Frequency Response Analysis is a technique that has been successfully applied on power transformers to detect mechanical damage to windings since its development over 40 years ago

A review of transformer FRA measurement and diagnosis techniques

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ABSTRACT

Frequency Response Analysis (FRA) is a successful technique to detect mechanical damage in power transformers with greater sensitivity than other measurements. The SFRA method is commonly used today and requires a benchmark FRA measurement for comparative diagnostic methods. The use of numerical indices to quantify differences in two FRA signatures is described. It is important to understand the importance of understanding the physical meaning behind the frequency responses of windings through modelling and simulation.

KEYWORDS:

Frequency Response Analysis, Sweep Frequency Response Analysis, Windings, Numerical Indices, FRA Interpretation

1. Introduction

Frequency Response Analysis (FRA) is a technique that has been successfully applied to power transformers to detect mechanical damage to windings since its development over 40 years ago [1]. One example of such damage is shown in Figure 1.1. FRA grew from low voltage impulse test techniques, which record, for example, the neutral current when an impulse is applied to a terminal. These techniques had been successful in both detecting winding damage and understanding the impulse response for system transient studies. The raw impulse response, however, varies with cabling and impulse generator parameters, and the frequency response (the ratio of output voltage to input voltage across a range of frequencies) eliminated some of the uncertainties caused by measurements, has better reproducibility and was easier to interpret. Frequency response can be obtained using a fast Fourier transform algorithm (FFT) to convert impulse data (or any time series data with a suitable frequency content) into the frequency domain, but it is generally considered easier to obtain good signal-to-noise ratios, good frequency definition and rejection of interference required for reliable site measurements using a network analyser. A network analyser uses a swept frequency sine wave as the input signal whilst measuring the input and output signals through a narrow band filter tracking the frequency. This is the technique (sometimes called SFRA) most commonly used today.

With SFRA, it is relatively easy to choose the measurement bandwidth and frequency range and can generally use low voltages even in noisy environments. Initial studies showed the capability of the technique to detect winding movement, shorted turns and, in particular winding partial axial collapse with far greater sensitivity than impedance and capacitance measurements[1-2]. Measured under power frequency, transformer impedance, winding-to-ground and inter-winding capacitances do change if the physical distances that determine them change, and hence can defect major winding deformations. However, the wide frequency range employed by the SFRA measurement makes it sensitive to local movement or minor deformation of the winding as well. SFRA effective-

SFRA effectively measures the transfer admittance of the winding using multiple frequency points, generally in the range 2Hz to 2MHz

Since SFRA is a low voltage wide frequency measurement technique, many factors can contribute to 'false' deviations

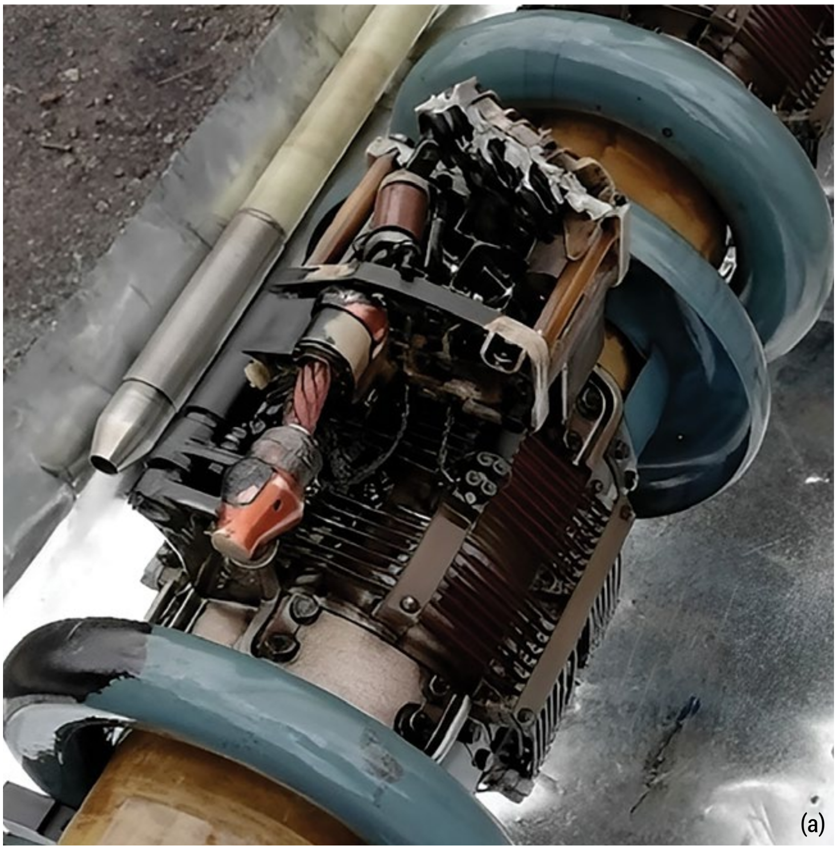


Figure 1.1. (a) Damaged on-load tap changer and (b) damaged B phase of HV winding

ly measures the transfer admittance of the winding using multiple frequency points, generally in the range 2Hz to 2MHz. Geometric dimension-dependent electrical parameters, i.e., winding inductances and capacitances, cause resonance and anti-resonance points across the frequency range, and localised geometric deformation of winding can therefore show itself as both frequency shifts and amplitude changes when being compared with a fingerprint measurement on the intact winding. FRA is normally used as a comparative diagnostic method in which a reference FRA trace is compared to the newly obtained FRA trace, and the mechanical condition of the winding is evaluated based on the deviations between the two traces. The fingerprint, i.e. a benchmark FRA measurement for comparison, is therefore vitally important and is ideally obtained when the winding is known to be undamaged, but can be obtained from another phase or another identical transformer albeit with lower detection sensitivity and more complicated interpretation.

Since it is a low voltage wide frequency measurement technique, many factors can contribute to 'false' deviations. For instance, at higher frequencies, care needs to be applied to earthing lead arrangements, especially when a long bushing is present. The tap-changer position causes the frequency response to change, so that change must be consistent between measurements. It is usual to ensure that the whole tap winding is included in the measurement as this is often the winding most vulnerable to mechanical damage.

The standardised measurement methods following IEC 60076-18 help to ensure the accuracy of the FRA measurement results and allow them to be practically applied to detect and diagnose winding deformations

This needs for a reliable benchmark measurement taken when the transformer is new, but which might not be needed for several decades, drives standardisation in both the measurement device and the configuration of the transformer when the measurement is taken. We need to understand the sources of variation first and then standardise the measurement methods to reduce them. This was achieved with CIGRE working group A2.26 [3] and then the development of IEC 60076-18, which introduced standard measurement configurations and reporting [4].

The standardised measurement methods following IEC 60076-18 greatly help to ensure the accuracy of the FRA measurement results and allow this comparative technique to be practically applied to detect and diagnose winding deformations. The "standard" FRA measurement connection method tends to be the winding end-to-end open circuit measurement chosen for its sensitivity to most deformations [5]. It has to be recognised, however, that one of the aims of the standard was to set out a minimum set of benchmark measurements, a very small subset of the possible combinations of winding connection and tap-changer position, which could be used. A much wider set of measurements might be useful for diagnosing particular faults.

Direct comparison between the newly obtained FRA trace with the fingerprint will often yield the "normal – no deviation" diagnostic result. However, deviations may sometimes appear, which suggest an "abnormal" diagnostic result, and require further detailed diagnosis, for instance, end-to-end short-circuit measurements may be applied when it is necessary to eliminate the influence of the transformer core, and inter-winding measurements can be considered if the effect of inter-winding coupling on FRA results is of concern. In parallel to the development of IEC 60076-18, IEEE standard C57.149 [6] also recommends a minimum set of test connections for different types of transformers, and the end-to-end open circuit and end-to-end short circuit measurements appear to be the minimum set for each winding. In addition. Some countries and utilities have also developed technical guides with additional measurement requirements, e.g., Sweep Frequency Impedance (SFI) which measures the short-circuit transformer impedance versus the frequency [7]. In SFRA, the end-to-end open circuit measurement measures the transfer admittance of the winding, while the secondary winding is open-circuited, whereas, in SFI, it measures the impedance of the winding, when the secondary winding is shorted-circuited. Thus, the short-circuit impedance at power frequency can be extracted from SFI.

Through standardisation of measurements and connections, a considerable volume of FRA fingerprints for various transformers at different voltage levels and power ratings have been accumulated by the electrical power industry over the last decades. At present, the assessment of FRA results demands examination by skilled personnel as there is no reliable diagnostic or pass/fail criterion available in IEC and IEEE standards [4,6]. The lack of such criteria is due to several complicating factors, including

The key electrical parameters that influence frequency characteristics of winding are equivalent air core inductance, ground capacitance and series capacitance, which are dependent upon the type of winding

FRA plots of windings with low series capacitance have more resonances and anti-resonances in high frequencies, in contrast to those with high series capacitance which tend to have a much smoother and rising trend

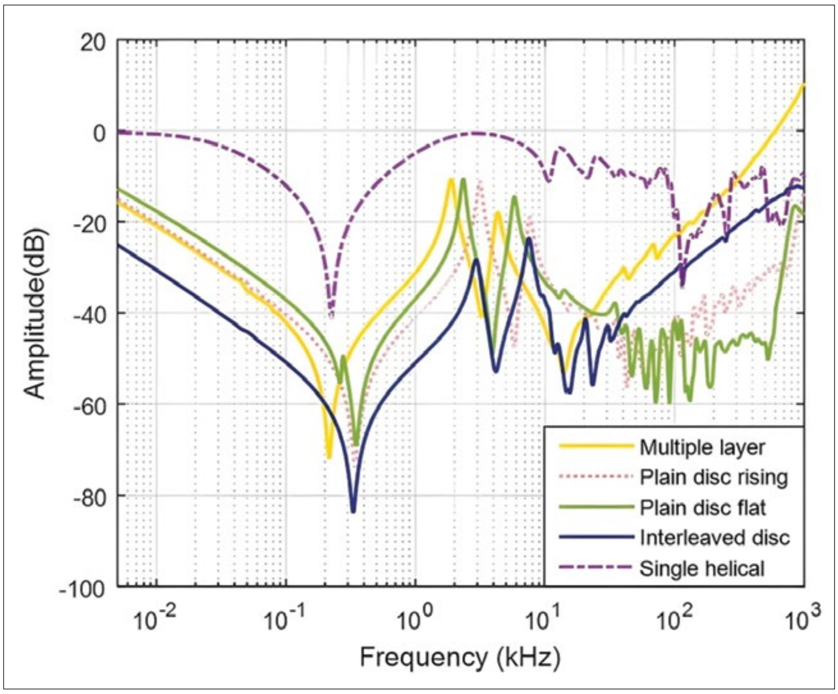


Figure 2.1 Typical FRA traces of different winding types [8]

Numerous indices have been proposed, and the performance of the numerical indices can be characterised by five criteria, including monotonicity, linearity, sensitivity, data size dependency, and index ratio

the variety and sophistication of winding designs and the influence of core magnetisation at low frequencies and cables and earthing at high frequencies, preventing the use of simple algorithms. Interpretation of FRA results is, therefore, still a challenge and the subject of active research, some of which are described in this article. The research aims are twofold but linked: to understand and model in detail how winding frequency response is determined by winding type, geometry and damage, and to be able to enumerate reliably deviations caused by that damage to provide a pass/fail criterion. In this context, the standard IEC 60076-18 is being revised to incorporate the significant additional site measurement experience accumulated since it was first published, as well as university research-based progress on modelling and simulations. This article sets out to review the research work so far carried out in the UTRA universities on the topic of FRA interpretation.

2. Winding design and how it influences FRA traces

Two types of winding design are commonly used in core-type transformers,

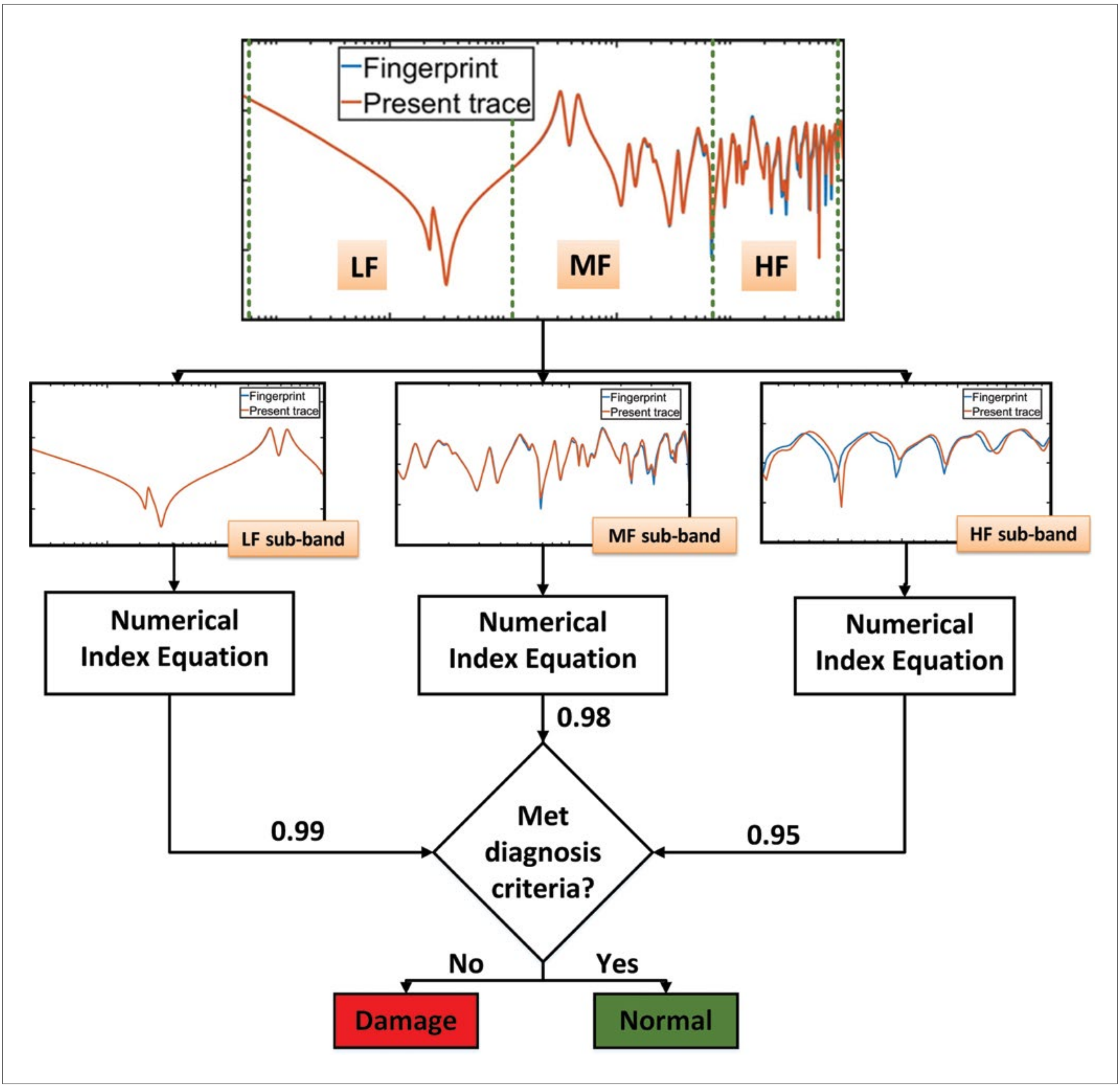


Figure 3.1 Application of a numerical index for FRA diagnosis [11]

which are helical and disc windings. The key electrical parameters of winding are equivalent air core inductance (L), ground capacitance (Cg) and series capacitance (Cs), and Cs is most dependent upon the type of winding. The space coefficient , is also critical in determining the features of the winding's FRA trace.

Helical winding

Helical windings are mainly used in high current, low voltage applications such as generator transformers where BIL is lower than 325 kV. In a helical winding structure, winding conductors are placed around the core in a way to form a helix where conductors are parallel to each

Figure 3.2. Forced buckling of LV winding

A winding assessment factor called Standard Deviation of Difference is proposed for quantitatively identifying the degree of deviation between two FRA signatures

other in the radial direction. Each layer of helical winding consists of a small number of winding turns, and typically a winding has a couple of layers. Typically, the series capacitance of helical winding is comparably smaller, and therefore, its FRA trace usually has multiple resonance points in high frequencies. Due to LV voltage application, the FRA magnitude of helical winding also tends to be higher than the other types of windings.

If multiple layers are used in a high-voltage winding design, they tend to have a high series capacitance.

Disc-type winding

Disc windings are commonly used in power transformers due to their mechanical stability. In contrast to helical winding, disc-type windings are typically used with higher voltage levels. In a disc-type winding, turns of conductors are placed in a flat disc, and these discs can be connected in series or parallel depending on the design considerations. The individual conductors in the disc are insulated from each other. Pressboard spacers are mounted between discs to acquire the required mechanical strength while maintaining oil circulation through windings. Typically, the series capacitance of plain disc winding (also called continuous disc winding) is higher than helical winding, and interleaved disc winding has an even higher series capacitance.

Typical FRA measurement results of different winding types are presented in Figure 2.1, where the x-axis from 5 Hz to 1 MHz is in the logarithmic scale. Empirically, the transformer core dominates the FRA feature in the frequency region from 2 Hz to 2 kHz, winding interaction, which means the inductive and capacitive coupling from the non-tested winding to the winding under test, dominates the FRA feature in the region from 2 kHz to 20 kHz, and the features dominated by the winding itself will also be visible in the frequency region from 20 kHz to 200 kHz [9]. In Figure 2.1, it can be seen clearly that FRA plots of windings with low series capacitance have more resonances, and anti-resonances in high frequencies, in contrast to those with high series capacitance which tend to have a much smoother and rising trend in the region from 20 kHz to 200 kHz.

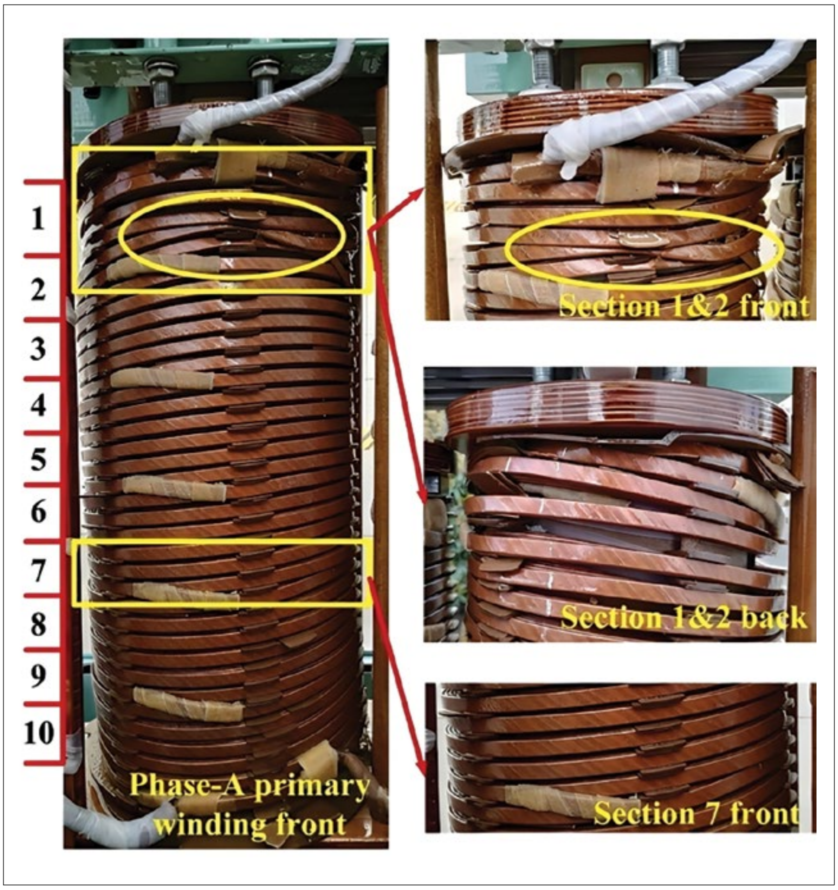


Figure 3.3 Axial collapse of the disk-type winding

3. FRA numerical indices

FRA diagnosis can be assisted by employing numerical indices, which quantify the differences in two FRA signatures [10- 11]. A mathematical equation is used to extract a single value from the reference and present FRA traces. The assessment of the transformer condition is then carried out based on the quantified value of the indices, as depicted in Figure 3.1.

Some researchers used the FRA data in the whole frequency range, whereas others divide the whole frequency range into several frequency regions to reach reliable assessments. IEC and IEEE standards [4,6] stated that the division of frequency regions is not standardised yet.

Numerous indices have been proposed, and the performance of the indices can be characterised by five criteria, including monotonicity, linearity, sensitivity, data size dependency, and index ratio [11-12]. To evaluate and compare the characteristics of indices, different case studies are considered through an experimental setup which consists of a single-phase transformer with HV and LV windings. The windings correspond to a medium voltage transformer of about 1 MVA. The HV winding is a continuous disc winding, and the LV winding is a helical winding. In the experimental setup, three commonly occurring mechanical faults, axial displacement (AD), radial deformation (RD), and disk space variation (DSV) are implemented in various steps, as shown in Figure 3.2 and Figure 3.3.

These implemented mechanical faults result in detectable resonant frequency

Table 3.1. The equations of the winding assessment factor

$\overline{SDD(i)} = -2\left(\sqrt{\frac{\sum_{j=1}^{WS}(Z(j) - (\overline{Zw(i)})^2}{WS - 1}}\right), i = 1,2,3 \ldots N$		
Where $\overline{Z(i)} = X(i) - Y(i)$	$\overline{Zw(i)} = \overline{Xw(i)} - \overline{Yw(i)}$	$\overline{Xw(i)} = \frac{1}{WS}\sum_{j=1}^{WS} X(j)$
$\overline{Yw(i)} = \frac{1}{WS}\sum_{j=1}^{WS} Y(j)$	$WS = 10 + 6\left(\frac{f_{res} - 200}{200}\right)$	

shifts and amplitude changes in the FRA measurement results [11].

In this context, a winding assessment factor called Standard Deviation of Difference (SDD) is proposed for quantitatively identifying the degree of deviation between two FRA signatures [11]. In this method, the mean deviation of difference is calculated to evaluate the degree of deviation between two FRA signatures, which is further standardised with the total number of measurement samples, thus, called Standard Deviation of Difference (SDD). In this proposed method, SDD is evaluated in a frequency window with a specific window size (WS). The window slides from the starting frequency to the ending frequency of the FRA trace with a specific window step (Wstep=1), as shown in Figure 3.4. Consequently, the entire frequency range of the FRA signature is scanned, and SDD is evaluated in each window. Accordingly, a vector is obtained that characterises the deviation between two FRA signatures as a function of frequency. Hence, the calculated SDD and the measured FRA signatures can be drawn on the same scale in a graph, as shown in Figure 3.5. The idea was first presented in [14] and proved to be an effective method for quantifying deviations between two FRA signatures in many cases. The equations of the winding assessment factor are given in Table 3.1.

Thus, the proposed method can detect faults with high sensitivity, and it also resolves the problem of fixed frequency sub-bands. The minimum value of SDD (MSDD) indicates the maximum deviation between two FRA traces. It is worth noting that MSDD has lower values for the cases with deformations than those

Understanding the physical meaning behind the frequency responses of winding, which is the relationship among winding geometry, transformer equivalent electrical components and corresponding FRA spectra, is key

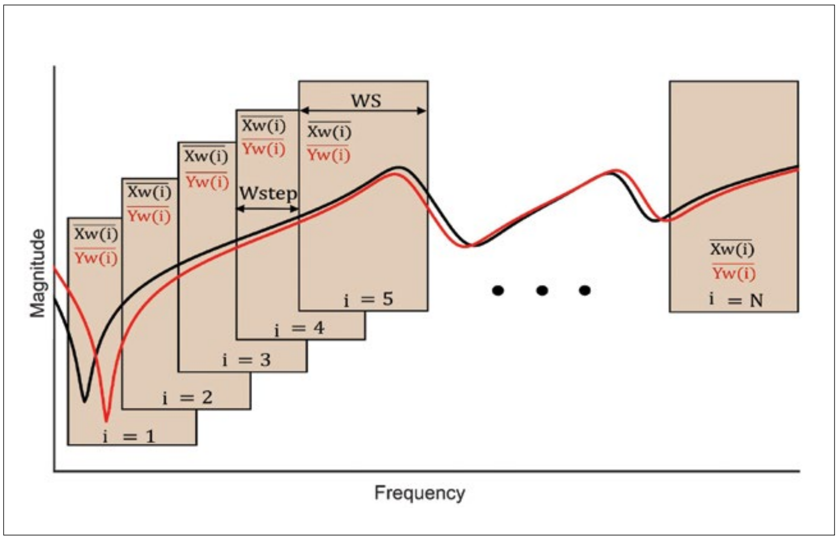


Figure 3.4 The basic principle of the winding assessment algorithm [13]

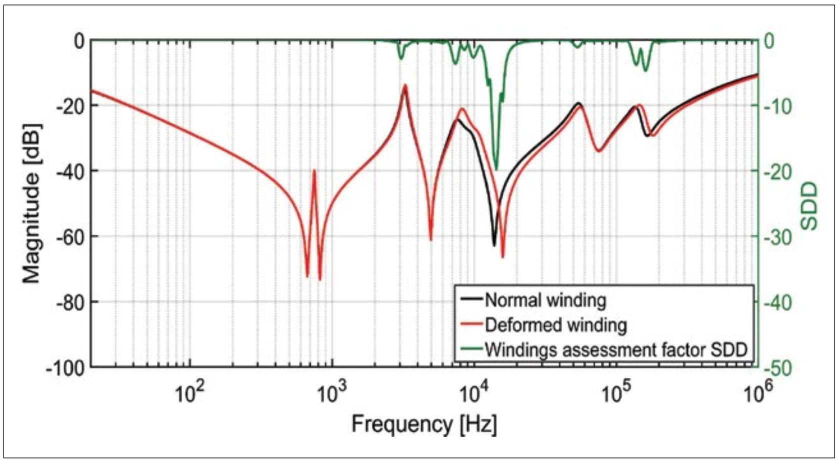
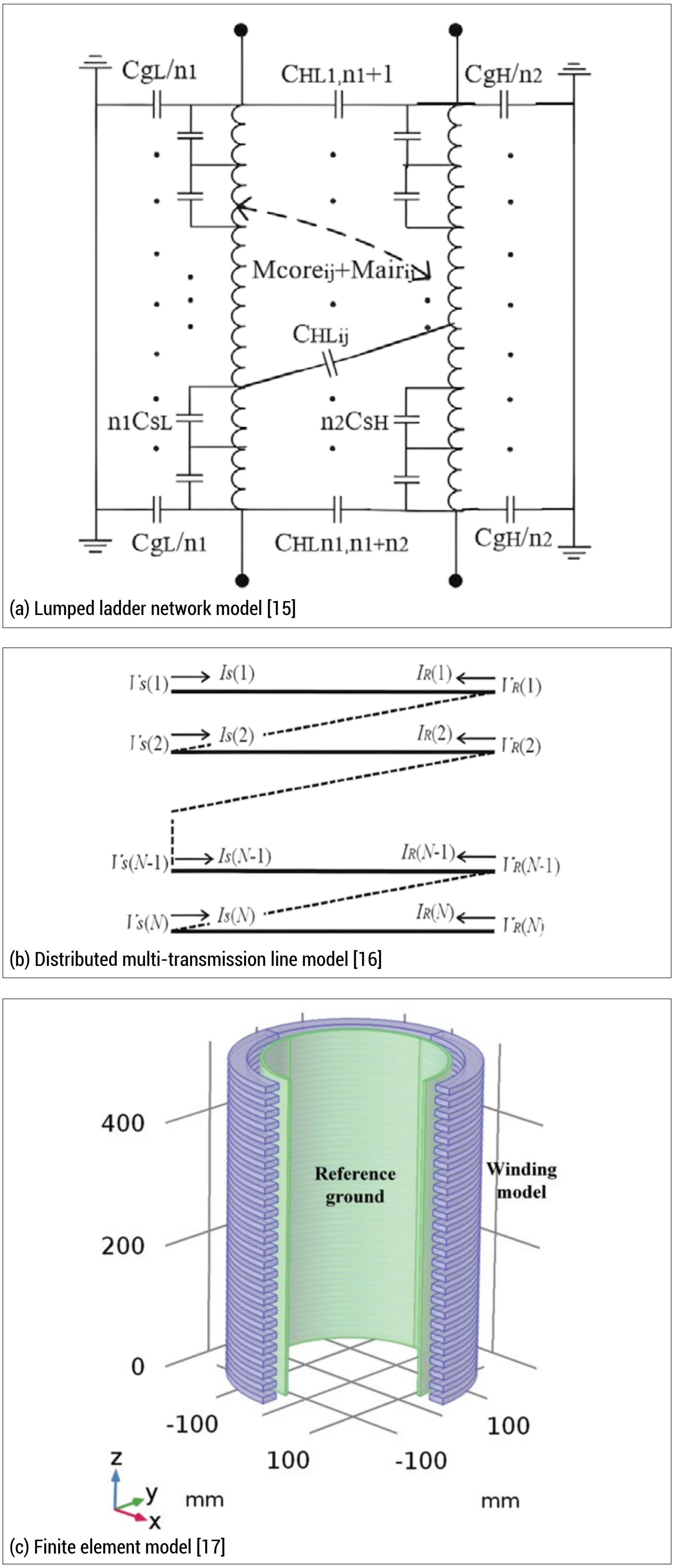


Figure 3.5 Application of the proposed method for identification of the degree of deviation between two FRA signatures of a three-phase transformer [13]



(a) Lumped ladder network model [15]

(b) Distributed multi-transmission line model [16]

(c) Finite element model [17]

Figure 4.1 Different white box modelling methods

in normal cases. Thus, it is possible to set a threshold to MSDD as a diagnostic criterion, e.g., in [11] MSDD = -5 was employed as a threshold for time-based FRA comparisons; MSDD <- 5, indicates abnormal condition whereas MSDD> -5 indicates normal condition [11]. Note the diagnostic criterion is only valid for these case studies.

The paper [7] was developed based on SFI measurements, which were applied to large power transformers of more than 20 units of 110 kV and 5 units of 220 kV. The frequency range of SFI is from 10 Hz to 1 MHz, with a frequency resolution step of less than 2 Hz around the power frequency. The paper [7] recommended that four parameters, including the impedance value at power frequency, the slope rate of the SFI trace between 10Hz and 500Hz, the resonant frequencies, as well as the correlation coefficient between the measured trace with the fingerprint, can be used for diagnosis. Appendix D of [7] gave threshold values for the correlation coefficient to determine the "normal – slight – obvious – severe deformed" winding status.

4. Interpretation of FRA features

As a comparative technique, the difference between FRA reference and measurement results can indicate the existence of winding mechanical faults. Therefore, understanding the physical meaning behind the frequency responses of winding, which is the relationship among winding geometry, transformer equivalent electrical components and corresponding FRA spectra, is key. Numerous sensitivity studies, either by experiment or simulation, have been implemented to gain an understanding of FRA physics, but a widely accepted general FRA interpretation guidance still needs to be developed.

The challenge remains to work back from the FRA result to determine the transformer winding characteristics although progress has been made

Table 4.1 Comparisons among white box models

Models	Advantages	Drawbacks
Lumped element network model	Physical meaning, accurate, wider frequency range up to 1-2 MHz. can represent the core, three phases.	Complex, long time for calculation
Distribution multi-transmission line model	Physical meaning, accurate, wider frequency range up to 10 MHz, specialised in the fast transient study	Not sufficiently practical for the whole transformer, for certain deformation simulation
Finite element model	Physical meaning, accurate, flexible in performing practical deformation	Long computation time and large memory of computer required

4.1 Different modelling methods

Three types of transformer models have been developed for the FRA study: the white box model, the black box model and the grey box model. White box models are based on the laws of physics. They consist of a large number of lumped circuit elements whose parameters are calculated from transformer design data. Three types of white box models are used. The first model is **lumped element network model**. As shown in Figure 4.1 (a), it divides the winding into several sections, and each section is represented by electrostatic and electromagnetic components, including series and ground capacitance, magnetising inductance, air core and mutual inductance. This model is the most widely used white box model. The second model is **distributed parameters model**. As shown in Figure 4.1 (b), it is constructed based on the multi-transmission line theory, and each turn is represented by a transmission line. Transmission line theory is applied to calculate the voltage and current vectors at each sending and receiving end. The third model is the finite element model. As illustrated in Figure 4.1 (c), it requires the usage of FEM software, such as COMSOL Multiphysics® or ANSYS. A 3D geometrical model can be built in the design module of ANSYS, followed by a meshing process.

The electrical potential of each small section in the meshed grid is solved through stepwise physical equations. Table 4.1 summarises the main advantages and disadvantages of the three types of white box modelling methods. The white box models rely on the assistance of the transformer manufacturer to provide design information. Significant success has been achieved in building 'white box' models of transformers capable of accurately reproducing experimental results when all transformer design details are available [9,15], and the challenge remains to work back from the FRA result to determine the transformer winding characteristics although progress has been made on this as described later in this article.

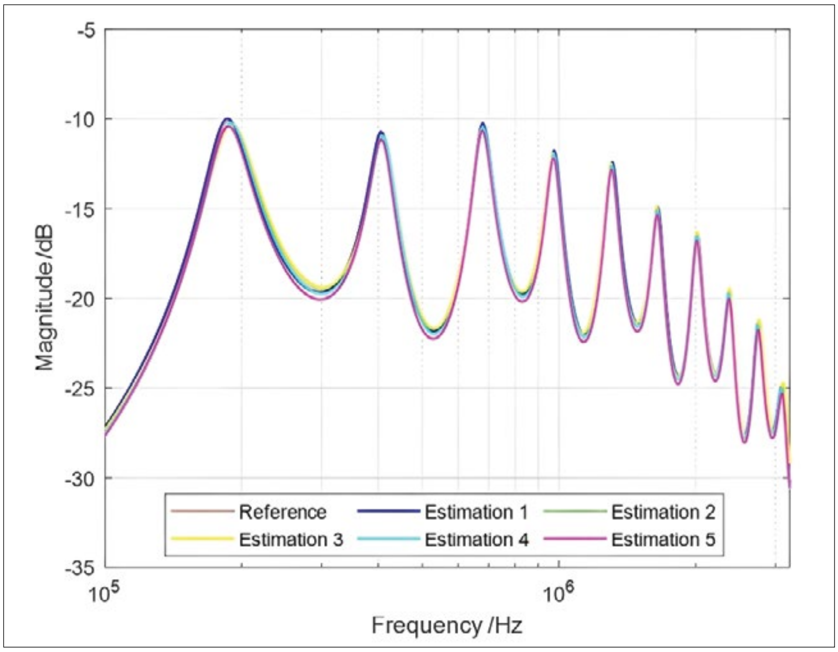


Figure 4.2 Reference FRA and the FRA reproduced by the estimated geometry [18]

The grey box model demonstrates the physical behaviour of the transformer without the design input from the manufacturer

The black box model is constructed purely based on FRA measurement data. The model circuit is established according to the number of resonances appearing on the FRA trace. Values of electrical parameters in the circuit are adjusted by algorithms to reproduce the FRA until the calculated results match with measurement results with good accuracy. However, the black box model circuit does not provide any information about internal voltages and currents. The parameters of black box models have no direct link with the transformer's geometrical dimensions.

The grey box model is in between the white box and black box models. It has the same physical-laws-based circuit model as a white box model, but the model parameters are estimated using terminal measurement data without any knowledge of the internal geometries.

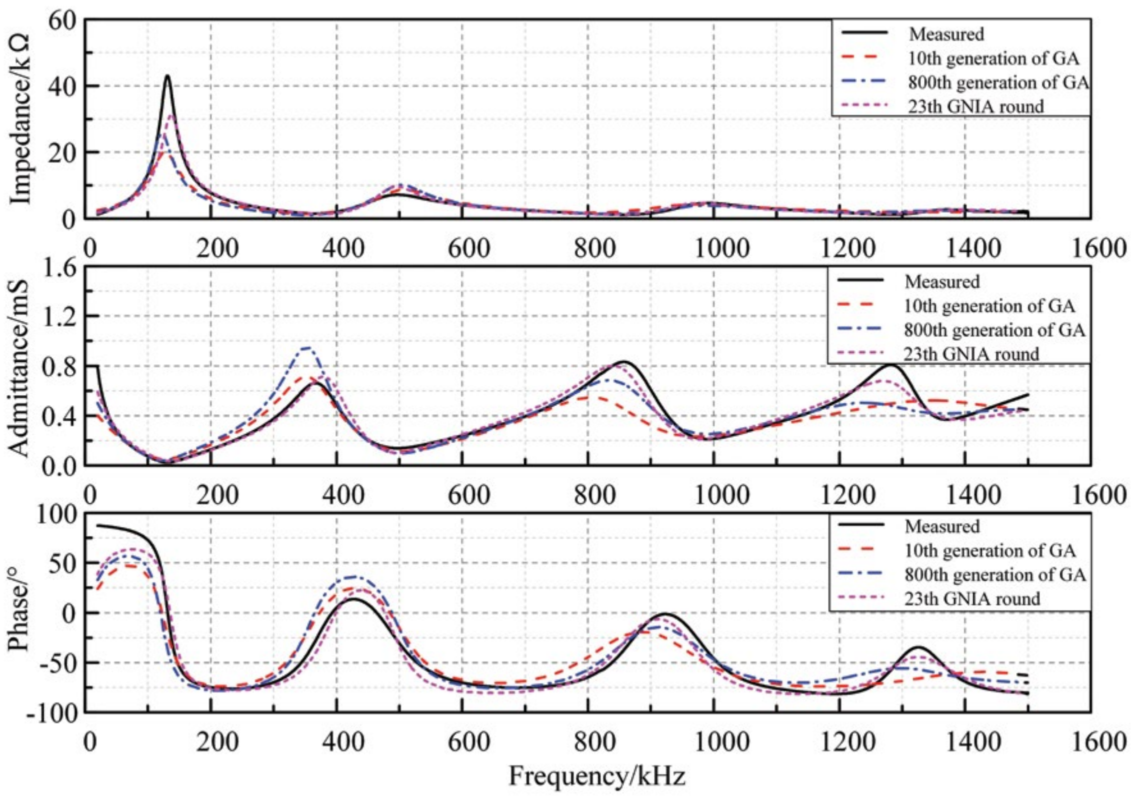


Figure 4.3 Comparison of frequency response traces among measurement, GA and GA combined with IA [19]

With the combination of Genetic Algorithms and Iterative Algorithms, the accuracy and efficiency of the identification process can be greatly enhanced

The grey box model demonstrates the physical behaviour of the transformer without the design input from the manufacturer. Hence it is useful for the utility to manage its in-service transformers. The grey box model parameters are identified using parameter estimation methods, and Artificial Intelligence algorithms are often employed to assist this optimisation process. ANN, GA and PSO are the most popular meta-heuristic methods for optimisation problems. Using these algorithms, the electrical parameters of transformer equivalent circuits or even the geometrical dimensions of windings can be estimated. The differences between the FRA fingerprints generated from the estimated and reference values are used as a quantitative indicator to assess the optimisation accuracy. Figure 4.2 shows a comparison between the reference FRA of a single winding and the FRA generated by the grey box model, which estimated winding geometry parameters by using the GA.

The combination of the Genetic Algorithm (GA) and Iterative Algorithm (IA) was used to identify the ladder network parameters of the tested single winding from its FRA traces [18,20]. In the first step, GA searches for the suboptimal solutions of the network parameters among given ranges of network parameters by comparing their FRA traces with the measurement. In the second step, IA computes and optimises the correction values by comparing the differences between two FRA traces at consecutive iterative steps. Therefore, with the combination of GA and IA, the accuracy and efficiency of the identification process can be greatly enhanced. Several FRA traces obtained in GA and IA are shown in Figure 4.3. The final obtained ladder network parameters can be used to diagnose the winding deformation, i.e., the deformation position localisation and severity evaluation.

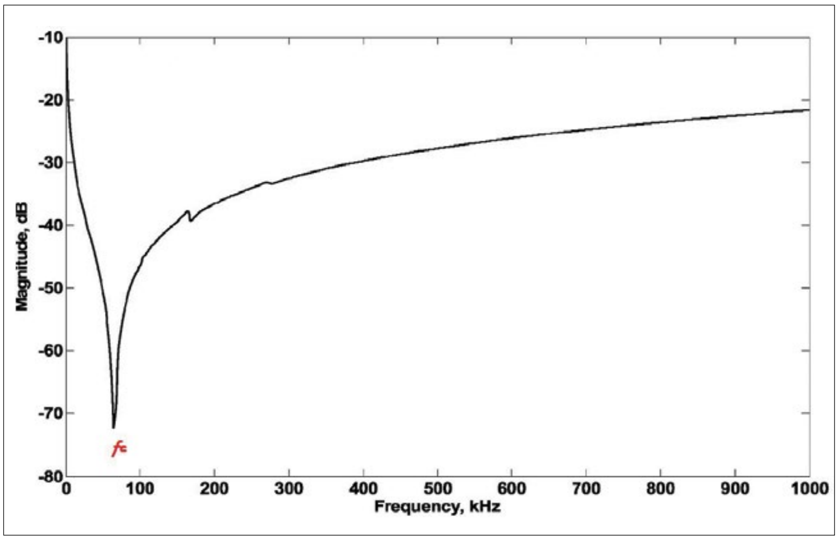
4.2 Understanding FRA features through modelling and simulation

FRA analytic interpretation has been developed for a single winding structure by taking advantage of the lumped ladder network model and understanding the transient behaviours of the voltage propagation along the winding. The FRA responses for different winding structures have been categorised in terms of the high- or low-series capacitance , as it controls the spacing coefficient , which is regarded as a key factor determining the degree of non-linear distribution of the impulse voltage along the winding [15]. The FRA responses of windings of high series capacitance exhibit an increasing trend of magnitude across the frequency range with little resonances and anti-resonances, as exemplified by interleaved disc-type winding in Figure 4.4(a). The windings of low series capacitance display the steady magnitude trend in their FRA responses with the features of resonances and quasi-antiresonances or anti-resonances, as shown in Figure 4.4 (b) for a single layer or a continuous disc winding.

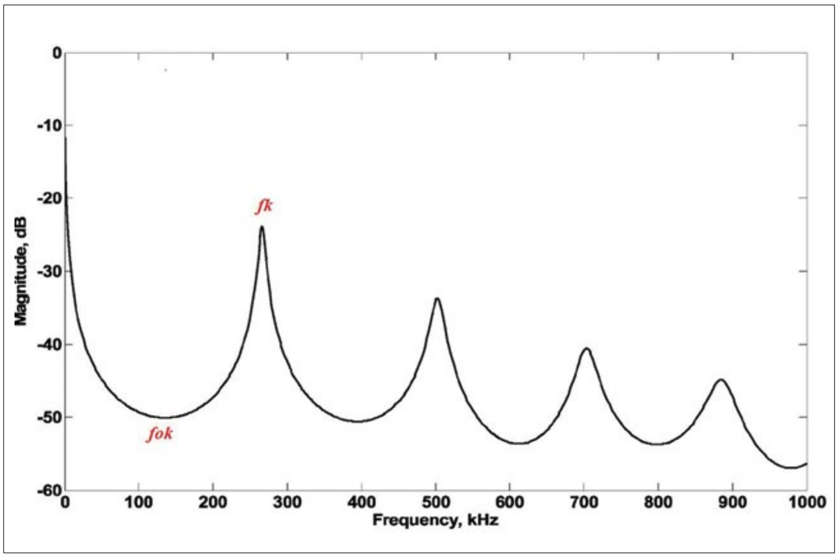
FRA analytic interpretation has been developed for a single winding structure by taking advantage of the lumped ladder network model and understanding the transient behaviours of the voltage propagation along the winding

Based on the mathematic descriptions of lumped element ladder network model, the equations in Table 4.2.1 have been derived from providing accurate predictions of the pseudo-anti-resonant, resonant and critical anti-resonant frequencies [16]. These equations are only valid for the simplified model of a single air core winding discussed here.

From the formulas, it can be noticed that α has the dominating effect on the shape of frequency response. These equations explain well why windings with low series capacitance, such as plain disc windings and single helical windings, always have multiple resonances, whereas windings with high series capacitance, such as interleaved disc type windings, always have



(a) Interleaved disc winding (Cg=144 pF, Cs=278pF, α=0.72)



(b) Continuous disc winding (Cg=168 pF, Cs=7pF, α=4.89)

Figure 4.4 Typical FRA responses of different winding structures [15]

Table 4.2.1. Equations for pseudo-anti-resonant, resonant and critical anti-resonant frequencies

Description	Definition	Equation	Numbering
Pseudo-anti-resonance	Local minimum between the adjacent resonances, where the frequency response amplitude would be concave without the sharp drop into the large negative dB value as for the normal anti-resonance, showing a U-shape.	$f_{0k} = \frac{1}{2\pi\sqrt{L_s C_s}} \frac{1}{\sqrt{1 + \frac{4\alpha^2}{((2k-1)\pi)^2}}}$	(2.1)
Resonances	A local maximum in amplitude and sometimes resonant frequencies are also called natural frequencies of winding	$f_k = \frac{1}{2\pi\sqrt{L_s C_s}} \frac{1}{\sqrt{1 + \frac{\alpha^2}{(k\pi)^2}}}$	(2.2)
'Critical' anti-resonance	Where the frequency response amplitude would drop sharply to a large negative dB value.	$f_c = \frac{1}{2\pi\sqrt{L_s C_s}}$	(2.3)

A double-peak feature is commonly observed in medium frequency regions for supergrid autotransformers in the UK

less or no resonance. All the formulas are published in CIGRE TB812 [12], and further extrapolations of analytical equations for a single winding with an iron core with mutual inductive coupling considered can be found in [12,16].

When two windings are incorporated into the model, the influence of coupling between windings becomes non-negligible. The mutual inductance and the interwinding capacitance between two windings are considered. A double-peak feature is commonly observed in medium frequency regions for a transformer with more than two windings, e.g., an autotransformer. Sensitivity studies have shown the first resonance of the double peak is mostly dependent on the three-phase coupling through the tertiary delta connection, while the second resonance of the double peak is produced as the series and the common windings are strongly coupled due to their relatively close turn ratio [9].

5. Conclusions

Significant progress has been made towards understanding and modelling FRA results in UTRA universities. It is a part of the pathway to developing reliable pass/fail analysis and criteria for practical use. Ultimately the goal of introducing methods and criteria for FRA interpretation into standards appears achievable.

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