EFFECT OF THE ASYMMETRICAL AXIAL DISPLACEMENT OF TRANSFORMER WINDINGS ON FRA CHARACTERISTICS

Hossein Taghizade Ansari¹, Abolfazl Vahedi ²*  
1-PhD student, Iran University of Science and Technology, School of Electrical Engineering  
2-Professor, Iran University of Science and Technology, School of Electrical Engineering  
*Corresponding, Email id: (Hossein_taghizade@elec.iust.ac.ir)

Received: 01.11.2019  Revised: 10.12.2019  Accepted: 06.01.2020

Abstract  
Frequency response analysis (FRA) is one of the most reliable and useful methods for mechanical fault detection in transformers. The winding axial displacement is one of the mechanical fault types that can occur in transformers. Axial displacements cause the detailed model parameters changing, in response to which FRA characteristics will also change. Numerous researchers have considered winding axial displacements as a symmetrical movement of disks. However, one of the most prevalent types of winding axial displacements is asymmetrical axial displacement which has not been considered by any prior studies. In this paper, physical asymmetrical and symmetrical axial displacements of the first disk of the LV winding were simulated and FRA characteristics were obtained for these cases. Finally, experimental tests were performed on an experimental transformer to validate the simulation results.

Keywords  
FRA, Fault detection, Displacement, Axial, Transformer, Asymmetrical

INTRODUCTION  
The transformer is one of the most expensive elements in power systems. Moreover, it plays a vital role in energy transmission. Needless to say, failure to detect faults in transformers will lead to following items: 1- Power systems outage and lack of service to some consumers and in turn staggering costs. 2- Huge repair and replacement costs of transformers. With these in mind, the advantages of the on-time condition assessment of transformers is undeniable [1, 2]. It has been indicated in [3, 4] that 19% of the total faults occur in the windings which include short circuit between winding turns [5], a short circuit between ground and winding turns, and a short circuit between LV and HV windings. Mechanical faults are one of the winding failure reasons causing the winding displacement and finally development of short circuit [6, 7, 8]. Winding axial displacement, winding radial displacement, and winding deformation are various types of the mechanical faults [8]. Transfer function (TF) method [9, 10, 11, 12, 13], leakage reactance method [14, 15, 16], and frequency response analysis (FRA) are various methods of the transformer winding condition assessment. But, FRA is known as the most reliable and useful method to identify winding deformation and winding displacement [8, 18]. Furthermore, two different methods exist to perform the frequency response measurement: sweep frequency response analysis (SFRA) and impulse frequency response analysis (IFRA) also known as low-voltage impulse (LVI). SFRA method has some important advantages over LVI, such as a higher signal-to-noise ratio (SNR), etc. In the SFRA method, an AC voltage is applied at one terminal of a transformer and the output is measured at the other terminal. The typical frequency of the supply signal varies from 10 Hz to 2 MHz. In IFRA or LVI method, the controllable pulses are used as an input signal and the output signal is measured, where the Fourier transforms of both signals are mathematically processed to construct the frequency response characteristics [19].

The FRA method is based on the fact that any winding has a unique transfer function where changes in the parameters will alter the amplitude, resonance points, and the phase of a transfer function [20]. In order to use this method, transformer components should be presented by electrical parameters comprising resistors, capacitors, and self/mutual inductances, whose values vary due to any winding displacement causing changes in the FRA characteristics. As a result, the FRA characteristic of a healthy condition is different from that of a faulty condition [1, 6, 21, 22]. Although a large number of studies have been performed on the detection of the winding axial displacement using FRA method [6], [17-21], [23-25], [27,28] but having said that, they have considered only the symmetrical axial displacement of the windings and none of them have worked on the asymmetrical axial displacement of windings which is a very common case. In this paper, the effect of asymmetrical axial displacement of the winding which is a probable case in transformers was investigated on FRA characteristics using simulation and an experimental test.

TRANSFORMER MODELING FOR FRA TEST  
In this paper, an experimental single-phase transformer has been made and simulated. Table 1 presents the detailed design information of the experimental transformer.
Table 1 Detailed Design Information of the Experimental Transformer

|                     | Outer Winding | Inner Winding |
|---------------------|---------------|---------------|
| Inner Diameter      | 150 mm        | 101 mm        |
| Number of Turns     | 90            | 60            |
| Number of Disks     | 18            | 15            |
| Number of Turns in each Disks | 5   | 4             |
| Size of Rectangular Conductor | 2.8*4 mm | 4.9*4.9 mm |
| Outer Diameter      | 188 mm        | 145 mm        |
| Space between Disks | 5 mm          | 6 mm          |
| Height of Winding   | 160 mm        | 165 mm        |

The experimental transformer is shown in Fig. 1. There have been different models of the transformer for high-frequency range including a detailed model, multi-transmission line (MTL) and hybrid model [27-29]. The detailed model of the transformer is used in this paper with Fig. 2 illustrating this model. Obtaining detailed model parameters is essential for using this method. In the next section, detailed model parameters are explained using a numerical method.

Fig. 1. Experimental Transformer

Fig. 2. Detailed Model of Transformer [21]

CALCULATION OF DETAILED MODEL PARAMETERS USING NUMERICAL METHOD

Finite element method is used to calculate the detailed model parameters under healthy and winding axial displacement conditions. The arrangement of LV and HV disks is shown in Fig. 3.

The references [21, 28, 30] have fully described the calculation of detailed model parameters. In order to calculate the capacitance between two disks, voltage V is applied to the disks where the capacitance between two disks is calculated using (1):

\[ C = \frac{\varepsilon_0 A}{d} \]
EFFECT OF THE ASYMMETRICAL AXIAL DISPLACEMENT OF TRANSFORMER WINDINGS ON FRA CHARACTERISTICS

\[ W = \frac{1}{2} CV^2 \]  

(1)

Where, \( W \), \( C \), and \( V \) represent the electrostatic energy, capacitance, and voltage respectively. For example, 1 V applied to the first disks of LV and HV and the electrostatic energy calculated by FLUX software is \( 2.96 \times 10^{-12} \) J. Therefore, using the equation (1), the capacitance between the first disks of LV and HV is 5.92 pF as observed in Table 2 indicating the capacitance between the HV and LV disks.

The self-inductance of a disk is calculated using (2). Wherein this equation, \( \varphi \), \( L \), and \( I \) represent Leakage flux of the disk, self-inductance of the disk respectively:

\[ \varphi = LI \]  

(2)

Similar to the self-inductance calculation, mutual inductance can be calculated using (3), where \( \varphi_{AB} \), \( L_{AB} \), and \( I_A \) denote the magnetic flux of disk B generated because of disk A current, the mutual inductance between disks A & B, and current of disk A respectively:

\[ \varphi_{AB} = L_{AB}I_A \]  

(3)

In order to calculate the resistance of the disk, the current I is applied to the disk where the resistance of the disk can be calculated using (4).

\[ P = RI^2 \]  

(4)

In order to calculate the resistance of insulation between two disks, voltage \( V \) is applied over the insulation surrounded by two disks where the resistance of insulation can be calculated using (5):

\[ P = \frac{V^2}{R} \]  

(5)

Table 2 The Capacitance between the HV and LV Disks (pF)

| C_{11LVHV} | 5.92   | C_{81LVHV} | 6.36  |
|------------|--------|------------|------|
| C_{22LVHV} | 6.34   | C_{91LVHV} | 6.48  |
| C_{33LVHV} | 6.32   | C_{101LVHV} | 6.56 |
| C_{44LVHV} | 6.33   | C_{111LVHV} | 6.56 |
| C_{55LVHV} | 6.48   | C_{121LVHV} | 6.48 |
| C_{66LVHV} | 6.56   | C_{131LVHV} | 6.33 |
| C_{77LVHV} | 6.56   | C_{1316LVHV} | 6.32 |
| C_{88LVHV} | 6.48   | C_{141LVHV} | 6.34 |
| C_{99LVHV} | 6.34   | C_{151LVHV} | 5.92 |

Where, \( P \), \( V \), and \( R \) represent loss power of disk, disk current, and disk resistance respectively.

Notice that the experimental transformer is made without a tank. So, the capacitance between windings and the ground should be eliminated. Furthermore, the simulation and experimental test have been performed without considering a magnetic core owing to the fact that within a high-frequency range (usually higher than 10 KHz), inductance changes due to increased eddy current in the core. Indeed, the magnetic field originated from eddy current prevents the penetration of magnetic flux into the core [31]. Therefore, within a high-frequency range, the magnetic core can be overlooked. Thus, the parameters of the transformer detailed model are applicable to a high-frequency range.

**SIMULATION OF FRA TEST ON HEALTHY TRANSFORMER**

In this section, the FRA test is conducted on a healthy transformer. In this paper, the end-to-end configuration is chosen for the FRA test. This configuration is displayed in Fig. 4.
The magnitude of the end-to-end voltage function of LV winding in healthy conditions is shown in Fig. 5.

Typically, FRA characteristics are drawn up to 2 MHz since the effect of measurement wires on FRA characteristics is very high within the frequency range higher than 2 MHz [32]. However, FRA characteristics in this paper have been calculated up to 20 MHz. According to Fig. 5, four resonance and anti-resonance frequencies are present arising from the resonance between capacitors and inductors in the detailed model as reported in [6], [17-21]. In the next section, experimental FRA test is carried out on a healthy transformer to validate simulation results.

EXPERIMENTAL FRA TEST ON A HEALTHY TRANSFORMER

The experimental test is performed by the FRA analyzer device made by OMICRON Company as seen in Fig. 6.

Fig. 6 displays the schematic view of the FRA test circuit already shown in Fig. 6. As seen in Fig. 7, there are 3 different wires used as output measurement represented by blue, input measurement represented by red, and the actuation represented by yellow.
As mentioned earlier, the configuration of the FRA test is end-to-end. The magnitude of the end-to-end voltage function of LV winding is revealed in Fig. 8. There is one resonance and anti-resonance frequencies between 1 MHz to 5 MHz in Fig. 8 as with Fig. 5. According to Fig. 5 and Fig. 8, these figures are almost similar within a frequency range up to 2 MHz where the differences are in the magnitude of resonance and anti-resonance frequencies. Consequently, according to the above-mentioned fact, simulation is validated by the experimental test.

**SIMULATION OF 25 MM ASYMMETRICAL AXIAL DISPLACEMENT OF FIRST DISK OF LV WINDING**

Fig. 9 illustrates the arrangement of the transformer disks in this condition. Although the asymmetrical displacement of winding disks is very common since the strength of clamps holding disks in their positions is not the same, this condition never developed in previous studies. In this condition, only the first disk of LV winding moves in an asymmetrical condition like Fig. 9 while other disks are in the primary position. The magnitude of the end-to-end voltage function of LV winding in healthy and 25 mm asymmetrical axial displacements of LV winding’s first disk condition is shown in Fig. 10.

In Fig. 10, the red trace belongs to the 25 mm asymmetrical axial displacement of LV winding’s first disk condition while the blue trace represents the healthy conditions. According to Fig. 9, when the 25 mm asymmetrical axial displacement has occurred, resonance and anti-resonance have occurred at a higher frequency. In the next section, the experimental test is performed for validating the simulation results.
EXPERIMENTAL FRA TEST ON 25 MM ASYMMETRICAL AXIAL DISPLACEMENT OF LV WINDING'S FIRST DISK

Fig. 11 depicts a real 25 mm asymmetrical axial displacement of LV winding's first disk of the experimental transformer. The magnitude of the end-to-end voltage function of LV winding in healthy conditions and 25 mm asymmetrical axial displacement of LV winding's first disk condition is shown in Fig. 12. In Fig. 12, red trace belongs to 25 mm asymmetrical axial displacement of LV winding's first disk condition while blue trace indicates the healthy condition. According to Fig. 12 and Fig. 10, the transformer modeling and simulation results are validated against each other. In the next section, experimental FRA test is conducted on 25 mm asymmetrical axial displacement of LV winding's first two disks.

Fig. 10. The magnitude of End-to-End Voltage Function of LV Winding in Healthy Conditions and 25 mm Asymmetrical Axial Displacement of LV Winding’s First Disk Condition

EXPERIMENTAL FRA TEST ON 25 MM ASYMMETRICAL AXIAL DISPLACEMENT OF LV WINDING'S FIRST TWO DISKS

Fig. 14 reveals a real 25 mm asymmetrical axial displacement of LV winding's first two disks. The magnitude of end-to-end voltage function of LV winding in this condition and healthy condition is shown in Fig. 15. According to the Fig. 14, as 25 mm asymmetrical axial displacement of LV winding’s first two disks occurs, resonance and anti-resonance have occurred at a higher frequency. It is obvious that the severity of each conditions is in proportion of the magnitude of axial displacement.

Fig. 11. A Real 25 mm Asymmetrical Axial Displacement of LV winding’s First Disk

Fig. 12. The Magnitude of End-to-End Voltage Function of LV Winding in Healthy Conditions and 25 mm Asymmetrical Axial Displacement of LV winding's First Disk Condition

COMPARISON BETWEEN THE ASYMMETRICAL AND SYMMETRICAL DISPLACEMENTS OF THE WINDING DISKS

This section examines the difference between the asymmetrical and symmetrical axial displacements. The magnitude of end-to-end LV winding voltage function for 10 mm symmetrical axial displacement and 25 mm asymmetrical axial displacement of first disk of LV winding is shown in Fig. 13. In Fig. 13, the blue trace represents the asymmetrical condition. According to Fig. 13, although the asymmetrical condition (25 mm) is severe than the symmetrical condition (10 mm), the resonance and the anti-resonance of the symmetrical condition occur at a higher frequency than that of the asymmetrical condition. With this in mind, it is clear that the asymmetrical axial displacement is less obvious in FRA characteristics than in the symmetrical axial displacement.

Fig. 12. The Magnitude of End-to-End Voltage Function of LV Winding in Healthy Conditions and 25 mm Asymmetrical Axial Displacement of LV winding’s First Disk Condition

Fig. 13. The Magnitude of End-to-End Voltage Function of LV Winding in Healthy Conditions and 10 mm Symmetrical and 25 mm Asymmetrical Axial Displacement of LV Winding’s First Disk Condition
CONCLUSION
According to the results, when an asymmetrical axial displacement of windings which is a common case occurs, the resonance and the anti-resonance would occur at higher frequencies. Furthermore, larger shifts on the resonance and anti-resonance frequencies from the healthy condition yield more dramatic asymmetrical axial displacements.

Fig. 13. The Magnitude of End-to-End Voltage Function of LV Winding for 10 mm Symmetrical Axial Displacement and 25 mm Asymmetrical Axial Displacement of First Disk of LV Winding

These facts were proven by simulation and experimental tests. Thus, the transformer model employed in this paper is verified and applicable to other scenarios. Examining the asymmetrical axial displacement of the winding and comparison of the symmetrical and asymmetrical axial displacement are the main novel ideas of this paper which have not been mentioned in past researches while it is a serious condition that may cause catastrophic problems. In the future work, intelligent detection of this fault and classification of transformer faults using FRA will be done.

Fig. 14. Real 25 mm Asymmetrical Axial Displacement of LV Winding’s First Two Disks

Fig. 15. The magnitude of End-to-End Voltage Function of LV Winding in Healthy Conditions and 25 mm Asymmetrical Axial Displacement of LV Winding’s First Two Disks
EFFECT OF THE ASYMMETRICAL AXIAL DISPLACEMENT OF TRANSFORMER WINDINGS ON FRA CHARACTERISTICS

REFERENCES
1. Hadi Tarimordi, Gevork B. Garehpetian, Novel Calculation Method of Indices to Improve Classification of Transformer Winding Fault Type, Location, and Extent, IEEE Transactions on Industrial Informatics, vol. 13, no. 4, August 2017.
2. Naser Hashemnia, A. Abu-Siada, S. Islam, Detection of Transformer Bushing Faults and Oil Degradation using Frequency Response Analysis, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 22, No. 6, December 2015.
3. R. S. Bhide, M. S. S. Srinivas, A. Banerjee and R. Somakumar, Analysis of Winding Inter-turn Fault in Transformer: A Review and Transformer Models, Kandy, Sri Lanka, IEEE ICSET 2010.
4. K.S.R. Rao, K.N. Nashuruladin, Artificial Neural Networks and Genetic Algorithm for Transformer Winding/Insulation Faults, Power and Energy Systems, Langkawi, Malaysia, 2008.
5. K. Usba, S. Uska, Inter Disc Fault Location in Transformer Windings Using SFRA, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 22, No. 6; December 2015.
6. Omar Aljohani, Ahmed Abu-Siada, Application of DIP to Detect Power Transformers Axial Displacement and Disk Space Variation Using FRA Polar Plot Signature, IEEE Transactions on Industrial Informatics, vol. 13, no. 4, August 2017.
7. V. Behjat, A. Shams, V. Tamjid, Characterization of Power Transformer Electromagnetic Forces Affected by Winding Faults, Journal of Operation and Automation in Power Engineering, Vol. 6, No. 1, Jan. 2018.
8. Ana C.de Azevedo, Ivan Rezende, Antonio C.delaba, Jose C.de Oliveira and et. al, Investigation Of Transformer Electromagnetic Forces Caused By External Faults Using FE, IEEE/PES Transmission & Distribution Conference and Exposition, Latin America, 2006.
9. Mehdi Bigdeli, Mehdi Valdian, Ebrahim Rahimpour, Davood Azzian, Transformer winding diagnosis using comparison of transfer function coefficients, The 9th Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand - Conference 2011, Khon Kaen, Thailand, 17-19 May 2011.
10. Paulraj, T. Hari Kishan Surjith, P. Dhana Sekaran, P. Modeling and location of faults in power transformer using Transfer Function and Frequency Response Analysis, 2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies, Ramanathapuram, India, 8-10 May 2014.
11. Kalpana Patel, Narottam Das, A. Abu-siada, Syed Islam, Power transformer winding fault analysis using transfer function, 2013 Australasian Universities Power Engineering Conference (AUPEC), Hobart, TAS, Australia, 29 Sept.-3 Oct. 2013.
12. Sibabrata Pradhan, Sisir Kumar Nayak, Winding Dislocation of a Power Transformer and its Analysis to Locate and Estimate the Deformation, 2018 2nd International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE), Shillong, India, India, 1-2 June 2018.
13. Rajesh Rajamani, Muthiah Rajappa, Kamalasenan Arunachalam, Balasuhammad Madanmohan, Interturn short diagnosis in small transformers through impulse injection: on-line on-load self-impedance transfer function approach, IET Science, Measurement & Technology, Vol. 11, No. 8, 2017.
14. Kamran Dawooda, Mehmet Aytaç Canarb, Bora Alboyaca, Diagnosis of axial displacement in transformer windings using finite element analysis, Journal of Mathematical Sciences and Modelling, 1 (1) (2018) 27-32.
15. Luis M. R. Oliveira, Antonio J. Marques Cardoso, Leakage Inductances Calculation for Power Transformers Inter-turn Fault Studies, IEEE Transactions on Power Delivery, Vol.30, No. 3, June 2015.
16. Li Peng, Zhang Bao-hui, Hao Zhi-guo, Hu Xiao-jing, Chu Yun-long, Research on Monitoring of Winding Deformation of Power Transformer by On-line Parameter Estimation about Leakage Inductance, 2006 International Conference on Power System Technology, Chongqing, China, 26 Feb 2007.
17. P. Mulkherjee, L. Satish, Diagnosing Axial Displacement in an Actual, Single, Isolated Transformer Winding, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 24, No. 2, April 2017.
18. J.R. Secue, E. Mombello, Sweep Frequency Response Analysis (SFRA) for the Assessment of Winding Displacements and Deformation in Power Transformers, Electric Power Systems Research 78 (2008) 1119–1128.
19. J. J. Huang, W. H. Tang, Y. L. Xin, J. J. Zhou, Q. H. Wu, Fault Identification for Transformer Axial Winding Displacement Using Nanosecond IFRA and SFRA Experiments, 3rd Asia Conference on Power and Electrical Engineering, 2018.
20. S.A. Ryder, Diagnosing Transformer Faults Using Frequency Response Analysis, IEEE Electrical Insulation Magazine, 2003.
21. Naser Hashemnia, A. Abu-Siada, S. Islam, Improved Power Transformer Winding Fault Detection using FRA Diagnostics – Part 1, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, No. 1; February 2015.
22. A. Torkaman, V. Naeini, Recognition and Location of Power Transformer Turn to Turn Fault by Analysis of Winding Imposed Force, Journal of Operation and Automation in Power Engineering, joape.2019.5735.1428.
23. A. Abu-Siada, N. Hashemnia, S. Islam, Mohammad A. S. Masoum, Understanding Power Transformer Frequency Response Analysis Signatures, IEEE Electrical Insulation Magazine, Vol. 29, No. 3, May/June 2013.
24. Zhongyong Zhaoi, Syed Islam, Naser Hashemnia, Di Hui, Chenguo Yaoi, Understanding Online Frequency Response Signatures for Transformer Winding Deformation: Axial Displacement Simulation, International Conference on Condition Monitoring and Diagnosis, Xi’an, China, 2016.
25. Fei Lu, Lei Jin, Siwei Liu, Yi Liu, Hua Li and et. al, General Diagnosis of Transformer Winding Axial Displacement Faults Based on FEM Simulation and On-site Experiments, 2016 Electrical Insulation Conference (EIC), Montréal, Qué, Canada, 19-22 June 2016.
26. Ebrahim Rahimpour, Jochen Christian, Kurt Feser, Hossein Mohseni, Transfer Function Method to Diagnose Axial Displacement and Radial Deformation of Transformer Windings, IEEE Transactions on Power Delivery, vol. 18, no. 2, April 2003.
27. Vahid Behjat, Mojtaba Mahvi, Vahid Tamjid, Power Auto-transformer Mechanical Faults Diagnosis Using Finite Element based FRA, International Journal of Smart Electrical Engineering, Vol.8, No.1, Winter 2019.
28. M. F. M. Yousuf, Chandima Ekanayake, Tapan K. Saha, Hui Ma, A Study on Suitability of Different Transformer Winding Models for Frequency Response Analysis, Power and Energy Society General Meeting, San Diego, CA, USA, 22-26 July 2012.
29. V. Coman, A. Buta, An Approach of the Transformer Modeling in order to Simulate the Behavior of a Welding Machine, Modelling, Identification, and Control, Innsbruck, Austria, 2002.
30. E. Bjerkan, High Frequency Modeling of Power Transformers - Stresses and Diagnostics, Norwegian University of Science and Technology, 2005.
31. J.Wilder Herrera Portilla, Guillermo Aponte Mayor, Jorge Pilete Guerra, Carlos Gonzalez-Garcia, Detection of Transformer Faults Using Frequency-Response Traces in the Low-Frequency Bandwidth, IEEE Transactions on Industrial Electronics, vol. 61, no. 9, September 2014.
32. Frequency Response Analysis for Power Transformers, 1st ed. (Zanjan: Nikan Ketab, 2010).