A Novel Methodology for Detecting and Quantifying Transformer Winding Deformation Using Frequency Response Analysis

ANIL KUMAR GS
Lecturer in EEE
Central Polytechnic College
Thiruvananthapuram

SHANMUGHAN MS
Lecturer in EEE
Government Polytechnic College
Muttom Thodupuzha

UNNIKRISHNAN P
Lecturer in EEE
Government Polytechnic College
Perinthalmanna

KAMAL VV
Lecturer in EEE
Kerala Government polytechnic College
West Hill

Abstract— A transformer has windings and its structural integrity depends on several factors such as system short circuits,mechanical shocks during transporting,reduction of pressure of winding clamping etc.A transformer can experience severe electromagnetic forces on its winding structure during short circuits. These electromagnetic stresses can lead to winding deformation in both the radial and axial directions.Obviously it will lead to transformer failure. Historicallythe winding deformation and movement in transformer winding is detected by the measurement of leakage inductance. However immediate radial deformation results in a significant change in the leakage inductance. But axial deformation has less change in leakage inductance. Thus leakage inductance measurement method has less sensitivity.Another method was introduce in 1978 based on the frequency response analysis(FRA). In FRA testing method a signal is injected in to one terminal at the same time the response at the other terminal is measured. The commonly used methods for signal injection are swept frequency method(SFRA) and Impulse method(IFRA). This topic proposes a methodology for locating and quan tifying winding deformation in transformers.It is based on the fitting of a Gray Box transformer model to FRA measurements. Here the FRA measurements were recorded both before and after the fault. The refined variations in the key parameters of the model can be then used to quantify winding deformation with in power transformers.

Key words: Frequency response analysis, Swept frequency response analysis (SFRA), Impulse response analysis (IFRA), Gray box transformer model. Winding deformation. Keywords: Frequency response analysis, Swept frequency response analysis (SFRA), Impulse response analysis (IFRA), Gray box transformer model. Winding deforma tion,Buckling

I. INTRODUCTION

A significant number of power transformers worldwide are operating beyond their designed lifespan to reduce infrastructure costs. However, the probability of transformer failure rises sharply in the later stages of its life, with potentially catastrophic consequences, including loss of life and severe economic and environmental damage. Regular monitoring of transformer conditions is crucial to anticipate maintenance, repair, or replacement needs, especially for aging equipment.

Transformers face structural challenges such as short circuits, mechanical shocks during transport, or reduced winding clamping pressure over time. These factors can cause severe electromagnetic forces, leading to radial and axial winding deformation and eventual transformer failure. Frequency Response Analysis (FRA) has emerged as a key tool for detecting winding deformation by comparing a transformer's unique frequency response signature before and after faults. Techniques like Black Box modeling and radar imaging are being explored to enhance the interpretation of FRA data and improve fault classification and diagnostics

II.FRA MEASUREMENTS

An approach which has been adopted by many researchers has been the use of a transformer model based on its geometric parameters (White Box model). The ratio nale behind this approach is that a change in the geometry of a transformer will affect the physically representative parameters used in the model. A number of researchers in this area have been actively using transformer models to aid in the investigation of winding deformation. Research by Islam investigated the sensitivity of model param eters on FRA. Deformation and displacement faults were simulated by modifying the model's series capacitance at various locations throughout the winding. Later research by Sofian et al. demonstrated how the FRA of a deformed winding aligned with the sim ulated FRA from a transformer model whose parameters were analytically derived from the revised geometry. In the research by Jayasinghe et al. , changes were made to ca pacitance and inductance model parameters in order to simulate winding deformation. The results were then compared with those obtained from experimental methods. A similar approach was adopted by Tang et al. to investigate the detection of minor wind ing deformation and displacement using higher frequency FRA measurements. The parameters of such White Box transformer models are generally determined using fi nite element tools or precise analytical techniques. Such an approach requires detailed information on the internal geometry and material structure of the transformer which is not commonly available outside of the laboratory . In earlier research published by the authors of this paper, a Gray Box transformer model was developed to support the interpretation of FRA . Like the White Box model, the Gray Box model is based on the geometric parameters and material properties of the transformer, however many of the model parameters may be unknown and will need to be estimated by fitting the model's transfer function to external measurements. As a demonstration of the model's potential, the effect of varying levels of winding deformation on a transformer's FRA was simulated by changing appropriate parameter values within the transformer model. To date a number of other researchers have also used model simulation studies to in vestigate the effect of transformer winding deformation on FRA including . However a more robust evaluation of the effectiveness of a model in the detection of winding deformation, and the methodology implemented in this paper, is to test if the model parameters estimated directly from the FRA would correctly change to reflect a physi cally altered winding structure. This approach will facilitate quantifying the degree of deformation and identify which winding(s) are affected. The experimental validation of this approach is provided via buckle tests on a 1.3 MVA 11 kV/433 V distribution transformer. 2.2 FRA assessment methods and interpretation The principle of the FRA method consists of measuring the transformer response over a wide frequency bandwidth. Currently, the test is usually performed on an un loaded and de-energized transformer. Different types of input signals and various stages can be considered. According to the input signal nature, two main measurement meth ods exist: impulse frequency-response analysis (IFRA) and sweep frequency-response analysis (SFRA) methods. The IFRA method uses a single non-periodic signal as ex citation or input which is injected into any of the available transformer terminals. The maximum value of input impulse may reach hundreds of volts and the wide frequency content is suitably ensured by the waveform of the input pulse.

This excitation causes induced voltages in the remaining ends of the same transformer. These induced signals depend on the transformer structure and are measured as an interesting output to eval uate. The frequency spectrum of the injected signal (input) and the measured signal (output) are obtained through mathematical procedures, such as fast fourier transform (FFT). Finally, the ratio between the two frequency spectra is obtained. In the SFRA measuring method, the excitation signal or input is a sinusoidal signal with a LV am plitude (usually in the 1–20 V range), which is applied to a transformer terminal in a frequency sweep (in the hertz to milli-hertz range). Again, the transfer function (TF) is obtained from the output/input ratio for various frequencies . The IFRA technique is very quick (requiring only a few minutes) whereas the SFRA technique is rather slow (about 2 h).Four different test configurations are normally used for making FRA measurements. These are: (i) end to end open circuit test; (ii) end to end short circuit test; (iii) capacitive inter-winding test; and (iv) inductive inter-winding test. The end 6 to end open circuit test is performed on one winding (HV or LV). The input signal is connected to one terminal of the winding while the output signal is measured from the other end of the winding. This concept applies for Y-connected as well as D-connected windings and also for single phase units. The secondary winding of the same phase is left open during these measurements. The end to end short circuit test is conducted on one winding in a similar fashion. However, the two terminals of the secondary winding are connected together for the short circuit test. In the capacitive inter-winding test, the input signal is applied at one terminal of the primary winding and the output signal is measured at one terminal of the secondary winding while all other terminals are left floating. The fourth test configuration i.e., the inductive inter-winding test is similar to the capacitive test discussed above, except that the open terminals of the primary and secondary measured windings are connected to ground. Other terminals of unmeasured windings are left floating to avoid unwanted influences on the response. In this test, the input signal should be supplied at the HV terminal and measured at the LV terminal. In addition to winding, the FRA may also be applied to transformer bushing to check its condition. Conventional methods have very low sensitivity for detecting winding deformations. However, FRA technique can be a successful diagnostic method for de tecting movement of the windings, core and/or deformation of transformer windings. Techniques such as LVI with TF method and sweep frequency method (SFM) can be applied for such purposes to obtain frequency responses. FRA is basically a compara tive method, and FR measured in the range from 20 Hz to 2 MHz, is compared either to previous results on the same, similar units, or another phase of the same transformer which are used as reference fingerprints . Generally, at the beginning of a new type of technology, computer modeling is useful. Modeling allows the creation of many variations of simulated phenomena or test setup to save time and cost. Once models point to a useful outcome, then the technique is tried for in field applications. Thus, computer modeling has found applications in FRA of transformers . The first study on frequency response analysis was reported in 1978. However, the application of FRA method on power transformers became industrial practice approximately a decade ago. Now this technique has been standardized . However, there are still many challenges regarding the interpretation of the test results obtained by this method. There is no stan dard available to qualitatively identify the type of fault in the windings and quantify the degree of severity of the winding displacement. Thus, there are no clear guidelines for interpreting FRA data to unambiguously detect the faults in the transformers. A few researchers have used mathematical models to determine the resonant frequencies to relate frequency response data to the transformer mechanical structure and to quantify significant winding changes. Many researchers have focused on diagnostics and inter 7 pretation of FRA data for various deformations and research work is in progress in order to understand and analyze the data to detect such deformations.Approaches to interpret ing FRA data.are 1.White box modelling-requires information on the internal geometry and material structure of the transformer. It not requires terminal measurements. 2.Gray box modelling-similar to white box model. However the unknown model parameters are estimated by fitting the models transfer function to external measurements as in the case of black box model. . 2.3 Generic transformer Model The generic phase approach is particularly useful in FRA analysis due to the diverse range of tests and terminal combinations which may be connected. For exam ple, for the high voltage (HV) winding end to end open circuit test on a three-phase transformer there will be three tests comprised of the HV terminal combinations AC, BA and CB. For our model the generic HV terminals are designated X-Y-Z, and the corresponding low voltage (LV) terminals are x-y-z. The n section lumped parameter model for generic phase X is given in Fig.2.1. Each section of the HV and LV windings consists of the series combination of an inductive element L and a resistive element . L represents the frequency dependent self and mutual inductance relationships for a winding section. The term also takes into account the contribution of each winding section to the core losses associated with magnetic skin effect. The resistive element < encapsulates the DC resistance and frequency dependent skin and proximity effects for a winding section. To account for the capacitance between windings, a capacitive element CXx couples each equivalent winding section. The capacitance between turns and adjacent discs is modelled with the addition of CSX and CSx, for the HV and LV windings, respectively. The capacitance between the LV winding and ground is given by Cgx and the capacitance between the HV winding and the transformer tank walls is given by CgX . The capacitances CXY and CZX represent the capacitance between adjacent HV windings. To accommodate for dielectric losses associated with the ca pacitive coupling of each element, the non-ideal capacitance elements are comprised of a parallel combination of a frequency dependent resistance and an ideal capacitance." the model of the basic structural unit used was in the form of the series of capacitors and resistors. Moreover, parallel resistance is used to represent the surface resistance of the bushing. The generic phase approach is useful in FRA ,due to the diverse range of tests and terminal combinations. In the n section lumped parameter model HV and LV wind

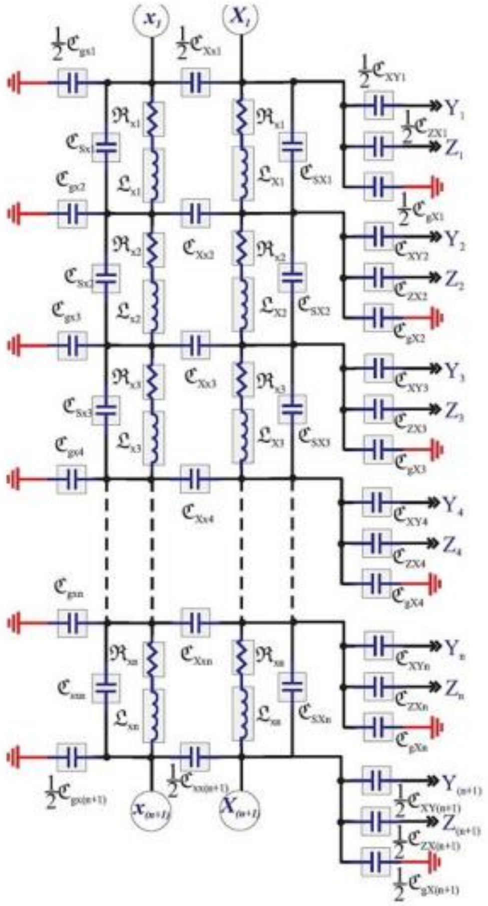
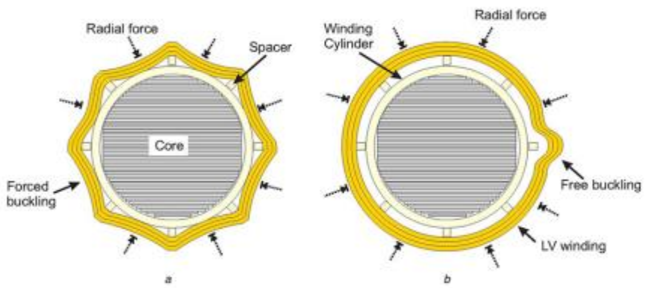


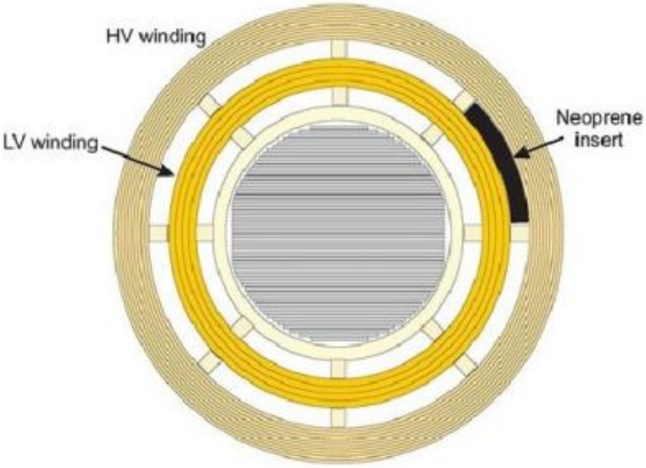
Figure 2.1: Generic transformer model, (Source:https://www.google.co.in, 01/08/2017) ing consists of the series combination of inductive elements and a resistive elements. The inductive elements represents frequency dependent self and mutual inductance for a winding section with the core losses associated with the magnetic skin effect. The DC resistance represents frequency dependent skin effect and proximity effects for a winding section. The capacitive element couples each equivalent winding

section. CsX-capacitance between turns and adjacent windings. Csx- capacitance between disc for hv and lv windings. CgX-capacitane between hv winding and transformer tank walls. Cgx-capacitance between lv winding and ground. Cxy,Czx – capacitance be tween adjacent hv windings. For dielectric losses associated with the capacitive cou pling of each element the non ideal capacitance are comprised of a parallel combination 9 of a frequency dependent resistance and an ideal capacitance

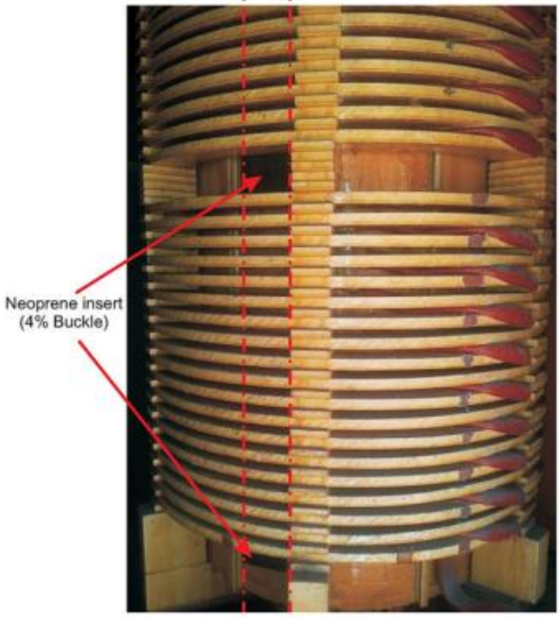
III.Short circuit forces and their potential consequences 3.1 Effect of leakage flux A short circuit can place tremendous forces upon transformer windings and the mechanical structure. Analysis of the leakage flux fields during a short circuit shows that the forces can be decomposed into radial and axial components. The radial leakage flux is predominantly at the winding ends and produces an axial force on the windings. This can result in an axial displacement of the HV winding with respect to the LV winding. The leakage flux which passes across the core window in the axial direction will produce an outward radial force on the HV winding and an inward radial force on the LV winding. The outward radial force is tensile in nature and can stretch the conductor or break a poor joint, which can lead to failure. However, the relatively high tensile strength of the conductor material means that failures in the outer winding due to tensile stress are unlikely. The inward radial force places compressive stress on the LV winding. This compression can lead to winding deformation known as buckling and is a common mode of failure. Buckling of the LV winding is the focus of this deformation study. 3.2 Buckling modes for the LV winding When the support structure of the LV winding has a greater stiffness than the LV winding conductors themselves, under compressive stress it is possible for the winding conductors to bend in between each of the spacers towards the core. This is known as forced buckling and is shown in Fig. 3.1a. Forced buckling in an LV winding will lead to an increase in the average distance between the HV and LV windings. This will result in a reduction in the HV to LV winding capacitance. Conversely, since the average dis tance between the LV winding and the core decreases, there is a corresponding increase in the LV to core capacitance. These geometric changes will also subtly influence the leakage inductance characteristics. Another buckling mode known as free buckling can occur when the conductor has a higher stiffness than the winding support structure. Un der these circumstances the winding can buckle both inwards and outwards around the circumference. This buckling mode is shown in Fig.3.1b. Figure 3.1: Buckling modes associated with radial stress on a transformer's LV winding,



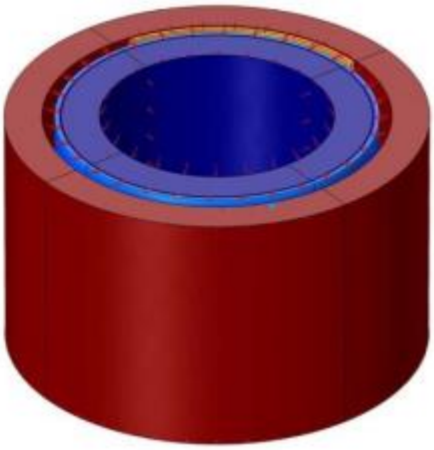
(a) Forced buckling (b) Free buckling, (Source:https://www.google.co.in, 01/08/2017) 3.3 Emulation of an outward radial buckle in the LV winding Because of the high capital costs associated with a transformer, it was necessary for the testing associated with this research to be non-destructive. Therefore, to obtain the FRA data associated with different levels of winding deformation, we propose to utilise a method which could emulate 'buckling' in the LV winding, however would be temporary in nature so that the transformer can be restored to its original condition at the end of the testing program. Whilst noting that buckling will induce changes to a winding's leakage inductance as well as its capacitance parameters, an induced change in capacitance can be more readily achieved in a non-destructive manner. Emulating the 12 Figure 3.2: Emulation of an outward radial buckle in the LV winding using a neoprene rubber insert between the HV and LV windings,



(Source:https://www.google.co.in, 01/08/2017) change in capacitance due to buckling of the LV winding requires the ability to reduce the HV to LV winding capacitance and increase the LV to core capacitance. Where 1 is the electrical permittivity of the dielectric medium between the two cylindrical conductors, L the cylinder length, (r0) is the inside radius of the outer con ductor and(ri) is the outside radius of the inner conductor.Both the HV to LV winding capacitance and the LV to core capacitance can be estimated from the coaxial cylin der relationship of (5). With reference to (5), the only parameter that can be altered without significant mechanical change is 1, the electrical permittivity of the dielectric medium. A change in 1 can be achieved by changing the dielectric material between the cylinders. To facilitate the change in the electrical permittivity required to emulate 'buckling', neoprene rubber was inserted between the HV and LV windings of an air cooled transformer, as depicted in Fig. 4. Since neoprene rubber has an electrical per mittivity of 6.7 (compared with 1 for air), the inserts will have the effect of increasing the HV to LV capacitance, and will therefore approximately emulate an outward radial buckle in the LV winding. Though a buckle in the LV winding would typically be in ward, the objective set forth in this paper is to quantify the degree of radial winding deformation using FRA, be it in either the inward or outward direction. 13 3.4 Transformer 'buckle' tests A 1.3 MVA 11 kV/433 V Dyn1 air cooled distribution transformer was used for the 'buckle' emulation modifications. The modifications involved the insertion of 6 mm neoprene rubber strips in between the phase A HV and LV windings. Each of the strips ran the full axial length of the winding as shown in Fig. 5. Four 'buckle' tests were Figure 3.3: Buckle emulated on phase A of a 1.3 MVA 11 kV/433 V transformer,



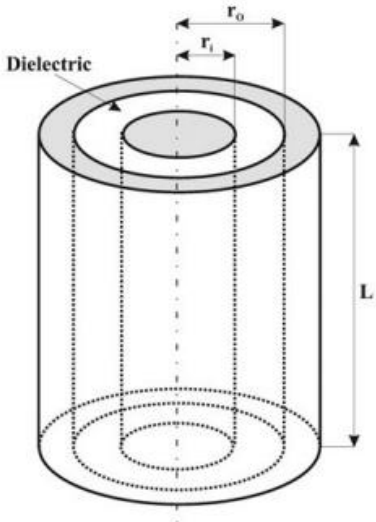
(Source:https://www.google.co.in, 01/08/2017) conducted in total. The first test was an unmodified baseline test which is referred to as 0 percentage 'buckle'. For the second test the transformer was modified such that the neoprene inserts covered 8 percentage of the LV winding's outer circumference. This coverage was increased in percentage to 16 for the third test and to 24 for the fourth. HV winding end to end open circuit, LV winding end to end open circuit and capacitive interwinding FRA tests were then conducted on each of the 'buckle' test cases. The resulting FRA tests for increasing levels of 'buckling' severity were recorded and a zoomed in view of their FRA responses is given in Figs. 6 and 7 (HV winding end to end open circuit and capacitive interwinding FRA tests, respectively).



In each of these 14 Figure 3.4: FEA model of the emulated winding deformation IET. (2017) figures there is an observable change in the frequency response of windings associated with phase A of the transformer. As anticipated, the degree of change coincides with the increasing degree of 'buckle'. Similar changes are also observed in the LV winding end to end open circuit FRA test results

IV. Parameter estimation for radial 'buckling'

4.1 Base line FRA Radial buckling results in changes to certain parameters. Given a baseline FRA for comparison a base line F R A would be equivalent to the FRA tests conducted after transformer installation and commissioning, knowledge of these parameters and the di rection of their expected change can be used to our advantage. The first step is to run the estimation algorithm, using the cost function , on the baseline FRA to determine the baseline parameter values. Other than the parameters specific to the deformation type being investigated, the remaining parameter values can all be fixed after this first run. The estimation algorithm is then re-run with the 'buckled' transformer FRA data. This approach significantly limits the degrees of freedom associated with the model, making the estimation algorithm more sensitive to the subtle parameter changes that are being investigated. The windings are much more sensitive to atmospheric variations such as temperature and humidity which can vary widely throughout the course of a day of test ing. One area that is particularly sensitive to changes in both humidity and temperature is the losses associated with the permittivity of the insulation material. Variation in the complex permittivity results in changes in the resonant damping levels within the transformer's frequency response . As a result, the estimated parameter values may be influenced by changes in atmospheric conditions. To detect the subtle changes expected in the model parameters as a result of the 'buckle' tests, we need to adopt an approach which will minimise the influence of both temperature and humidity. Given a signifi cant change in the temperature and absolute humidity associated with the transformer insulation, by using inter-phase comparisons to supplement those of the reference FRA. We have adopted this approach at a parameter level in the following manner. Rather than look at the absolute value of a parameter, we use the relative difference between similar parameters on different phases. An example is to monitor the relative difference between the interwinding capacitances .This differential approach removes the common mode effects due to changes in the atmospheric conditions since only the absolute value of the parameters is affected.



this paper used transformer modelling techniques in conjunction with FRA measurements to determine parameter changes within a trans former structure. The validity of the approach was demonstrated in the following man ner. The first step was to record baseline FRA results for the transformer under consid eration. Next a Gray Box model was fitted to the base line FRA in order to determine the baseline model parameters. The third step was to introduce a winding 'buckle' into one phase of the transformer. The FRA tests were repeated and the Gray Box model fitting algorithm was applied to the post-buckle FRA results. The subtle variation in the model capacitance parameters were clearly indicative of the induced winding structural change, demonstrating the methodology's potential. Whilst FRA has found widespread 18 application as a tool that can be used to potentially identify winding deformation, this research has demonstrated experimentally how it can be used to quantify the severity of this deformation. It is proposed that this approach could be used to support an auto mated deformation detection algorithm within a commercial FRA package

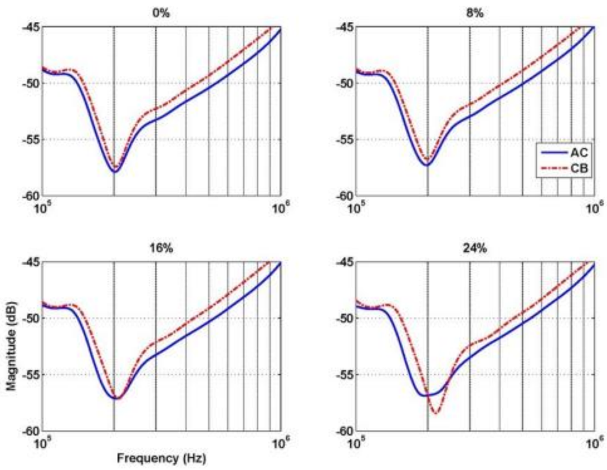


Figure 4.2: Zoomed in view of the AC and CB HV end to end open circuit FRA tests. The tests are based on winding 'buckling' of percentage 0, 8, 16 and 24 Source: IET. (2017)

To confirm that the degree of change in the interwinding capacitance is correct, the change relative to the baseline value is compared with that predicted by a FEA model of the problem using the COMSOL Multiphysics suite of software. The resulting FEA electrostatics model shown in Fig. 8, is comprised of coaxial cylinders representing the 1.3 MVA transformer's HV and LV windings (red and dark blue in colour, respectively), a cylinder between the two windings which represents the insulation press board (light blue), and a cylindrical section to represent the added neoprene strips between the two windings (brown), and the model's electric field lines (red arrows). The results are presented in Table 4.1 The estimated percentage change in the value of the capacitance relative to the amount of 'buckling' is very close to that predicted by FEA. Whilst the results in this paper were determined using Gray Box modelling techniques on a modified power transformer, these results align well with the findings of researchers who have utilised White Box models and simulated deformation using FEA. Examples include which tracked the interwinding capacitive changes relative to deformation, and then tracked the differential shift in frequency associated with winding deformation induced capacitive change..

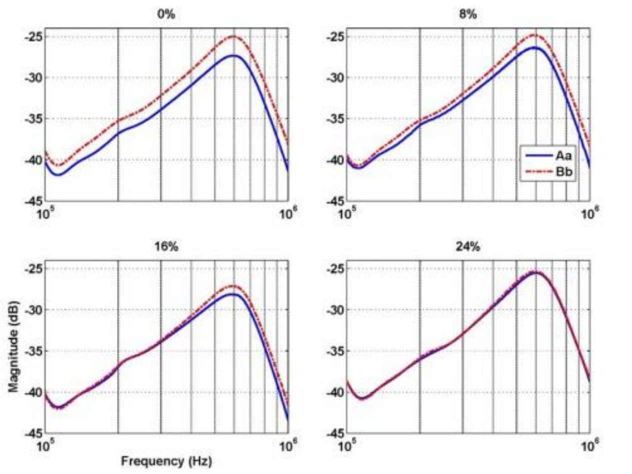


Figure 4.3: Zoomed in view of the AC and CB HV interwinding FRA tests. The tests are based on winding 'buckling' of percentage 0, 8, 16 and 24 Source: IET. (2017)

Interwinding capacitance estimates

We have adopted this approach at a parameter level in the following manner. Rather than look at the absolute value of a parameter, we use the relative difference between similar parameters on different phases. An example is to monitor the relative difference between the interwinding capacitances i.e. CAai- CBbi where CAai is the 20 Table 4.1: Model and FEA estimates for the change in the phase A interwinding capac itance based on the emulation of outward radial 'buckling' for 0 (Baseline), 8, 16 and 24% of the winding circumference Source: IET, (2017)

% Bukling	% Change(model)	% Change(FEA)
0	-	-
8	+2	+3
16	+5	+6
24	+7	+9

capacitance per model section between the HV and LV windings of phase A and CBb icapacitance per model section between the HV and LV windings of phase B. We use this difference as an independent parameter for each of the 'buckle' test cases. This differential approach removes the common mode effects due to changes in the atmo spheric conditions since only the absolute value of the parameters is affected. Table 4.2 lists the algorithm's interwinding capacitance estimates of each phase for each of the 'buckle' test cases. As expected, the changes observed in the capacitance are not always consistent due to atmospheric variations and model accuracy limitations. It was for this reason that the differential approach was proposed. Table 4.3 evaluates the difference in interwinding capacitance relative to each phase for each of the 'buckling' cases. It is clear that there is a proportional increase in the interwinding capacitance relative to the level of 'buckling' when phase A is considered (columns CAai - CBbi and CAai -CCci); whereas the influence is not observed when the relative difference in the interwinding capacitance does not include phase A (column CBbi -CCci).

Table 4.3: Difference in interwinding capacitance for each of the 'Buckling' tests. All values in pF
Source: IET, (2017)

% Bukling	CAai-CBbi	CAai-CCci	CBbi -CCci
0 (Baseline)	+3.8	+4.8	+1.0
8	+5.1	+6.2	+1.1
16	+7.7	+8.5	+0.8
24	+8.9	+11	+2.1

Table 4.2: Buckling' test interwinding capacitance estimates for each phase. All values are in pF
Source: IET, (2017)

% Bukling	CAai	CBbi	CCci
0 (Baseline)	77.9	74.1	73.1
8	79.8	80.2	80.9
16	74.7	72.5	72
24	73.6	71.7	69.9

V. Conclusion

this paper used transformer modelling techniques in conjunction with FRA measurements to determine parameter changes within a transformer structure. The validity of the approach was demonstrated in the following manner. The first step was to record baseline FRA results for the transformer under consideration. Next a Gray Box model was fitted to the base line FRA in order to determine the baseline model parameters. The third step was to introduce a winding 'buckle' into one phase of the transformer. The FRA tests were repeated and the Gray Box model fitting algorithm was applied to the post-buckle FRA results. The subtle variation in the model capacitance parameters were clearly indicative of the induced winding structural change, demonstrating the methodology's potential. Whilst FRA has found widespread application as a tool that can be used to potentially identify winding deformation. It could be used to support an automated deformation detection algorithm within a commercial FRA package

REFERENCES

[1] **Steven D. Mitchell, James S. Welsh , " Methodology to locate and quantify ra dial winding deformation in power transformers**", IET Electric Power Applica tions,High Volt., 2017, Vol. 2, Iss. 1, pp. 17–24,

[2] **Yousof, M.F.M., Ekanayake, C., Saha, T.K., "Frequency response analysis to in vestigate deformation of transformer winding**", IEEE Trans. Dielectr. Electr. Insul., 2015, 22, pp. 2359–2367

[3] **Mitchell, S.D., Welsh, J.S, 'Modeling power transformers to support the interpre tation of frequency-response analysis**', IEEE Trans. Power Deliv., 2011, 26, pp. 2705–2717

[4] E. Rahimpour, J. Christian, K. Feser and H. Mohseni, "Transfer function method to diagnose axial displacement and radial deformation of transformer windings", IEEE Trans. Power Delivery, vol. 18, no. 2, pp. 493-505, April 2003

[5] **K. S. Vasefi, R. Iravani, "Frequency Response Analysis of Power Transformers to Diagnose Winding Deformation,"** IEEE Transactions on Power Delivery, Vol. 24, No. 4, 2009, pp. 1865-1874. This paper explores FRA techniques for detecting winding deformations under varied operating conditions.

[6] **Beroual, A., Malik, N.H., "A Review of Frequency Response Analysis Methods for Power Transformer Diagnostics,"** *Energies*, 2016, Vol. 9, Iss. 11, Article 879. This review covers FRA's applications in fault detection and challenges in diagnosing transformer conditions

[7] **B. Das and V. Santosh, "Mechanical Condition Assessment of Transformer Windings Using Frequency Response,"** International Conference on Condition Monitoring and Diagnosis, 2018. This study compares FRA results pre- and post-deformation, offering insights into fault diagnosis.

[8] **M. Wang, A.J. Vandermaar, and K.D. Srivastava, "Review of Condition Assessment of Power Transformers in Service,"** *IEEE Electrical Insulation Magazine*, Vol. 18, No. 6, 2002, pp. 12-25. While broader in scope, it discusses winding deformation assessment through FRA.

[9] **Y. Li, S. Grzybowski, "Application of Advanced FRA Techniques in Transformer Diagnostics,"** IEEE International Symposium on Diagnostics, 2020. This research applies advanced modeling methods to refine FRA-based fault detection accuracy.