# Towards Objective Interpretation of Frequency Response of Power Transformers

M. Tahir, S. Tenbohlen

***Abstract*— Frequency Response Analysis (FRA) has attracted great attention as a diagnosis method of mechanical faults of power transformer windings. For interpretation of FRA results, circuit models are proposed in the literature. These circuit models require the estimation of the winding parameters to model and study the impact of different faults on FRA traces. Moreover, these lumped parameter models are limited to certain frequency due to difficulty in solving turn-based parameters. In contrast, this paper presents a new method to obtain a turn-based 3D high frequency model of transformer windings using Finite Element Method (FEM). In the proposed model, FRA traces are directly derived from a high frequency finite element model without employing the circuit model. The model automatically considers the frequency dependent effects of parameters. At first, the model is validated with measurements for healthy state of the windings. Afterwards, two case studies are considered in which axial displacement and radial deformation faults are implemented in both experimental setup and FEM model. Good principle agreement of simulation results with the measurements proves the applicability of the model for FRA interpretation. Finally, a MATLAB based graphical user interface (GUI) is developed to aid the detection of transformer faults.**

***Keywords***: Frequency Response analysis, Finite Element Method, Mechanical Fault, Numerical Indices, Radial Deformation

## I. Introduction

POWER transformers are integral and expensive equipment of all electric power networks at all levels from generation and transmission down to distribution. Thus, assessment of condition and diagnostic techniques are of great importance for improving power network reliability and service continuity [1]. Several techniques are available to diagnose faults within power transformers. Frequency response analysis (FRA) is a powerful technique for diagnosing transformer winding deformation and several other types of problems that are caused during manufacture, transportation, installation and/or service life [2]. Previous contributions in the FRA topic has led to the standardization of the measurement procedure. However, the interpretation of FRA results is still limited to analysis of the experts in the field since there is still no comprehensive reliable algorithm to assess the mechanical condition of power transformers based on FRA results [3, 4]. As it is very hard to implement mechanical faults on windings of a physical transformer without damaging it, recent studies [5-8] investigated the impact of several mechanical faults on the transformer FRA traces by randomly changing and estimating the value of particular electrical parameters of the transformer equivalent circuit models. This random alteration of parameters increase uncertainty and decrease the reliability of these circuit models in predicting the effect of different mechanical faults on FRA traces. Also, these lumped parameter models are limited to a certain frequency due to difficulties in estimating turn-based parameters. Additionally, constant values of parameters are used although these parameters are frequency dependent [9]. In contrast, this contribution introduces a turn-based 3D finite element method (FEM) model of transformer windings. In the proposed model FRA traces can be directly derived from the 3D FEM model, which eliminates the need of parameter estimation method. Moreover, it is also possible to implement a precise mechanical fault which is not possible in case of circuit models. In this regard, a single-phase transformer is simulated using 3D FEM, which emulate the transformer and FRA measurement operations. To evaluate the performance of the model in detecting minor winding deformations various levels of radial deformation (RD) fault and axial displacement (AD) fault are implemented in LV winding and HV windings respectively. The impact of each fault level on FRA trace is discussed in detail. Results of this study will facilitate an accurate and precise fault simulation using 3D FEM model of transformer that will ease the objective interpretation of transformer frequency response. Numerical indices are evaluated for sensitivity analysis of different connection schemes against different faults. Finally, a MATLAB based graphical user interface (GUI) has been developed to aid the detection of transformer faults. Experimental verification consisting of fault studies are carried to examine the developed automated package has also been reported as part of this work.

## II. Experimental setup and evaluation method

### A. *Experimental setup*

To validate the 3D FEM model with the measurements, an experimental setup is developed which consist of HV and LV windings as shown in figure 1. The windings correspond to a medium voltage transformer of about 1 MVA. The HV winding is a continuous disk winding (height = 865 mm) with 660 turns in 60 disks and the LV winding is a helical winding (height = 865 mm) with 24 turns and 12 parallel conductors in each turn. Two hollow, copper cylinders are employed

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outside and inside of the windings to model the tank and the core, respectively. As the FRA trace is measured above 10 kHz, and due to small skin depth in this range, the core can be replaced with the hollow metallic cylinder [10]. Four connection schemes recommended by standards are implemented in this research: end-to-end open circuit (EE-OC), short circuit (EE-SC), capacitive inter-winding (CI) and inductive inter-winding (II) connections [11, 12]. Figure 2 illustrates the measuring diagram of the EE-OC, EE-SC, CI and II configurations.

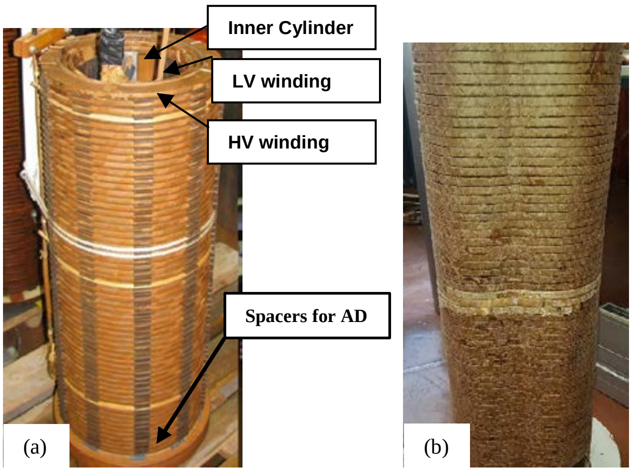



Figure 1. Measurement setup and different mechanical faults (a) axial displacement (AD) in HV (b) radial deformation (RD) of LV

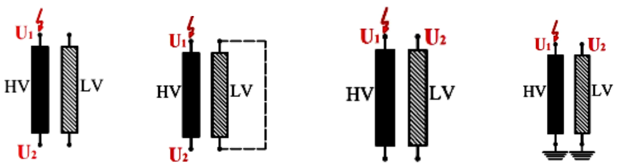



Figure 2. Connection schemes for FRA measurement (a) end-to-end open circuit (EE-OC) (b) short circuit (EE-SC) (c) Capacitive inter-winding (CI) (d) Inductive inter-winding (II)

## B. *Evaluation Method*

To analyze the sensitivity of different connection schemes, and to discuss the reliability of 3D FEM model in predicting numerical indices, four numerical indices, namely standard deviation (SD), correlation coefficient (CC), Euclidean distance (ED) and cross-correlation factor (CCF), are evaluated from both the simulated and measured FRA traces. Different numerical indicators are used for FRA interpretation in the literature [13, 14]. In this paper, the numerical indices which show linear and monotonic behavior with increased level of faults are utilized. Moreover, some of the indices exhibit the same behavior in respect of the changes in the FRA trace. Therefore, the results of the CCF for different faults are presented here, which can be a very good representation of other indices.

$$SD=\sqrt{\frac{\sum_{i=1}^{N}\left(Y(i)-X(i)\right)^2}{N-1}} \tag{1}$$

$$CC=\frac{\sum_{i=1}^{N}X(\mathrm{i})\,\mathrm{Y(i)}}{\sqrt{\sum_{i=1}^{N}[X(\mathrm{i})]^2\sum_{i=1}^{N}[Y(\mathrm{i})]^2}} \tag{2}$$

$$ED=\sqrt{\sum_{i=1}^{N}\left(Y(i)-X(i)\right)^2} \tag{3}$$

$$CCF=\frac{\sum_{i=1}^{N}(X(\mathrm{i})-\bar{X})(Y(\mathrm{i})-\bar{Y})}{\sqrt{\sum_{i=1}^{N}\left[X(\mathrm{i})-\bar{X}\right]^2\sum_{i=1}^{N}\left[Y(\mathrm{i})-\bar{Y}\right]^2}} \tag{4}$$

A MATLAB based Graphical User Interface (GUI) was developed to compare and perform the statistical analysis of transformer FRA traces as shown in figure 3. The key features of the MATLAB-GUI and associated program are as follows:

- Read the raw data files of the reference and measured FRA signal
- Plot the measured FRA signal in comparison to the reference FRA signal
- Evaluation of the selected numerical indices in wide and short frequency bands
- Analysis of the obtained numerical indices to detect presence of fault

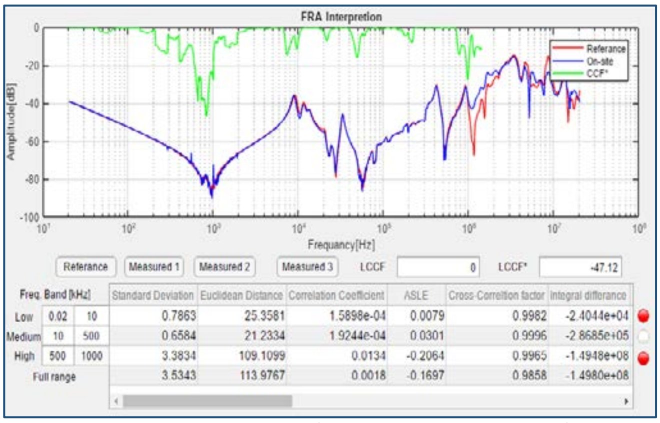
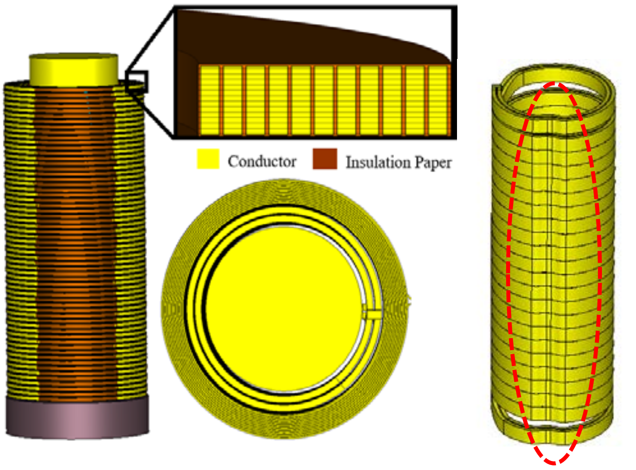



Figure 3. MATLAB based-GUI for statistical interpretation of FRA measurements

## III. 3D FINITE ELEMENT METHOD MODEL

The main idea of using a 3D FEM model is to replicate the transformer and FRA measurement operations. The model accurately consider the frequency dependent parameters of the transformer winding, and directly calculate the FRA trace from the FEM model similar to the real procedure of measuring the transformer FRA trace.




(a) Healthy windings (b) RD in LV winding

Figure 4. 3D FEM model

Analogous to the real measurements, a sinusoidal voltage source is connected to one terminal of the winding to sweep its frequency and then calculate the voltage at the other end of the winding. Figure 4 shows the 3D FEM model of 1 MVA single phase transformer identical to the experimental setup shown in figure 1(a). High frequency modeling is carried out in the design module of CST MW STUDIO using high frequency solver [15]. The FRA simulation is a three-step process. At first, a geometric model is created, identical to the experimental setup. Secondly, a high frequency model is developed which incorporates the frequency dependent parameters. And lastly, this model is excited with a sinusoidal voltage source to calculate the FRA traces for different connection schemes.

## IV. RESULTS AND DISCUSSION

To validate the model, the simulation results are compared with the measurements for the healthy case of the windings for different connection schemes as shown in figure 5. The results are compared over a frequency range from 10 kHz to 1 MHz and a good principle agreement between simulation and measurement verifies the applicability of the model for high frequency applications. It is worth to mention, there is slight miss-match between simulation and measurements at some resonance points, which is mainly due to design simplifications applied in the LV and HV windings. But these differences do not impair the applicability of the model regarding the interpretation of FRA.

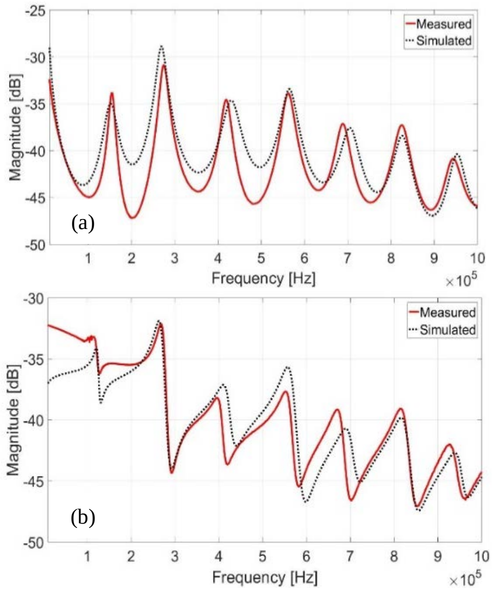



Figure 5. Comparison of measurement and simulation for different measurement schemes for healthy case of winding (a) EE-OC (b) II

## V. CASE STUDIES

In order to check the applicability of the model in predicting the effects of mechanical variations on the FRA traces, two widely occurring winding faults, axial displacement (AD) and radial deformation (RD), are implemented in both the experimental model and the 3D FEM model.

### *A. Case 1: Axial displacement (AD)*

AD is introduced on the HV winding, with various levels of AD being implemented, by changing the number of spacers at the bottom of the winding as shown in figure 1(a). Five steps of AD are implemented in the HV winding in an upward direction, each one a step of 10 mm. Moreover, different connection schemes are applied to detect the one most sensitive against AD. Figure 6 shows that the model behavior towards AD is completely in accordance with the reality. These results validate the FEM model to be used for predicting the windings behavior in mechanical changes. As can be seen in the simulated and measured FRA traces in Figure 6, the impact of the AD on FRA traces is noticeable in the medium (100 kHz-600 kHz) and high frequency (600 kHz-1 MHz) range. Results also show that AD fault shift the resonance frequencies to the right in the medium and high frequency range with a slight change in magnitude. The effect is more prominent with the increased degree of the fault.

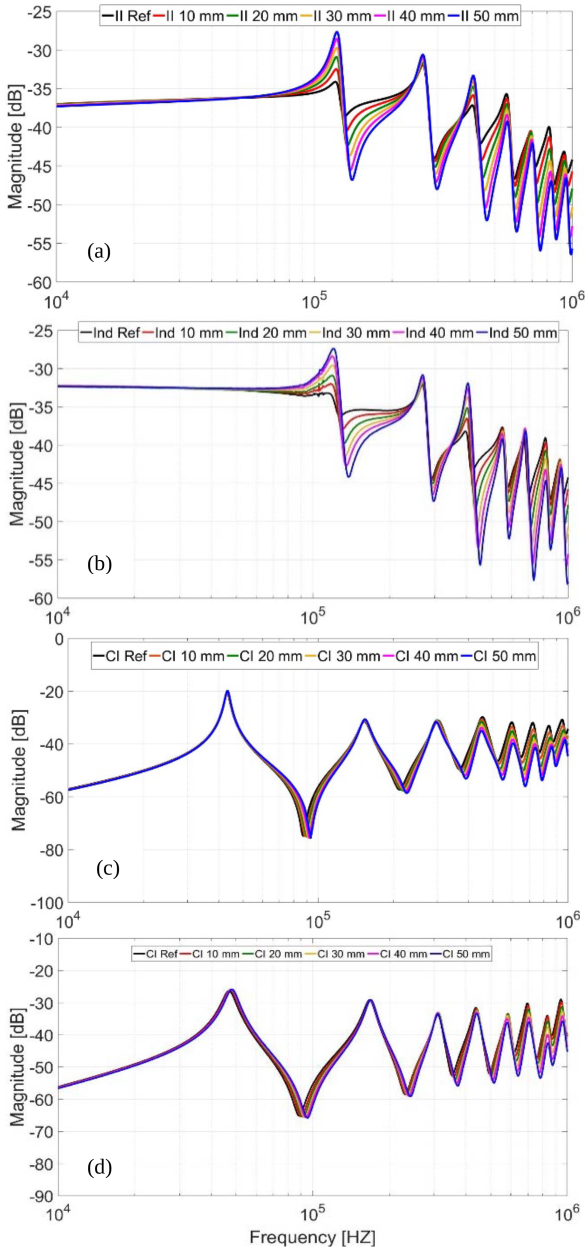



Figure 6. FRA traces for different levels of AD (a) II simulation (b) II measurement (c) CI simulation (d) CI measurement

### *B. Case 2: Radial deformation (RD)*

To investigate the behavior of the 3D FEM model against the RD, a setup is designed to deform the LV winding in increasing steps. One section of the LV winding is deformed through the winding height in five steps; in each step, the radius of that section is decreased by 2.5 mm. Figure 1(b) shows the deformed winding as described in [16]. Similar RD is implemented in 3D FEM model as shown in figure 4(b).

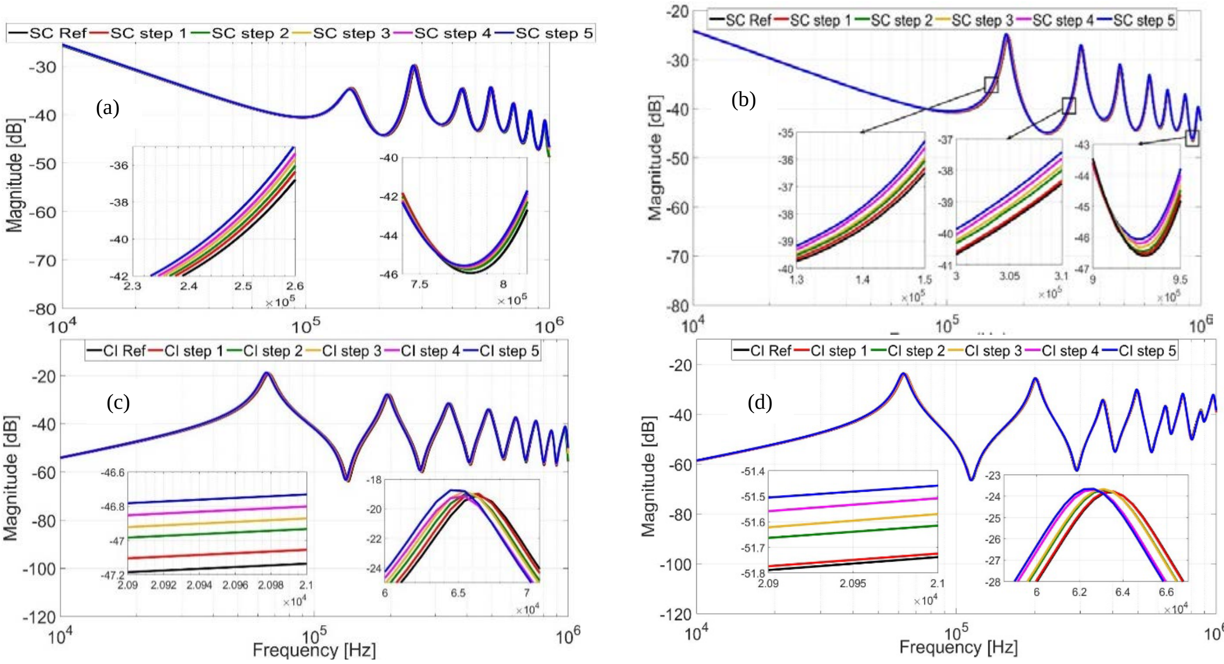



Figure 7. FRA traces for different levels of RD (a) EE-SC simulation (b) EE-SC measurement (c) CI simulation (d) CI measurement

Moreover, different connection schemes are applied to detect the most sensitive scheme against RD. Figure 7 shows that the model behavior towards RD is completely in accordance with the measurements. These results prove the consistency of the FEM model to be used for predicting the windings behavior under different mechanical changes. As can be seen in the simulated and measured FRA traces in figure 7, the impact of the RD on FRA traces is obvious in the medium (100 kHz-600 kHz) and high frequency (600 kHz-1 MHz) range. Contrary to the effect of AD faults on FRA traces, RD faults shift the resonance frequencies to the left in the medium and high frequency range with a slight change in magnitude. The effect is more pronounced with an increasing degree of the fault.

## VI. Sensitivity analysis

Figure 8 shows the linear and monotonic behaviour of CCF against different fault levels of AD and RD for inductive inter-winding (II) connection scheme. It also shows that despite the slight mismatch between the measurement and simulation results, the numerical indices that correspond to the changes in the traces with the degree of the fault are in good agreement with each other. Figure 9 shows the sensitivity comparison of different connection schemes for 50 mm of AD and 12.5 mm of RD. The result shows that both measured and simulated results are in good agreement. There are slight differences between simulation and measurement results, which are due to some simplifications applied to the design of LV and HV windings. However, the general shape of CCF against different faults for different connection schemes remains the same and thus, the model works satisfactorily in predicting the numerical indices. The following results can be derived from the CCF sensitivity comparison:

- AD: II and CI connection schemes show highest changes to detect the AD faults. In the simulation results, the same connection schemes have the best sensitivity to detect AD fault.
- RD: II connection scheme shows the maximum sensitivity to detect RD faults. Simulation results follow the measurements.

To summarize, different connection schemes have different sensitivities to detect different mechanical changes. The result shows that end-to-end measurements (OC and SC) have quite similar sensitivity, while inter-winding measurements shows the highest sensitivity to detect the applied mechanical failures in the experimental setup used in this investigation. It is important to mention that this derived sensitivity is also depends on the definition of the used index.

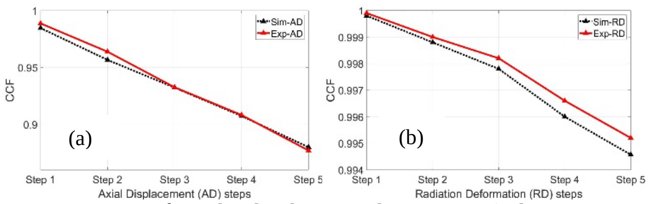



Figure 8. CCF of simulated and measured FRA traces (inductive inter-winding) for different fault levels (a) AD (b) RD

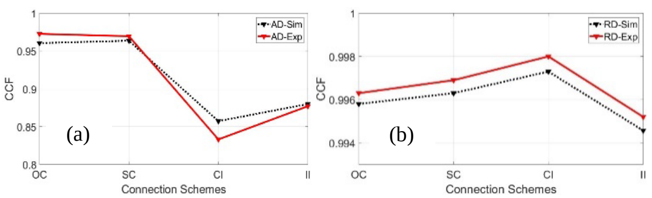



Figure 9. CCF of different connection schemes for different faults (a) 50 mm AD (b) 12.5 mm RD

## VII. Conclusion

This paper presents a high frequency modelling method to predict the FRA traces of transformers. In the proposed HF model, it is possible to extract the FRA traces directly from the 3D FEM model of the transformer. The model was validated with measurements with both healthy and deformed windings. Two different mechanical faults were implemented and their impact on the FRA traces were studied. The developed GUI can aid to the assessment of frequency response measurements as it accurately calculates the numerical indices and provide fault indication and assessment based on frequency ranges as prescribed in IEEE standard. For sensitivity comparison, different numerical indices were evaluated. Based on the results, it can be concluded that CCF, SD, ED and CC show monotonic behavior with increasing degree of mechanical deformation and can thus be used to detect the changes in FRA traces. However, along with monotonicity, variations of the indices due to the repeatability of the measurements is another important factor in discussing the detectability of the faults. The sensitivity of different connection schemes against different faults in terms of CCF is analyzed and it was noticed that inductive and capacitive inter-winding connection schemes has the best sensitivity to detect the mechanical faults in the experimental setup used in this research.

## VIII. ACKNOWLEDGEMENTS

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