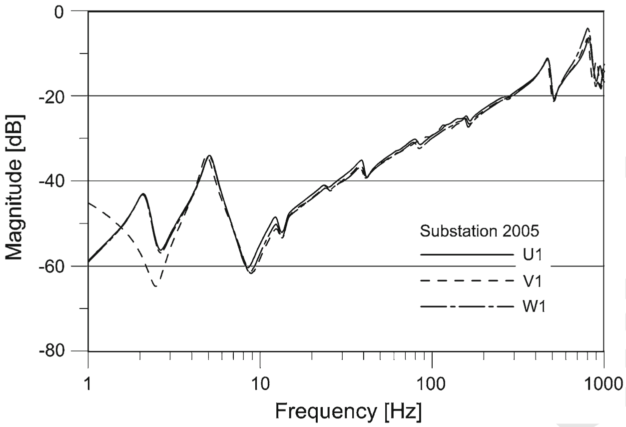

Fig. 5 Measurements on the different phases. Primary windings

According to the diagnosis grid for measurements on the same phases and on different phases (DMSPDP) given in Table 8, the final diagnosis is an abnormal condition and the typified fault is a short circuit. Also the analysis based on measurements on different phases indicates that the fault is associated with phase V.

B. Secondary windings

Figure 6 shows the measured magnitude frequency response on the same phases for the secondary windings. The different diagnosis steps for this case are described below.

Step 1 Individual evaluation of each measurement pair on the same phases.

Table 12 summarizes the results based on measurements on different phases (DMDP).

This analysis indicates that the MNC 1 is the condition that best explains the measurements on phases U2 and W2, but with a lower consistency value. The measurements on phase V2 are directly related to an abnormal condition. The conclusion of this step is that there is a failure, and the diagnosis procedure leads to step 2.

Step 2 Measurement evaluation using the abnormal behavior model based for measurements on the same phases.

Table 11 Diagnosis summary based on measurements on different phases (DMDP). Primary windings

Measurement pair	Phase	Abnormal condition having the highest consistency	
		Condition Id.	Consistency index
U1–V1	U1	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00
V1–W1	V1	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00
W1–U1	W1	27. Low variations in the measurements system observable in Range 1, 2 and low interference in Range 3 and 4	0.75

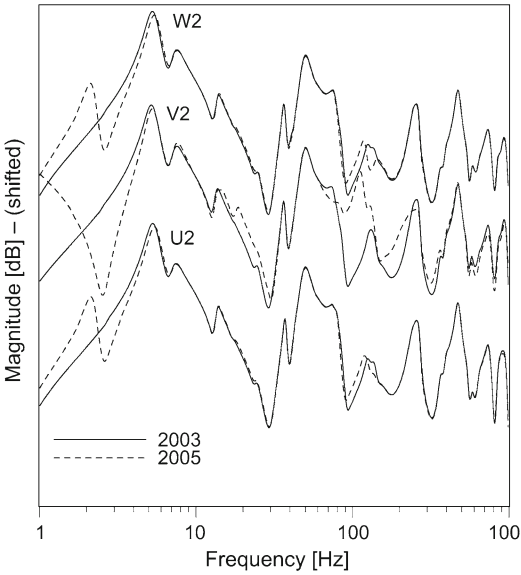

Fig. 6 Measurements on the same phases. Secondary windings

The three pairs of measurements are processed with the abnormal behavior model, Table 13 summarizes the results:

Step 3 Final diagnosis based on measurements on the same phases (DMSP).

The diagnosis result based on measurements on the same phases indicates a short circuit fault.

Step 4 Assessing the measurement quality

Because the measurements are not consistent with the normal behavior model, this step is skipped.

Step 5 Supplementary analysis based on measurements on different phases (DMDP).

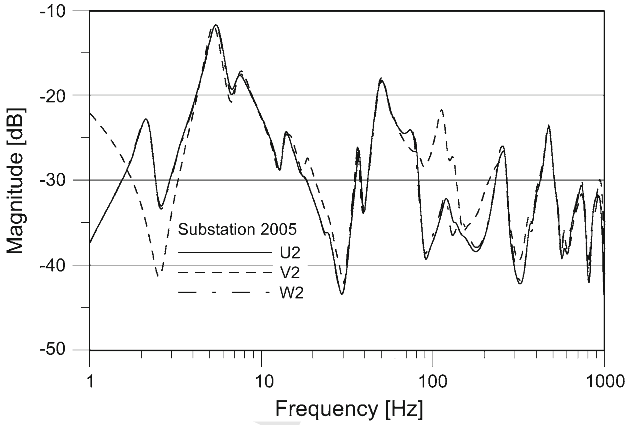

Fig. 7 Measurements on different phases. Secondary windings

Since a typified fault condition was diagnosed by the DMSP, the next step is to evaluate the measurements using the model based on measurements on different phases. In this case a diagnosis is based on records of different phases using the present records to confirm the presence of failure. Figure 7 shows the present measured magnitude frequency response on different phases (2005).

The measurements are evaluated with the normal behavior model based on measurements on different phases. An abnormal state is detected for the measurement pairs U2–V2 and V2–W2; the measurements pair W2–U2 is consistent with the ANC. For the measurements having abnormal conditions an analysis with the abnormal behavior model is performed indicating that a short circuit fault is the condition that best explains the measurements. Table 14 summarizes the results based on measurements on different phases (DMDP).

Table 12 Diagnosis summary using the normal behavior model. Secondary windings

Measurement pair	Phase	ANC consistency index	MNC having the highest consistency	
			Condition Id.	Consistency index
U2N2(A)/U2N2(B)	U2	0.31	1.Variations due measurement system observable in range 1	0.26
V2N2(A)/V2N2(B)	V2	0.14	–	–
W2N2(A)/W2N2(B)	W2	0.34	1. Variations due measurement system observable in range 1	0.26

Table 13 Diagnosis summary using the abnormal behavior model. Secondary windings

Measurement pair	Phase	Abnormal condition having the highest consistency	
		Condition Id.	Consistency index
U2N2(A)/U2N2(B)	U2	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00
V2N2(A)/V2N2(B)	V2	4. Short circuit fault with important mechanical change, detected in frequency ranges 2 and 3	1.00
W2N2(A)/W2N2(B)	W2	1. Short circuit fault without important mechanical damage due to deformation and displacement	1.00

Table 14 Diagnosis summary based on measurements on different phases (DMDP). Secondary windings

Measurement pair	Phase	Abnormal condition having the highest consistency	
		Condition Id.	Consistency index
U2–V2	U2	3. Short circuit fault without important mechanical damage due to deformation and displacement	0.89
V2–W2	V2	3. Short circuit fault without important mechanical damage due to deformation and displacement	1.00
W2–U2	W2	0. ANC	1.00

According to the diagnosis grid based on measurements on the same phases and on different phases (DMSPDP) given in Table 8, the final diagnosis is an abnormal condition and the typified fault is short circuit. Also the analysis based on measurements on different phases allows to relate the fault to phase V.

The analysis performed on secondary windings using the abnormal behavior models based on same and different phases resulted in more severe conditions than those identified for the primary windings, giving an indication of the voltage level in which the damage is present.

5.2 Application Example 2—diagnosis based on measurements made on both the same and different phases

In the following the condition of the primary windings of a 66/13.8/6.6 kV 20/20/6 MVA YYD transformer is investigated. Reference measurements (A) made in 2003 are available and also measurements (B) made in 2005. The two sets of data were obtained at substation.

Figure 8 shows the measured magnitude frequency response on the same phases. The different diagnosis steps for this case are described below.

Step 1 Individual evaluation of each measurement pair on the same phases.

As noted in Sect. 4.3 the measurements are first checked for consistency with the ANC. For the three phases the consistency index is $0.2 < \mathrm{CNS}_{\mathrm{ANC}} < 0.8$; therefore, an analysis of consistency and relevance with the MNCs is performed. This analysis indicates that the MNC 4 (moderate interference) is the condition that best explains the measurements related to phases V1 and W1. The measurements related to phase U1 are more consistent with MNC 5 (severe interference). Table 15 summarizes the results of the normal behavior model for the measurements on the same phases.

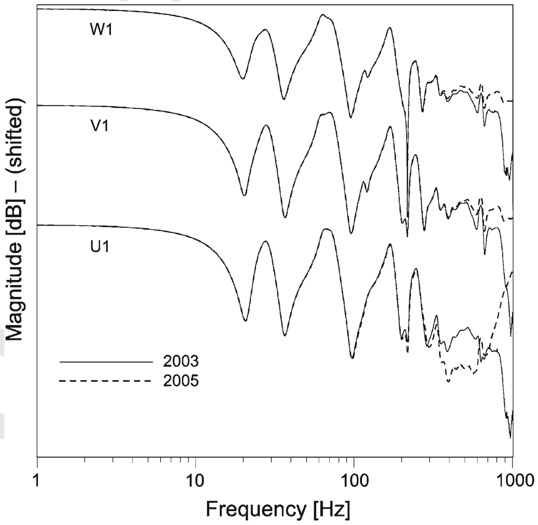

Fig. 8 Measurements on the same phases. Primary windings

The MNCs 4 and 5 identify significant changes in the measurement reproducibility conditions as an effect of external interference or changes in the measurement system layout (system grounding and test leads) whose effects are observed in the high frequency range.

Since consistency values for the MNCs are greater than 0.75, these conditions are assumed. The conclusion is that

Table 15 Diagnosis summary using the normal behavior model. Primary windings

Measurement pair	Phase	ANC consistency index	MNC having the highest consistency		Reproducibility conditions (measurement quality)
			Condition Id.	Consistency index	
U1N1(A)/U1N1(B)	U1	0.23	5. Low interference in range 3 and medium interference in range 4	0.88	Slightly low
V1N1(A)/V1N1(B)	V1	0.35	4. Medium interference in ranges 4	1.00	Slightly high
W1N1(A)/W1N1(B)	W1	0.32	4. Medium Interference in ranges 4	1.00	Slightly high

there were a low reproducibility between measurements instead of a failure and the diagnosis procedure leads to step 4.

Step 4 Assessing the measurement quality

Since the three measurement pairs are consistent with modified normal conditions, the quality of the measurements is checked as next step. The condition having the highest consistency is determined for each measurement pair, giving a linguistic description of them (see last column of Table 9).

The diagnosis given by experts from the visual inspection of the measurement records is the normal condition of the transformer, which is compatible with the actual normal operation of the transformer. The measurements were made as part of preventive equipment maintenance.

6 Conclusions

The proposed normal behavior models, one for diagnosis based on measurement on the same phases and the other for diagnosis based on measurements on different phases, show high robustness and sensitivity. Both fault detection and identification of normal deviations in the records are satisfactorily performed.

The failure type identification in the models of abnormal behavior is limited. This is a consequence of the fact that SFRA is sensitive not only to deformation, displacement and short circuit faults in the windings, but also to changes such as those in the leads connecting HV/LV windings to the bushings for example, about which there is no enough information to allow its typification.

The transformer condition evaluation on the base of measurements on the same phases in the presence of low test reproducibility between reference and present measurements can erroneously lead to an incorrect diagnosis of abnormal condition of the windings by the normal behavior model. This situation has been identified and dealt with through a second diagnosis based on the measurements on different phases.

The diagnosis based on measurements on different phases has the advantage that the measurements are performed under similar test conditions, i.e. with the same measuring equipment, layout and procedure, similar noise and interference environments. These conditions have similar effects on all three measurements. Hence, if the analysis of measurements on the same phases gives an abnormal condition of the windings *and* the analysis of measurements on different phases gives a normal condition, the conclusion is that the measurements were done under low reproducibility conditions.

The proposed general model is not restricted to the evaluation of specific transformers. Transformers of different sizes that range from 17 MVA to 150 MVA have been diagnosed successfully.

The model is not limited to the analysis of measurements made using a particular terminal connection either. If there is no reference data the measurements on different phases are used, which were performed under the same test conditions. On the other hand, if reference data are available it could be possible that the corresponding test layout and that of the present measurement differ. This situation is identified by the model based on both measurements on the same and on different phases (DMSPDP) as a condition of low reproducibility between measurements performed on the same phases.

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7 Appendix: Principles of fuzzy causal diagnosis—FCD

SFRA diagnosis can be considered as an uncertain reasoning problem, since the information, knowledge and representation of the observed features in the measurements by means of parameters have uncertain nature. Consequently, a solution method based on the principles of FCD described by Dubois et al. [4] has been adopted. This methodology combines the features of classical diagnostic methods based on consistency and abductive diagnosis, through the calculation of consistency and relevance indices. In applying FCD, observations may or may not be accurate and the relationship between symptoms and causes may or may not be fully known, as in the case of transformer diagnosis. The variables used in SFRA diagnosis and the calculation procedure of consistency and relevance indices are given next.

a. *Attributes* (p_x) Parameters used to describe the variations observed in the measurements. For example, the correlation coefficient (CC), min-max ratio (MM), average percentage of coincident critical points (Pcrt), among others.
b. *Observations (Oi)* Parameter intervals to describe the uncertainty in the parameter measurement and calculation. The individual value of each parameter is transformed into an interval according to the expression:

$$O_i = [p_x - \Delta p_x, p_x + \Delta p_x], \qquad (22)$$

   where p_x is the value of the parameter p_x (e.g. CC, ARA, etc.) calculated for both measurements, Δp_x is a value representing the uncertainty in the parameters. It can be given by an expert, or can be expressed as in terms of the standard deviation of the parameter (σ_x).
c. *Fuzzy symptoms* K_i^e. are possibility distributions representing the knowledge of the more or less plausible values of parameter p$_x$, at given state, *e*. As an example Fig. 9 shows the type of possibility distribution used for the parameters Pcrt, CC, MM$_1$ and AMMRR.

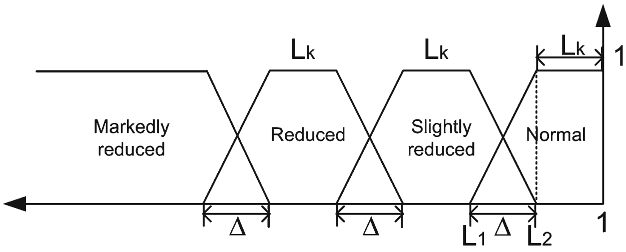


Fig. 9 Type 1 possibility distribution

For parameters to be calculated by frequency ranges, the limits of the possibility distributions describing the normal values of an attribute vary according to the frequency range; they are sharper for low frequencies and more relaxed as frequency increases. This characteristic is a consequence of the following tendencies observed during the measurements:

1. Since the measurement is made using a logarithmic sweep, there is more information in the low-frequency range.
2. The accuracy of the meter decreases as the frequency increases.
3. The higher the frequency, the more sensitive is the measurement to external interference and noise.

As an example, Fig. 10 shows the limits for the normal AAE attribute as a function of the frequency range.

The pairs [0,1], [L1(R1),1] and [L2(R1),0] are the limits of the type 2 possibility distribution of the normal AAE attribute for the first frequency range (R1). Similarly, the pairs [0,1], [L1(R4),1] and [L2(R4),0] are the range limits for the fourth frequency range (R4).

d. *Consistency index calculation between an observation and a fuzzy symptom*: The presence of a state e is consistent with the observation O_i if and only if $O_i \cap K_i^e = \varnothing$ [4]. For example, if in presence of state e the more or less plausible values of the attribute ADV in range 4 belong to the set that describes the concept *markedly increased*, then the consistency between a particular observation Oi such as the one shown in Fig. 11 and the symptom is calculated as

$$\begin{aligned} &\mathrm{cs}\left(O_i(u), K_i^e(u)\right) \\ &\quad = \sup\left\{\min\left(\pi_i^O(u), \pi_i^e(u)\right) : u \in U_i\right\} \\ &\mathrm{cs}\left(O_i(u), K_i^e(u)\right) \\ &\quad = \sup\left\{\begin{array}{l} \min\left(\pi^O_{\mathrm{ADV-R4}}(u_1), \pi^e_{\mathrm{ADV-R4}}(u_1)\right) \\ \min\left(\pi^O_{\mathrm{ADV-R4}}(u_2), \pi^e_{\mathrm{ADV-R4}}(u_2)\right) \end{array}\right\} \\ &\quad = m_{12} \end{aligned} \tag{23}$$

where

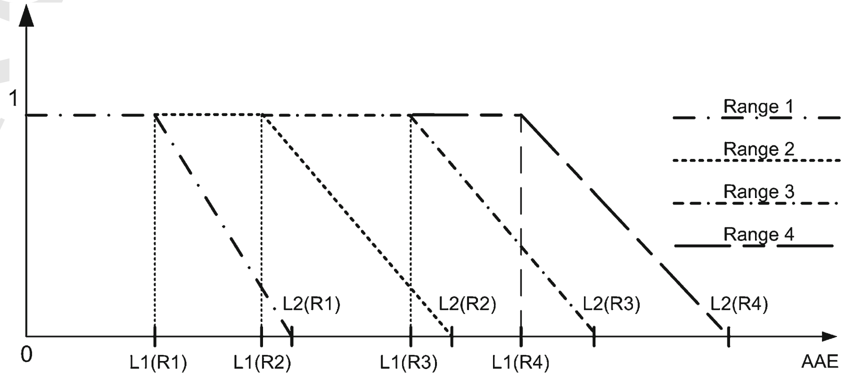
$$O_i = O_{\mathrm{ADV-R4}} = \left[p_{\mathrm{ADV-R4}} - \Delta p_{\mathrm{ADV-R4}},\; p_{\mathrm{ADV-R4}} + \Delta p_{\mathrm{ADV-R4}}\right] = [u_1, u_2]$$

$p_{\mathrm{ADV-R4}}$: ADV value calculated between a pair of measurements in range 4.
$\Delta p_{\mathrm{ADV-R4}}$: value that represents the uncertainty of ADV in range 4.
$\pi^e_{\mathrm{ADV-R4}}$: possibility distribution representing the more or less plausible values of the parameter ADV in the range 4 in presence of state e.
$K^e_{\mathrm{ADV-R4}}$: fuzzy set corresponding to the distribution of possibility $\pi^e_{\mathrm{ADV-R4}}$.
A consistent value equal to 1 indicates that the observation and the fuzzy symptoms are entirely consistent.

e. *Relevance index calculation between an observation and a fuzzy symptom*: Once all states have been calculated it may happen that several states have consistency equal to 1. To select the one that best explains the present observations, the fuzzy inclusion between observations and symptoms that describe the different states is calculated by means of the Dienes–Rescher implication [4]. Following the example above, the relevance between the observation and the symptom is

$$\mathrm{rv}\left(O_i(u), K_i^e(u)\right) = \inf_{u \in U}\left(\pi_i^O(u) \underset{D}{\rightarrow} \pi_i^e(u)\right)$$

Fig. 10 Relationship between frequency range and AAE normal attribute



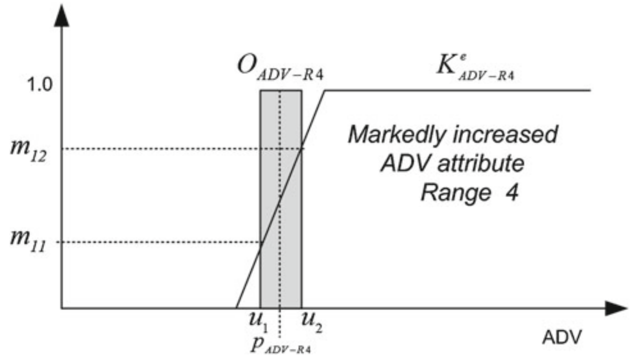


Fig. 11 Calculation of consistency and relevance indices

$$
\begin{aligned}
&\mathrm{rv}\left(O_i(u), K_i^e(u)\right) \\
&\quad = \inf_{u \in U} \left\{ \begin{array}{l} \max\left(1 - \pi^O_{\mathrm{ADV-R4}}(u_1), \pi^e_{\mathrm{ADV-R4}}(u_1)\right) \\ \max\left(1 - \pi^O_{\mathrm{ADV-R4}}(u_2), \pi^e_{\mathrm{ADV-R4}}(u_2)\right) \end{array} \right\} \\
&\quad = m_{11} \qquad (24)
\end{aligned}
$$

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