Optimization of FRA by an Improved Numerical Winding Model: Disk Space Variation

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Abstract

Frequency response analysis (FRA) is a well-established method used for condition assessment of transformer windings and has proven its sensitivity for detecting various mechanical and electrical faults. Although the FRA test procedures have been standardised, the interpretation of FRA results is still a challenge as it is limited to analysis of the experts in the field. Mainly, circuit models are proposed in the literature for supporting the interpretation of the transformer frequency response. However, these concentrated parameters models are limited to a certain frequency range, due to the difficulties in calculating parameters to build and solve a turn-to-turn model. Moreover, constant values for the parameters are employed in these models, while these parameters are frequency dependent. In contrast, this paper presents an improved numerical method to obtain a turn-based high frequency model of transformer windings. This model considers the frequency dependent effects of parameters. In the proposed model, FRA traces are directly derived from a high frequency finite element model (FEM) without employing the complex circuit model. For this purpose, a single-phase transformer is simulated using 3D FEM, which emulate the transformer and FRA measurement operations. First, the model is validated with measurements for healthy state of the windings. Afterwards, various levels of disk space variation (DSV) fault are implemented. This approach will facilitate the precise fault simulation and ease the objective interpretation of FRA.

1 Introduction

Power transformers are one of the most valuable facilities in electric power networks and therefore, they should be carefully monitored in order to maintain the reliability of the transmission and distribution networks [1, 2]. One of the most important aspects of the transformer assessment is the detection of mechanical deformations and displacements of the windings, which can result in many cases, from short circuits in the network as well as reduced clamping pressure due to insulation aging [3]. Though, with minor winding deformations a transformer may continue its normal operation, however, its capability to withstand further electrical and mechanical stresses substantially reduces which may lead to immediate transformer failure. Therefore, it is important to detect the minor winding deformations as soon as possible in order to enable suitable measures [4, 5]. Frequency response analysis (FRA) is a recently developed and a widely accepted tool to detect incipient winding deformation within power transformers [6, 7]. Nowadays, the FRA method is often used in both factory and field applications. Previous studies on FRA topic lead to the standardization of the measurement procedures [8-10]. However, the interpretation of FRA results is still a chellenge. In literature, various circuit models are proposed for interpretation of transformer frequency response [11]. In these models, different sections of the windings are represented by circuit elements such as resistors, inductors and capacitors. Afterwards, the values of these parameters are altered to simulate various mechanical defects and to predict their effect on the FRA traces. However, some mechanical changes are difficult to model and convert into changes, and involve an extra error. Whereas the precise simulation of the fault is very important to identify the minor winding deformations. Moreover, in these circuit models the parameters are derived through analytical equations thus constant values of these parameters are employed while in fact these parameters are frequency dependent [12]. These are the main drawbacks of the circuit models. This paper introduces an improved numerical method to obtain a turn based high frequency model of transformer windings which considers the frequency dependent effects of the parameters. In the proposed model, FRA traces are directly derived from a high frequency finite element model (FEM) without employing and solving the complex circuit models, which is the major novelity of this work. 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 disk space variation (DSV) fault are implemented. The impact of DSV on transformer parameters and FRA trace is discussed in detail. Results of this study will facilitate an accurate and precise fault simulation using high frequency 3D model of transformer that will ease the objective interpretation of transformer frequency response.

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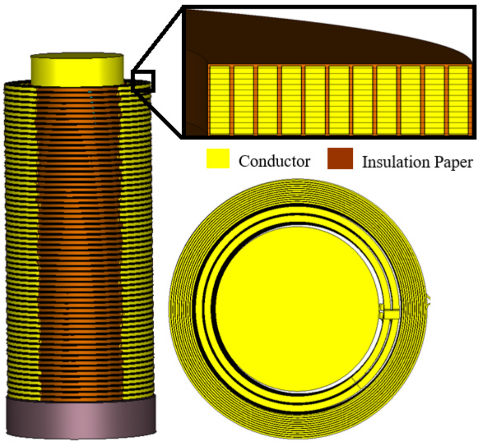
2 3D Finite Element model

The main idea of using 3D finite element model is to emulate the real transformer and FRA measurement operations. CST Microwave studio is used to simulate the transformer model geometry and the frequency response [13]. For this purpose, a single-phase transformer is modelled with 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 aluminium cylinders are used which are connected to the common ground of the test setup to model the potentials of the transformer core and tank. Since, the skin depth in the iron core and tank is very small above 10 KHz, their magnetic effects are negligible at high frequencies, and therefore, they can be replaced with hollow metallic cylinders without impairing the results [14].

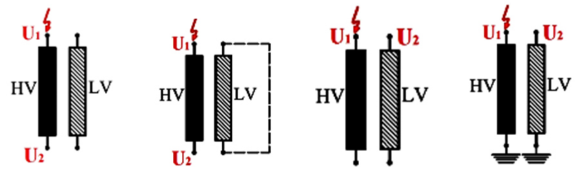


(a) 3D Finite Element Model

(b) Measurement setup **(c)** Disk space variation

Figure 1. Transformer model and mechanical fault

The FRA simulation is performed using high frequency solver in the design module of CST MW STUDIO. Analogous to the real measurements, an imaginary sinusoidal voltage source is connected to one HV terminal of a winding to sweep its frequency and then calculate the voltage at the other end of the winding. The FRA simulation is a three-step process. Firstly, a geometric model is created in the design module. Secondly, a high frequency model is developed which incorporates the frequency dependent parameters. Lastly, this model is excited with a sinusoidal voltage source to calculate the FRA traces for different connection schemes. Mainly, four connection schemes; end-to-end open circuit (EE-OC), end-to-end short circuit (EE-SC), capacitive inter-winding (CI) and inductive inter-winding (II) recommended by IEEE and IEC standards [8, 9] are employed in this research as shown in Figure 2.



(a) **(b)** **(c)** **(d)**

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) [8, 9]

The proposed model gives the three fold benefits to calculate the frequency response of transformer. Firstly, the model incorporates the frequency dependency of parameters. Secondly, FRA traces are calculated directly from the winding model without conversion into circuit elements. Lastly, different mechanical faults, which are difficult to implement in circuit models, can also be directly simulated in the windings model. Additionally, the proposed model is also useful to study the effects of windings electrical properties on the frequency response of transformer. For instance, it is possible to change the dissipation factor and permittivity of paper to simulate the different levels of moisture contents. A study on moisture diffusion recognition in small windings has been performed [15], but the model proposed in this paper can be easily employed for such a study to model different transformer windings with different constructions. These studies are the future steps to develop and enhance the application of the proposed HF transformer model.

3 Validation of HF FEM Model

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 3. The results are compared over a frequency range from 10 kHz to 1 MHz. The results of end-to-end short circuit (EE-SC) and inductive inter-winding (II) are presented in Figure 3. Results show a good principle agreement between simulation and measurement, that the simulation follows the measurements, which proves the applicability of the model for FRA studies. It is worth noting that there is slight mismatch between simulation and measurements at some resonance and anti-resonance points, which is mainly due to design simplifications applied in the LV and HV windings. However, these differences do not impair the applicability of the model regarding the interpretation of frequency response of transformer.

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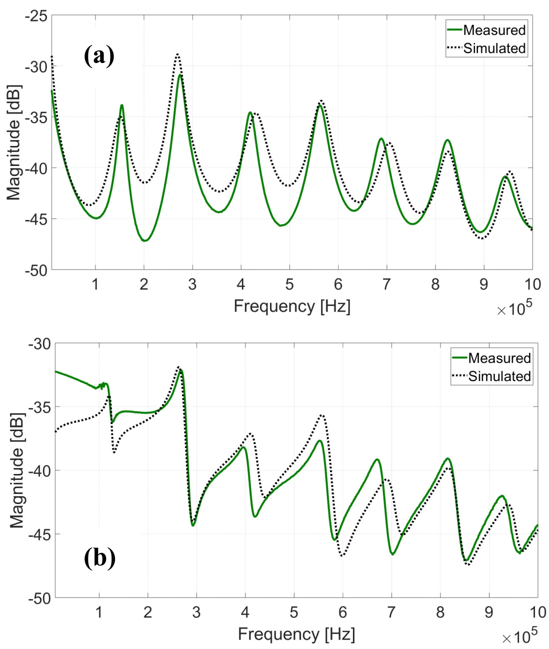


Figure 3. Comparison of measurement and simulation for different connection schemes for healthy case of windings **(a)** EE-SC **(b)** II

4 Disk space variation (DSV) fault

Disk space variation is one of the commonly occurring mechanical fault in power transformers [16]. It can occur due to short circuit current as well as reduced clamping pressure due to insulation aging. This fault changes the geometry of transformer windings as shown in Fig. 4. The axial forces for electromagnetically balanced windings act to axially compress them. When the axial compression force exceeds a certain limit, a fault called disk space variation occurs. This fault may result in an insulation damage on conductors, force amplification due to conductor displacements, and shorted turns [17]. In [18], DSV have been studied on a small test object without the information of the impact on real transformers. In [16], large windings displacements are studied while it is important to detect the minor winding deformations as soon as possible in order to enable suitable measures. Also, no one has investigated the overall displacement of the winding due to exceeded axial compression forces. Additionally, the sensitivity of different connection schemes to detect the DSV faults is also not discussed.

In order to check the applicability of the model in predicting the effects of mechanical variations on the FRA traces, a widely occurring winding fault, disk space variation (DSV) is implemented in both the experimental setup and the HF model. Two modes of DSV faults are studied;

- Location-based, in which DSV is applied at a specific location of HV winding as shown in Figure 5b.
- Overall-DSV, in which DSV is applied in the overall winding height as shown in Figure 5c.

(a) DSV fault between disk 2 and 3 is implemented by changing the space between disk 2 and 3 of HV winding. The space between disk 2 and 3 is increased by inserting the spacers as shown in Figure 1d. DSV is implemented in four minor fault levels; each step of 1 mm. Different connection schemes are applied to detect the most sensitive scheme against DSV. Figure 6 shows that the model behaviour towards DSV is completely in accordance with the reality. These results validate the FEM model to be used for predicting the windings behaviour against different mechanical changes. As the high frequency region (in between 600 kHz and 1 MHz in this case) is influenced by the winding structure. In the winding structure, the response is determined by the winding leakage inductances together with the winding series and ground capacitances. In this region, the series capacitance is the most influential factor in determining the shape of the response [8]. It can be seen in the simulated and measured FRA traces in Figure 6, the impact of the DSV on FRA traces is mainly in the high frequency range (600 kHz-1 MHz). As DSV changes the series capacitance of the winding, which affects the FRA traces at high frequencies. Moreover, DSV fault shifts the resonance frequencies to the right with a slight change in magnitude. This effect gets more pronounced with an increasing degree of the fault.

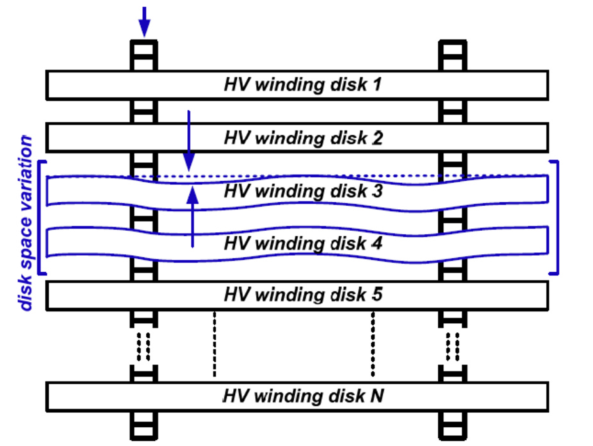
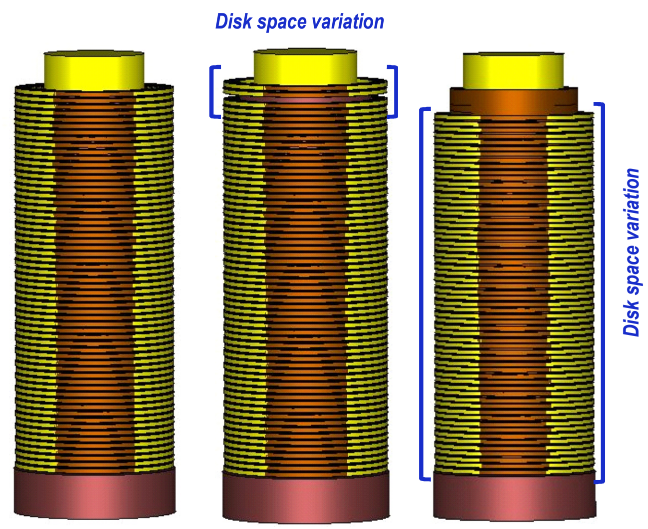


Figure 4. Disk space variation between disk 2 and 3 of transformer HV windings [19].



(a) **(b)** **(c)**

Figure 5. Different modes of DSV fault **(a)** healthy winding **(b)** DSV between disk 2 and 3 **(c)** DSV in full winding

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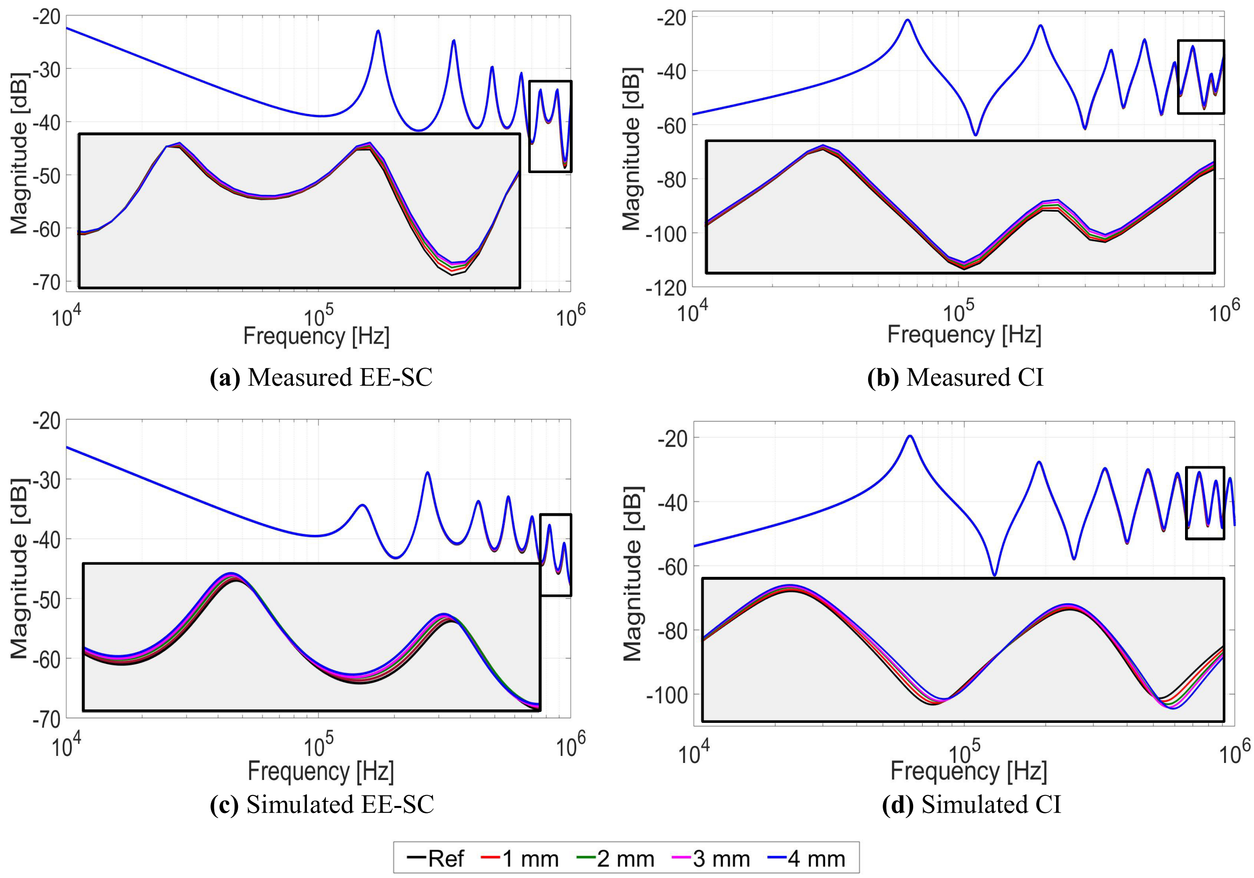
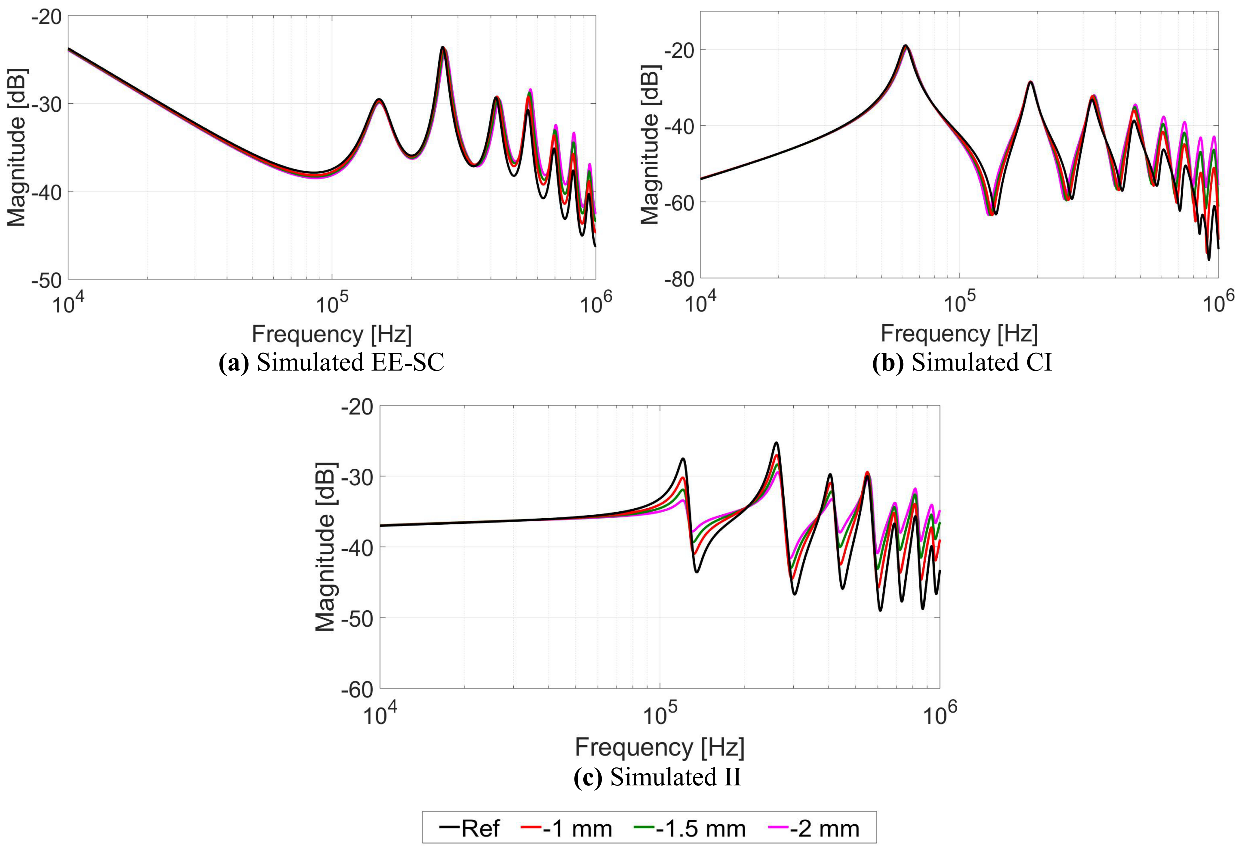


(a) Measured EE-SC **(b)** Measured CI

(c) Simulated EE-SC **(d)** Simulated CI

Figure 6. Measured and simulated FRA traces for different levels of DSV between disk 2 and 3



(a) Simulated EE-SC **(b)** Simulated CI

(c) Simulated II

Figure 7. Simulated FRA traces for different levels of DSV in full winding

(b) In order to understand the impact of DSV in the whole winding, due to reduction or loss of winding clamping, the space between each HV disk is reduced in three minor fault levels (-1 mm, -1.5 mm and -2 mm). Figure 7, shows that the overall-DSV fault affects the FRA traces in the middle (50 kHz-600 kHz, in this case) and high frequency region (500 kHz-1 MHz). The middle frequency region is influenced by the coupling between windings and, in this case, the overall winding height is also altered, thus the coupling between windings is changed. While the high frequency region is affected due to the change of the series capacitance of the winding. The effect is more prominent with an increased degree of the fault.

5 Evaluation of numerical indices

To analyse the sensitivity of different connection schemes, four numerical indices, namely standard deviation (SD), correlation coefficient (1-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 [20]. In this paper, the numerical indices which show linear and monotonic behaviour with increased level of faults are utilized. Moreover, all of the four indices exhibit same behaviour with respect to the changes in the FRA trace; therefore, the results of CCF for different levels of DSV fault are presented here which can be a very good representation of the other indices.

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

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

$$1-CC = 1-\frac{\sum_{i=1}^{N} X(\mathrm{i})\,\mathrm{Y}(\mathrm{i})}{\sqrt{\sum_{i=1}^{N}\left[X(\mathrm{i})\right]^2 \sum_{i=1}^{N}\left[Y(\mathrm{i})\right]^2}} \tag{3}$$

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

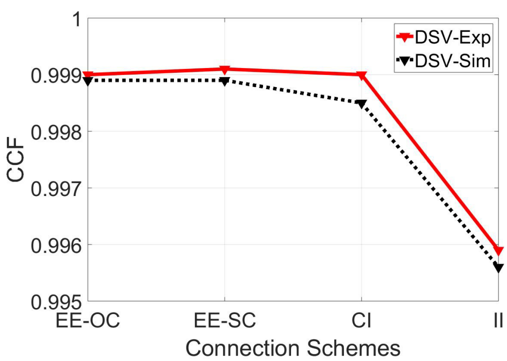


Figure 9. Sensitivity comparison of different connection schemes to detect DSV (between disk 2&3)

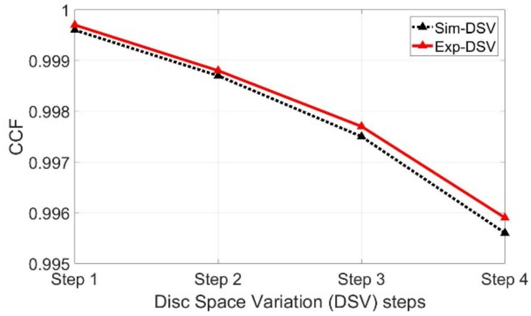


Figure 8. CCF of simulated and measured FRA traces (II) for different fault levels of DSV (between disk 2&3)

Figure 8 shows the sensitivity comparison of different connection schemes for 4 mm of DSV (between disk 2&3). The result shows that inductive inter-winding (II) connection scheme exhibit the maximum sensitivity to detect the DSV fault and the simulation results follow the measurements. Figure 9 shows the linear and monotonic behaviour of CCF against different fault levels of DSV for inductive inter-winding (II) connection scheme. It's worth noting 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. 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 design simplifications applied to the HF model. However, the general shape of CCF for different connection schemes and, for different levels of the fault remains the same and thus, the model works satisfactorily in predicting the numerical indices used for the interpretation of FRA results.

6 Conclusion

This paper presents an improved method to obtain a high frequency model of power transformer using FEM. In the proposed HF model, it is possible to extract the FRA traces directly from the 3D FEM model of the transformer without solving complex circuit models. The model was validated with measurements with both healthy and deformed windings. Two modes of DSV faults were implemented and their impact on the FRA traces was studied. For sensitivity analysis, different numerical indices were evaluated. Based on the results, it can be concluded that CCF, SD, ED and 1-CC show monotonic behaviour with increasing degree of mechanical deformation and thus, can 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 minor winding faults. The sensitivity of different connection schemes against DSV faults in terms of CCF is analysed and it was noticed that inductive inter-winding connection scheme has the best sensitivity to detect the disk space variation fault.

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