Improved Power Transformer Winding Fault Detection using FRA Diagnostics – Part 2: Radial Deformation Simulation

Naser Hashemnia, A. Abu-Siada and **S. Islam**
Curtin University
Perth, Western Australia

ABSTRACT

Frequency response analysis (FRA) is proven to be a powerful tool to detect winding deformation within power transformers. Although the FRA test along with the equipment are well developed, interpretation of FRA signature is still a challenge and it needs skilled personnel to identify and quantify the fault type if exists as at this stage, there is no reliable standard code for FRA signature classification and quantification. As it is very hard to implement faults on physical transformer without damaging it, researchers investigated the impact of various mechanical winding deformations on the transformer FRA signature by randomly changing the value of particular electrical parameters of the transformer equivalent electrical circuit. None of them however, precisely investigated the correlation between physical fault level and the percentage change in each parameter. In this paper, the physical geometrical dimension of a single-phase transformer is simulated using 3D finite element analysis to emulate the real transformer operation. A physical radial deformation of different fault levels is simulated on both low voltage and high voltage windings. The impact of each fault level on the electrical parameters of the equivalent circuit is investigated and the correlation between the fault level and the percentage change in each parameter of the equivalent circuit is provided. This will facilitate precise fault simulation using transformer equivalent electrical circuit and ease the quantification analysis of FRA signature.

Index Terms— **power transformer, condition monitoring, FRA, buckling deformation, Radial faults, Insulator winding Integrity.**

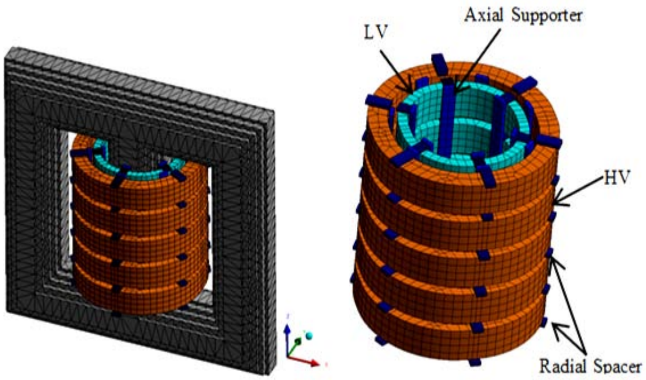
1 INTRODUCTION

SHORT circuit currents are the main reason of deformation and displacement of transformer windings due to the electromagnetic forces they produce [1]. Although a transformer may continue in normal operation with minor winding deformation, its capability to withstand further mechanical and electrical stresses substantially decreases which may lead to a sudden catastrophic failure. Therefore, it is essential to detect minor winding deformation as soon as possible and take a proper remedial action [2, 3]. Frequency response analysis (FRA) is a powerful diagnostic technique currently used to identify winding deformation within power transformers [2, 4-7]. FRA technique is based on the fact that transformer winding deformation and displacement change its impedances and consequently altering its frequency response. The change in transformer FRA signature is used for fault identification and quantification. The main drawback of FRA technique is its relines on graphical analysis that requires expert personnel to conduct the test and to analyse its results as so far, there is no general guideline for interpreting FRA signatures. There have been many attempts in the literature to understand the impact of various mechanical faults on the transformer FRA signature.

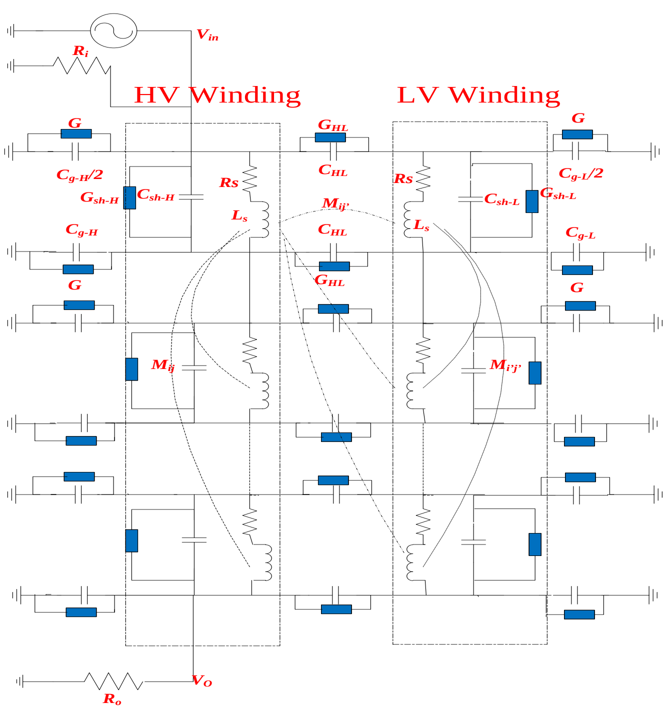
As practical fault implementation on real transformer is very difficult to perform without harming the transformer, most of these studies have been performed on a high frequency transformer equivalent circuit model by randomly changing the value of particular electrical parameters to simulate various mechanical faults [8, 9]. None of these studies really investigated the correlation between the fault level and the percentage change in the relevant electrical parameters for precise fault simulation. This paper presents a comprehensive analysis of the transformer winding radial (buckling) deformation. To emulate real transformer operation, 3D finite element software is used to simulate the physical geometry of a single-phase transformer. Various radial deformation levels are implemented in both high voltage (HV) and low voltage (LV) windings and its impact on the change of the equivalent electrical parameters is investigated. Impact of fault location as well as transformer size is also investigated as will be detailed in the sections below.

2 FINIT ELEMENT ANALYSIS

Maxwell software is used to simulate the transformer model geometry shown in Figure 1a. As shown in the figure, the transformer is single phase of shell-type. The model consists of metal shield core and pressboard spacers between LV and HV windings. In order to maintain the exact position of the low voltage winding, pressboard spacers are placed on core insulation. The HV winding consists of 5 disks, 820 turns and the LV winding consists of 4 disks, 130 turns.



(a)



(b)

Figure 1. (a) Power Transformer 3D model, (b) Transformer distributed parameters model.

The 3D transformer model is solved in magneto static and electrostatic solvers using Maxwell equations to extract the inductance, capacitance matrices while eddy current is used to calculate winding resistance. The high frequency equivalent electrical circuit of the transformer is shown in Figure 1b. In the model, HV and LV windings are represented by series resistance (R_s) and inductance (L_s) shunted by capacitor (C_s) and conductance (G_s). The capacitance between HV winding and LV winding (C_{HL}) shunted by dielectric conductance (G_{HL}) simulates the insulations between the two windings. Also, the mutual inductances (M) between relevant coils are represented. The dielectric insulation between the LV winding and the earthed core and that is between the HV winding and the earthed tank are simulated by a capacitance (C_g) and dielectric conductance (G). When short-circuit faults result in winding deformation in a transformer, a change in the parameters of the winding model will take place. To calculate the capacitance matrix of the transformer model, Maxwell 3D performs a sequence of electrostatic field simulations. In each field simulation, for an n-conductor system, n field simulations are automatically performed. The energy stored in the electric field associated with the capacitance between two conductors is given by[10]:

$$W_{ij} = \frac{1}{2}\int_{\Omega} D_i \times E_j . d\Omega \tag{1}$$

where, W_{ij} is the energy in the electric field associated with flux lines that connect charges on conductor i to those on conductor j, D_i is the electric flux density associated with conductor i and E_j is the electric field associated with conductor j.

The capacitance between conductors i and j is therefore:

$$C = \frac{2W_{ij}}{V^2} = \frac{1}{2}\int_{\Omega} D_i \times E_j . d\Omega \tag{2}$$

To calculate the inductance, the average magnetic energy W_{AV} is calculated first as:

$$W_{AV} = \frac{1}{4}\int_{V} B \times H dV \tag{3}$$

where B is the magnetic field density and V is the volume of the conductor. Then inductance can be calculated from the average magnetic energy and peak winding current I_{Peak} as below[10].

$$L = \frac{4W_{AV}}{I_{Peak}^2} \tag{4}$$

3 RADIAL FORCE FAILURE MODE

During short circuit fault, the electromagnetic forces acting on the coils may suddenly rise from a few pounds to tons. These forces oscillate at double of the circuit frequency [11]. The radial components of the electromagnetic forces in a transformer with concentric disk windings have never been considered significant due to the fact that radial strength of the winding is high enough to cope with these forces [4]. Winding radial buckling can be avoided by a perfectly round winding cross-section and by placing adequate radial spacer supports as shown in Figure 1a[12-14]. On the other hand spacer supports influence the buckling strength of windings which are subjected to radial electromagnetic forces [15]. Radial forces in disk windings of a two-winding transformer produce a hoop stress that tends to extend the radius of the outer winding and at the same time they produce a compressive stress in the inner winding producing buckling as shown in Figure 2. The mean hoop stress (σ_{mean}) in the conductor of the outer winding at the peak of the first half cycle of short-circuit current, assuming an asymmetry factor of 1.8 is [16, 17].

$$\sigma_{mean} = \frac{0.03W_{cu}}{he_z^2} \text{ kN/mm}^2\text{(peak)} \tag{6}$$

where W_{cu} is I^2R_{dc} losses in the winding in kW, h is axial height of the winding in mm and e_z is per unit applied voltage.

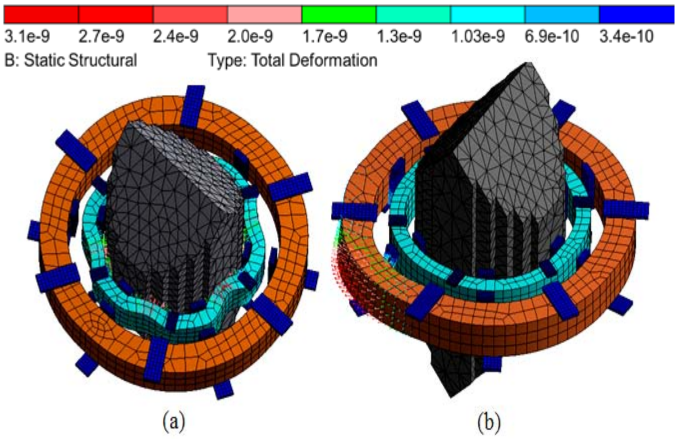


Figure 2. (a) Forced buckling (LV), (b) Free buckling (HV)

The inner winding is subjected to radial forces acting inwards (forced buckling) while it acts outward on the outer winding (free buckling) as shown in Figure 2. The failure modes include winding collapse or bending between supports. If the winding is of disk type, each disk is subjected to a radial force that can be calculated as [18, 19]

$$P_r = \frac{2\pi\, \sigma_{mean}\, n_c\, A_c}{D_w} \tag{7}$$

where, σ_{mean} is mean stress calculated in (6), P_r is the radial force in kN per mm of length, A_c is cross sectional area of the disk in mm^2 , n_c is number of conductors in each disk and D_w is the mean diameter of the winding in mm.

4 IMPACT OF BUCKLING DEFORMATION ON EQUIVALENT ELECTRIC CIRCUIT PARAMETERS

In order to exactly simulate radial deformation using transformer equivalent electrical circuit model, it is essential to detect the percentage change in the electrical circuit parameters that is corresponding to a particular fault level. According to [20-22], radial deformation is simulated by randomly changing the value of the capacitance HV and of LV windings while the change in inductance is neglected. The study did not emphasize the amount of change in the capacitance that is corresponding to the studied fault levels. The main contribution of this paper is that it investigates the correlation between various radial fault levels and the corresponding percentage change in electrical circuit parameters to facilitate accurate simulation of radial fault using transformer high frequency electrical equivalent circuit and to ease the quantification analysis of FRA signatures. In this regard, the physical geometrical dimensions of a single-phase transformer is simulated using 3D finite element and by means of coupling ANSYS magnetic part with ANSYS static structural mechanical part, various radial deformation levels which is calculated as the percentage ratio of the change in perimeter of the faulty disk with respect to the disk perimeter prior to deformation are implemented by controlling the level of the short circuit current through the windings. In case of a single phase transformer, current during transient condition can be approximately expressed as [4, 23]:

$$i(t) \approx I_0 e^{-\frac{t}{\tau}} + \sqrt{2} I_{SC}\left(\cos(\omega t + \psi - \varphi) - e^{-\frac{t}{\tau}}[\cos(\psi - \varphi)]\right) \tag{8}$$

where $\tau = \frac{L_{eq}}{R_{eq}}$; $I_{SC} = \frac{V}{\sqrt{{R_{eq}}^2 + \omega^2 {L_{eq}}^2}}$ and $\varphi = \tan^{-1}\frac{\omega L_{eq}}{R_{eq}}$

where ψ is the voltage angle when fault is occurred, I_{SC} is the steady state value of short circuit current, I_0 is the initial current at fault application, R_{eq} and L_{eq} represent the total series impedance of the winding, V is the supply effective voltage.

The calculated electromagnetic forces are used as input source of sequential FEM to predict the resultant mechanical forces considering the structural characteristics such as stress distribution and winding deformation. Radial force due to short circuit current and axial leakage flux within the gap between the HV and LV windings is calculated in finite element analysis as [4]:

$$F_{radial} = \pi\, D_{ave}\left(\frac{\sqrt{2}\mu_0 NI}{2H_w}\right)\left(\sqrt{2}NI\right) \tag{9}$$

where H_w, D_{ave}, N, I and μ_0 are respectively, winding height, average winding diameter, number of turns, RMS winding current and permeability of air.

To investigate the impact of fault location on the percentage change in various electrical parameters of the transformer equivalent circuit, radial deformation has been simulated in three different locations of the HV and LV windings as shown in Figure 3. Impact of transformer sizing is also investigated as will be elaborated in the following sections.

A. *Case study 1: 1MVA single-phase Transformer*

Figure 4 shows the variation of the magnetic energy after deformation on the top disk of HV winding due to short circuit current. Inductances associated with the deformed disks are calculated using Maxwell's equations. To calculate the capacitance matrix for the deformed winding a sequence of electrostatic field simulations is performed to measure the energy stored in the electric field associated with the capacitance between the HV and LV windings, HV winding and the core and the LV winding and tank. The electrical parameters matrices are extracted for normal and faulty conditions and the percentage change in each parameter due to buckling deformation is calculated as:

$$\text{Percentage change in parameter } x = \frac{x_n - x_f}{x_n} \times 100\% \tag{10}$$

where x_n and x_f are respectively the parameter (inductance or capacitance) values during normal and faulty conditions.

This procedure is performed for three different fault locations; top, middle and bottom of both HV and LV windings. The percentage changes in inductive and capacitive elements as a function of various fault levels are shown in Figures 5 and 6. Figure 5 reveals that the percentage change in the self-inductance of the deformed disk winding decreases after force buckling on LV winding with the increase in fault level. The percentage change in the capacitance between LV and HV windings at the fault location decreases with the increase of fault level, whereas the percentage change in the capacitance between the LV winding and the core increases since the distance between the deformed disk and core decreases. Figure 6 shows that, due to the free buckling that the HV winding exhibits, the percentage change in capacitance between HV winding and tank and the percentage change in the self-inductance of HV winding increase with the increase in fault level. The percentage change in the capacitance between HV and LV winding shown in Figure 6c has the same trend as the one shown in Figure 5c.

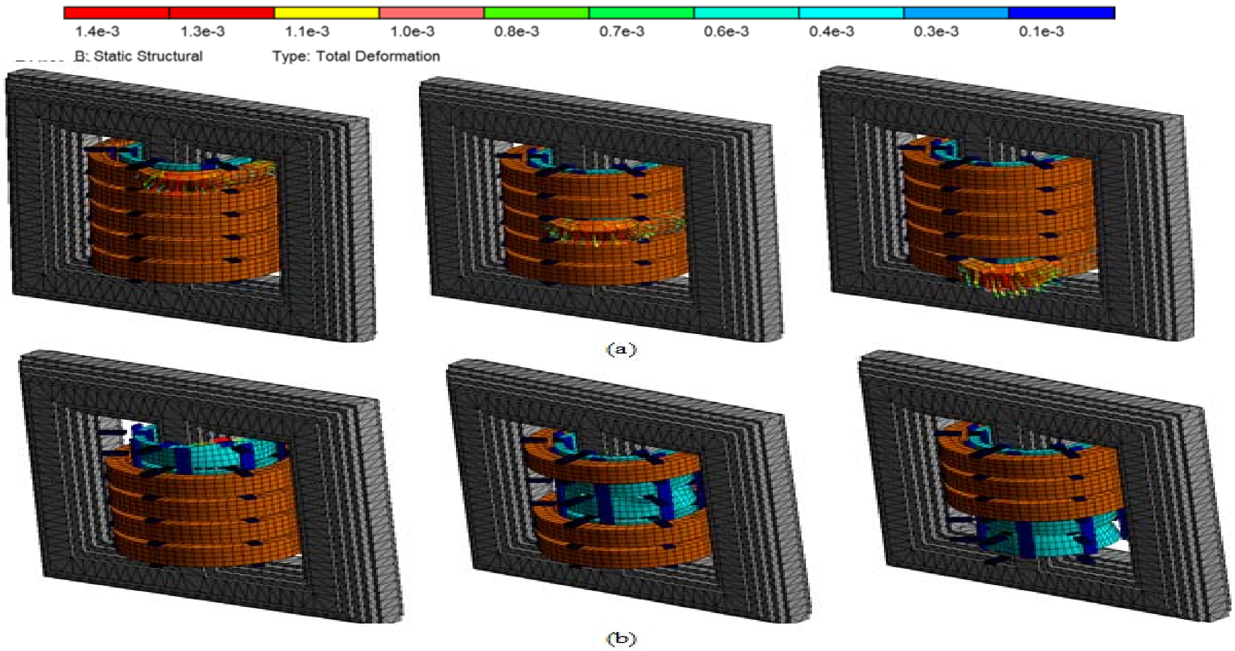


Figure 3. (a) Free buckling HV winding (Top, Middle and Bottom). (b) Force buckling LV winding (Top, Middle and Bottom)

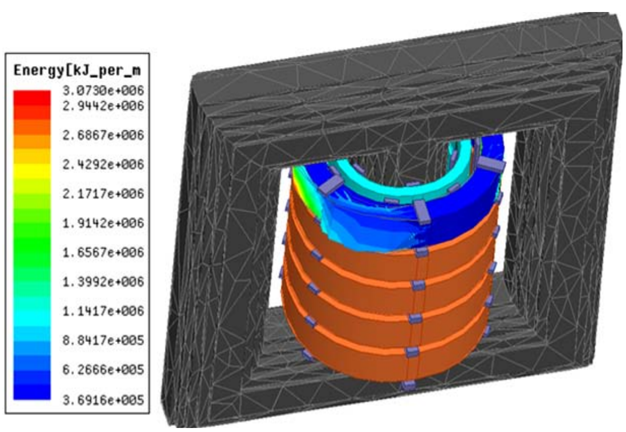


Figure 4. Variation of magnetic energy after deformation on top disk of HV.

Simulation results show that deformation location has a slight impact on the electrostatic and magnetoestatic fields. As a result the percentage change in the electrical circuit parameters is not significantly impacted by the fault location as shown in Figures 5 and 6.

B. Case study 2: 5MVA single-phase Transformer

To investigate the impact of transformer sizing on the electrical parameters variation due to radial deformation, the geometry of 5 MVA transformer is simulated and the same approach explained above is used to calculate the percentage change in the equivalent electrical parameters corresponding to various fault levels of free buckling deformation on the HV winding in three different locations as shown in Figure 7 and the change of electrical parameters is shown in Figure 8.

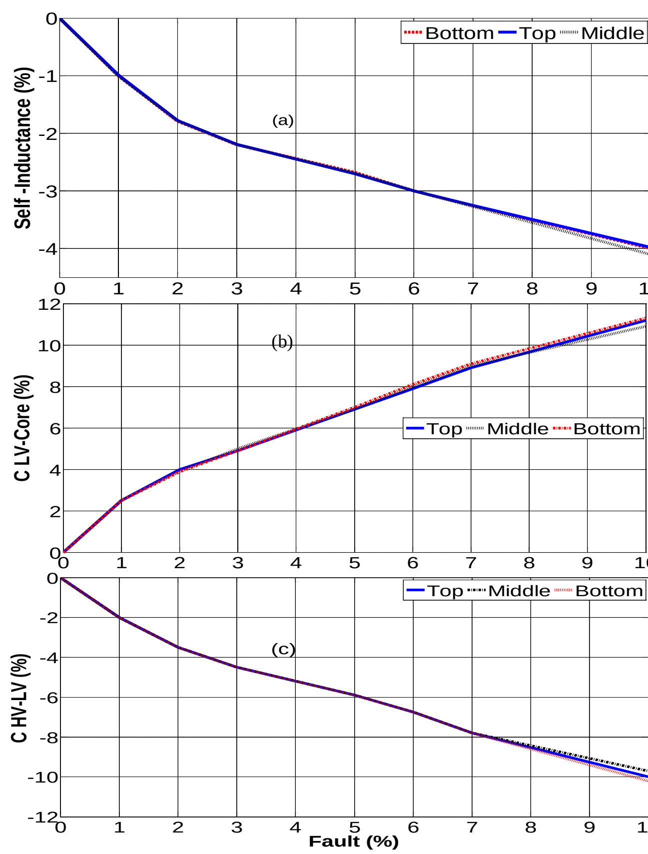


Figure 5. Variation of Inductance and Capacitance Matrices (Force buckling on LV winding) – 1MVA transformer

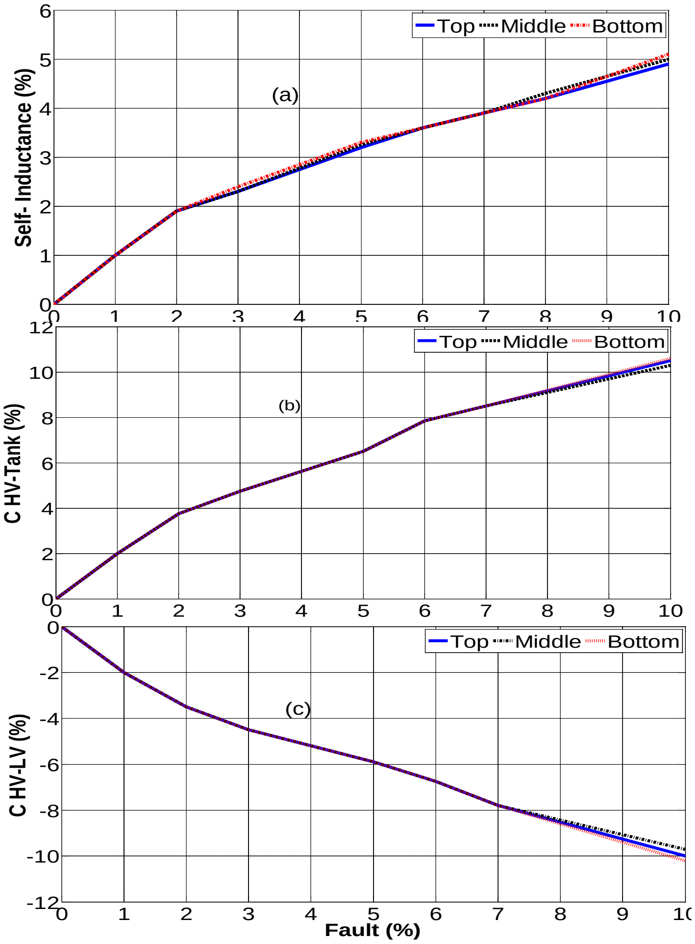


Figure 6. Variation of Inductance and Capacitance Matrices (Free buckling on HV winding)- 1MVA transformer

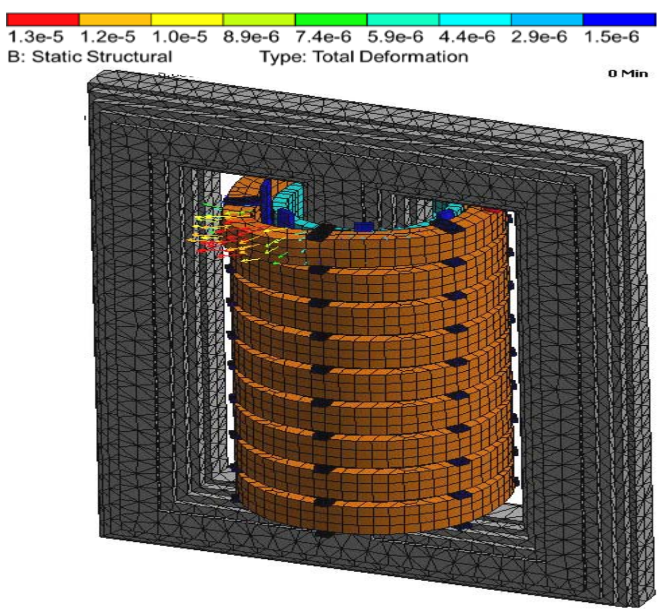


Figure 7 .Free buckling on the top of HV winding (5MVA)

Figure 8 reveals that the change in the electrical parameter due to free buckling deformation on the HV winding of a 5 MVA transformer is quite similar to the free buckling on the HV winding of a 1 MVA transformer. However parameters variation in the high rating transformer is slightly higher.

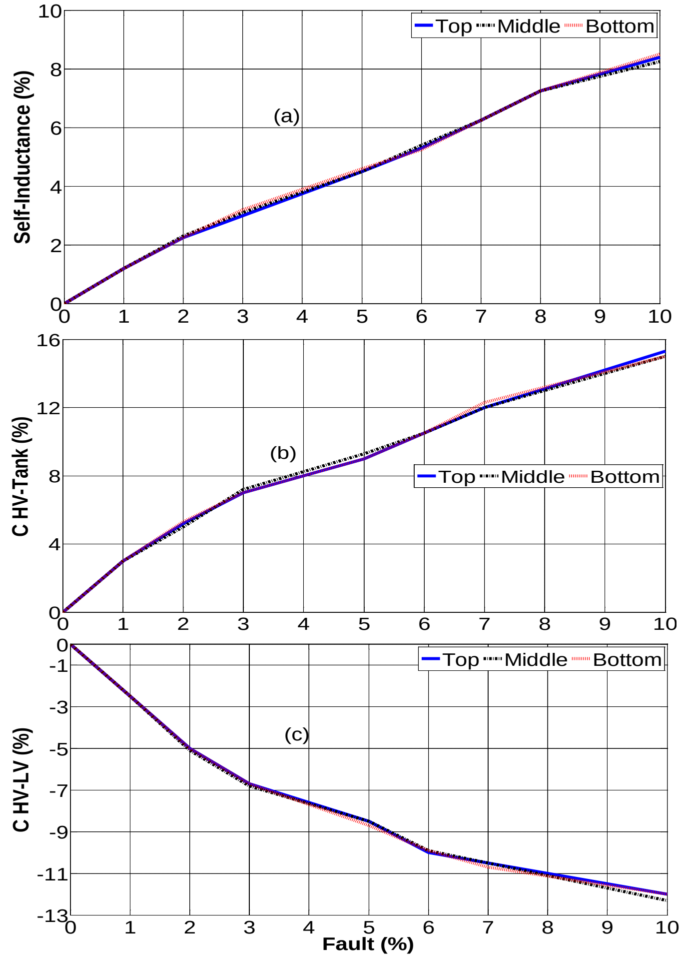


Figure 8. Variation of Inductance and Capacitance Matrices (free buckling on HV winding) - 5 MVA transformer

5 IMPACT OF PROPOSED PARAMETERS CHANGE ON FRA SIGNATURE

To investigate the effect of the parameters change proposed in the previous section on the transformer FRA signature, the transformer model (1MVA) shown in Figure 1b is energized by a sweep frequency AC source (V_{in}) of 10 volt and variable frequency (up to 1 MHz) and the FRA signature (Transfer function; TF= $20\ log10(V_o/V_i)$) is plotted against frequency for healthy and faulty conditions. The value of the electrical parameters corresponding to each fault level is calculated based on Figures 5 and 6. Figure 9 shows the influence of two fault levels of HV and LV winding buckling deformation (1% and 5%) that is simulated by only changing the capacitance matrix as proposed in the literature [20, 21] on the FRA signature. As shown in Figure 9, the fault impact on the FRA signature is hardly observable in the frequency range less than 500 kHz, while the resonance frequencies and magnitude are slightly changed and hardly observed at high frequency range. Figure 10 shows the effect of 1% and 5% buckling deformation on the FRA signature of the HV and LV windings by considering both capacitance and inductance variation to simulate the buckling deformation as proposed in this paper.

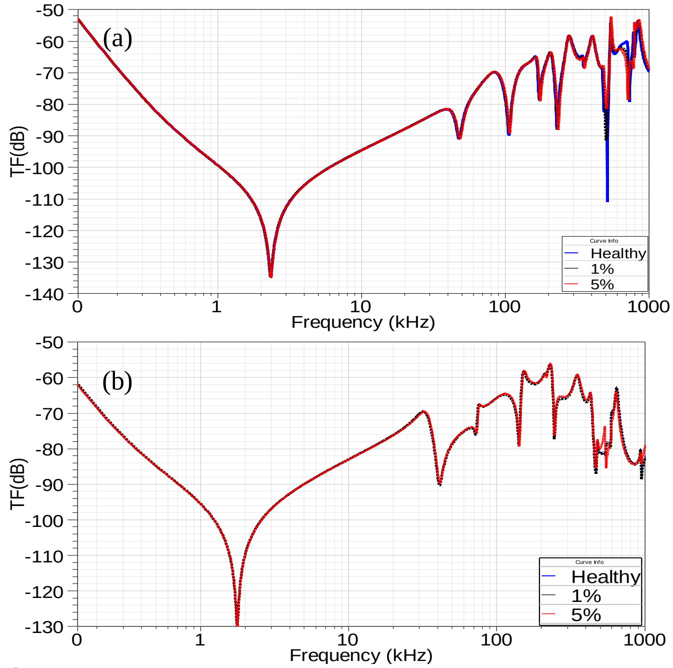


Figure 9. Effect of buckling deformation on FRA signature (simulated by changing capacitance matrix only) (a) Free buckling on HV winding (b) Force buckling on LV winding.

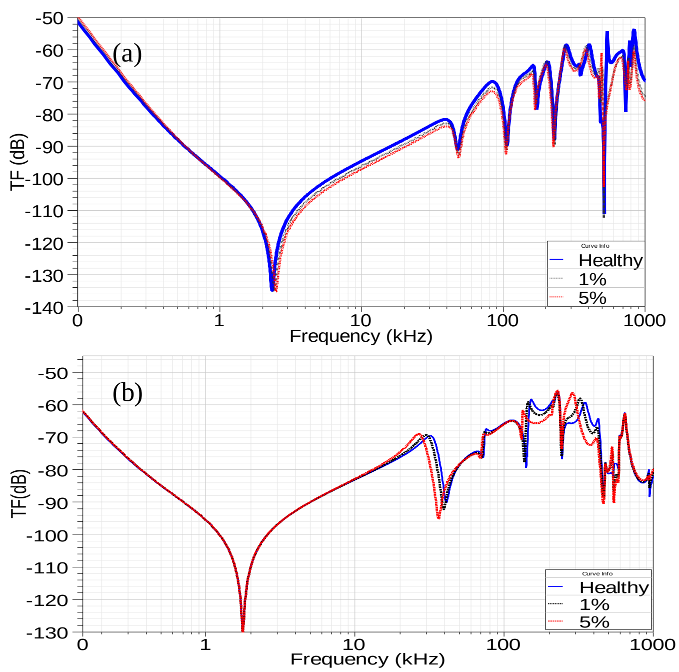


Figure 10. Effect of buckling deformation on FRA signature (simulated by changing capacitance and inductance matrices) (a) Free buckling on HV winding (b) Force buckling on LV winding.

In contrary with the FRA signatures shown in Figure 9, by considering both capacitance and inductance variation in simulating buckling deformation, the influence of the fault on the FRA signature is observable even for 1% fault level on the entire frequency rang. This aligns well with the practical results presented in [1, 9, 24, 25] that reveal buckling deformation influences the whole frequency range of the FRA signature. The change in the FRA signature in case of HV buckling fault in the low frequency range is attributed to the change in the magnetic flux distribution due to the fault as clearly shown in Figure 7.

Table 1and 2 summarize the variation of the resonance frequencies *Δf* due to 5% radial deformation with respect to the healthy FRA signature for both HV and LV windings of a two single phase transformers of different rating; 1MVA and 5 MVA investigated in the paper. Five resonance peaks in four frequency ranges (10-100 kHz, 100-400 kHz, 400- 600 kHz and 600-1MHz) are tabulated to quantify the change in peak resonances without and with considering inductance matrix variation as proposed in this paper. It is noted that variation in the FRA signature due to buckling fault starts in the frequency range above 400 kHz if only capacitance elements variation is considered. While variation in the FRA signature starts from the low frequency range when inductive elements are considered too which agrees with the practical measurements presented in [1, 9, 26] . Tables 1 and 2 show that with the increase in transformer rating, the shift in resonance frequencies will increase for the same fault level.

Table 1. Average effect of 5% buckling deformation (1MVA)

Resonance Frequencies (Normal Condition; kHz)		*Δf of Radial deformation* fault signature ; kHz			
		considering capacitance only		considering inductance and capacitance	
HV	LV	HV	LV	HV	LV
74.80	75.36	0	0	-5.01	+8.91
134.9	151.59	0	0	-2.5	+3.2
466.85	425.93	+3.2	+4.1	+ 9.2	+10.02
760.65	641.47	+5.23	+6.75	+ 17.21	+15.2
950.46	930.59	+10.5	+9.65	+ 19.36	+17.5

Table 2. Average effect of 5% buckling deformation (5MVA)

Resonance Frequencies (Normal Condition; kHz)		*Δf of Radial deformation* fault signature ; kHz			
		considering capacitance only		considering inductance and capacitance	
HV	LV	HV	LV	HV	LV
73.75	80.52	0	0	-6.25	+9.62
146.8	153.63	0	0	-3.51	+3.32
500.62	485.83	+4.2	+5.2	+ 10.25	+11.15
790.55	661.52	+6.16	+7.73	+ 18.31	+17.19
970.43	950.45	+11.52	+10.16	+ 20.14	+18.63

6 ONCLUSION

This paper presents an improved method using comprehensive finite element analysis to investigate the impact of various buckling deformation fault levels on the transformer equivalent circuit parameters. Based on simulation results presented in the paper, the following conclusions can be drawn:

- In contrary with other previous studies that neglected the variation of inductance elements in simulating transformer winding radial deformation, results of finite element analysis show that by considering capacitance and inductance elements variation, accurate buckling deformation can be emulated using the transformer equivalent circuit model.
- By considering the change in inductance and capacitance elements, a slight radial deformation could be detected through transformer FRA signature.

- The paper introduces effective charts that correlate the percentage change in each electrical parameter with various radial deformation fault levels. This facilitates precise simulation of radial deformation using transformer equivalent circuit and eases the quantification analysis of FRA signature.
- The percentage change of the electrical parameters due to radial deformation is almost independent on the fault location.
- The shift in the entire frequency range of the FRA signature can be used as an index for the detection of the radial deformation and the amount of change is correlated to the severity of fault level.

APPENDIX

Table 3 Transformer design data

Transformer Power	1MVA	5MVA
Transformer ratio	22.9kV/3.3kV	66kV/11kV
Outer radius HV	560mm	826mm
Outer radius LV	480mm	625mm
HV winding height	670mm	1576mm
LV winding height	670mm	1425mm

REFRENCES

[1] "IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers," IEEE Std C57.149-2012, pp. 1-72, 2013.

[2] P. S. Moses, M. A. S. Masoum, and H. A. Toliyat, "Dynamic Modeling of Three-Phase Asymmetric Power Transformers With Magnetic Hysteresis: No-Load and Inrush Conditions," Energy Conversion, IEEE Transactions on, vol. 25, pp. 1040-1047, 2010.

[3] W. Zhongdong, L. Jie, and D. M. Sofian, "Interpretation of Transformer FRA Responses— Part I: Influence of Winding Structure," Power Delivery, IEEE Transactions on, vol. 24, pp. 703-710, 2009.

[4] A. Hyun-Mo, L. Ji-Yeon, K. Joong-Kyoung, O. Yeon-Ho, J. Sang-Yong, and H. Sung-Chin, "Finite-Element Analysis of Short-Circuit Electromagnetic Force in Power Transformer," Industry Applications, IEEE Transactions on, vol. 47, pp. 1267-1272, 2011.

[5] P. S. Moses and M. A. S. Masoum, "Three-Phase Asymmetric Transformer Aging Considering Voltage-Current Harmonic Interactions, Unbalanced Nonlinear Loading, Magnetic Couplings, and Hysteresis," Energy Conversion, IEEE Transactions on, vol. 27, pp. 318-327, 2012.

[6] M. Arshad, S. M. Islam, and A. Khaliq, "Power transformer aging and life extension," in Probabilistic Methods Applied to Power Systems, 2004 International Conference on, 2004, pp. 498-501.

[7] E. Rahimpour, J. Christian, K. Feser, and H. Mohseni, "Transfer function method to diagnose axial displacement and radial deformation of transformer windings," Power Delivery, IEEE Transactions on, vol. 18, pp. 493-505, 2003.

[8] P. M. Joshi and S. V. Kulkarni, "Transformer winding diagnostics using deformation coefficient," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-4.

[9] K. Ludwikowski, K. Siodla, and W. Ziomek, "Investigation of transformer model winding deformation using sweep frequency response analysis," Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 19, pp. 1957-1961, 2012.

[10] A. Group, "Ansoft Maxwell," 16.0.0 ed. Australia Leading Engineering Application Providers Australia, 2013.

[11] M. Arshad and S. M. Islam, "Power transformer critical diagnostics for reliability and life extension," in Electrical and Computer Engineering, 2004. Canadian Conference on, 2004, pp. 625-628 Vol.2.

[12] M. R. Patel, "Dynamic Response of Power Transformers Under Axial Short Circuit Forces Part I - Winding and Clamp as Individual Components," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-92, pp. 1558-1566, 1973.

[13] M. R. Patel, "Dynamic Response of Power Transformers Under Axial Short Circuit Forces Part II - Windings and Clamps as a Combined System," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-92, pp. 1567-1576, 1973.

[14] M. Arshad, S. M. Islam, and A. Khaliq, "Power transformer asset management," in Power System Technology, 2004. PowerCon 2004. 2004 International Conference on, 2004, pp. 1395-1398 Vol.2.

[15] K. Pourhossein, G. B. Gharehpetian, and E. Rahimpour, "Buckling severity diagnosis in power transformer windings using Euclidean Distance classifier," in Electrical Engineering (ICEE), 2011 19th Iranian Conference on, 2011, pp. 1-1.

[16] "The short-circuit strength of the inner windings of transformers against radial forces," CIGRE, Paris, France,1962.

[17] K. Hiraishi, Y. Hori, and S. Shida, "Mechanical Strength of Transformer Windings Under Short-Circuit Conditions," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-90, pp. 2381-2390, 1971.

[18] W. M. J. R. B. Steel, J. J.Narbus, M. R. Patel, R.A.Nelson, "Dynamic measurements in power transformers under short-circuit conditions," ed: CIGRE, 1972.

[19] H. A. Thompson, F. Tillery, and D. U. Von Rosenberg, "The Dynamic Response of Low Voltage, High Current, Disk type Transformer Windings to through Fault Loads," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-98, pp. 1091-1098, 1979.

[20] A. Abu-Siada and S. Islam, "A Novel Online Technique to Detect Power Transformer Winding Faults," Power Delivery, IEEE Transactions on, vol. 27, pp. 849-857, 2012.

[21] M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Improved detection of power transformer winding movement by extending the FRA high frequency range," Power Delivery, IEEE Transactions on, vol. 20, pp. 1930-1938, 2005.

[22] S. D. Mitchell and J. S. Welsh, "Modeling Power Transformers to Support the Interpretation of Frequency-Response Analysis," Power Delivery, IEEE Transactions on, vol. 26, pp. 2705-2717, 2011.

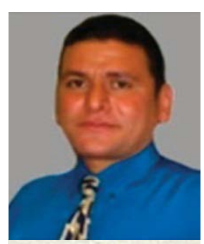
[23] E. Billig, "Mechanical stresses in transformer windings," Electrical Engineers - Part II: Power Engineering, Journal of the Institution of, vol. 93, pp. 227-243, 1946.

[24] J. Christian and K. Feser, "Procedures for detecting winding displacements in power transformers by the transfer function method," Power Delivery, IEEE Transactions on, vol. 19, pp. 214-220, 2004.

[25] J. Christian, K. Feser, U. Sundermann, and T. Leibfried, "Diagnostics of power transformers by using the transfer function method," in High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467), 1999, pp. 37-40 vol.1.

[26] C. A2.26, "Mechanical Condition Assessment of Transformer Windings Using Frequency Response Analysis (FRA)," CIGRE Brochure 3422008.

N. Hashemnia received BSc in electrical power engineering from Yazd University, Iran, in 2006 and Master of Electrical Utility Engineering from Cu rtin University in2010. He received a scholarship from the Cooperative Research Centre for Infra-structure and Asset Management in August2011 to enable him to pursue his PhD study at Curtin University. His research interests include power transformer condition monitoring and application of artificial intelligence to power systems.



A. Abu-Siada (M ’07, SM ’12) received his BSc and MSc degrees from Ain Shams University, Egypt, and the PhD degree from Curtin University, Australia, all in electrical engineering. Currently he is a senior lecturer in the Department of Electrical and Computer Engineering at Curtin University. His research interests include power system stability, condition monitoring, power electronics, and power quality. He is a regular reviewer for various IEEE Transactions.

S. Islam (M ’83, SM ’93) received the BSc from Bangladesh University of Engineering and Technology, Bangladesh, and the MSc and PhD degrees from King Fahd University of Petroleum and Minerals, Saudi Arabia, all in electrical power engineering. He is currently the John Curtin distinguished professor in electrical power engineering at Curtin University. He received the IEEE T Burke Haye Faculty Recognition award in 2000. His research interests are in condition monitoring of transformers, wind energy conversion, and power systems. Prof. Islam is an editor of IEEE Transactions on Sustainable Energy and IET Renewable Power Generation.