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Experimental Investigation on Model Transformer Windings to Analyze Axial and Radial Displacements

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Sweep Frequency Response Analysis (SFRA) method is an efficient method for predicting the geometric changes, and research on the optimum and unambiguous application is still in progress. In order to correlate integrity of transformer windings with changes in the frequency responses, a lot of measurements have to be performed and analyzed. The present work discusses special experimental investigations carried out on model transformer winding to study the various aspects of axial and radial winding displacements using SFRA test. The experimental results for axial and radial winding displacements are presented and analyzed. The analysis will help in understanding the health of an actual transformer and diagnosing it for any impending fault with respect to winding movements.

Keywords: *Sweep frequency response analysis (SFRA), Transformer windings, winding displacements, Clamping pressure, Distribution transformer.*

1.0 INTRODUCTION

The international survey of CIGRE shows typical failure rates for high voltage power transformers in the range of 1–2% per-annum [1]. Power utilities are interested to increase the life period of transformer and to decrease their life cycle cost. This can be achieved by using intelligent condition monitoring and diagnoses techniques to all types of faults. In a power transformer, failure can occur due to many kinds of mechanical impacts. They are transportation, short circuit current and installation impacts, etc. The important defect symptoms of mechanical degradation are loosening of winding clamping, loosening of core clamping, lead support failures, winding deformation, i.e. buckling, tilting, twisting and conductor insulation brittleness [2]. In addition as the transformer ages, the insulation shrinks and the clamping pressure may then be lost causing a reduction in strength. Even small winding deformation usually results in electromagnetic imbalance, which increases the stress during subsequent faults and initiates an in-service failure. Therefore, the test of winding deformation/displacement is greatly valuable for the safe operations of transformers and better planning of maintenance to improve their reliability.

In IEC 76-5 standard [3], short circuit reactance measurement is described as a diagnostic method to check the mechanical integrity of the winding. But, this method is not applicable to power transformers that are already in service due to its low sensitivity. Main methods used for detecting winding deformation/displacements are frequency response analysis (FRA) method [4–12], transfer function (TF) method, a low voltage impulse source and [8–11] sweep frequency voltage source. The sensitivity of TF method is restricted to the frequency range between 10 kHz and 1 MHz [4–5] resulting in difficulties for interpretation of faults. Swept frequency method (SFM) is preferred over TF method for detecting winding deformation/displacements due to the advantages of better signal–to–noise ratio, better resolution, repeatability and reproducibility of test results [13,14]. Budapest Colloquium CIGRE SC-12 Transformer committee recommended and concentrated on use of SFRA method for mechanical failure detection [15].

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Dick, *et al*. [4] introduced Low-Voltage Impulse (LVI) method for diagnosing mechanical deterioration of transformer winding and reported that more work is needed to correlate the frequency response with the damages. Hanrique E, *et al.* [6] introduced the transfer method of using low–voltage impulses as diagnostic tool. Al-Khayat *et al.* [13] discusses the modeling and testing of a power transformer using SFRA test. Lapworth *et al*. [14] discuss the practical use and sensitivity of SFRA technique in real situation with case studies. Hassig *et al*. discusses the technique and evaluation of SFRA measurement on power transformers. They suggested complex locus Polar plot method to compare the transfer function. But this method does not have any significant advantage over Bode plot method. Although the Frequency Response Analysis (FRA) method or Transfer Function (TF) method is already a common efficient method for predicting the geometric changes [16–24], research on the optimum and unambiguous application is still in progress. De Nigris, *et al*. [24] reported that SFRA method is adequate for evaluation of possible displacement and deformation of the winding as well as shorted-turns.

While FRA is emerging as the powerful diagnostics technique, there is still no standard about testing and judging deformations/ displacements using this method. In CIGRE SC-12 Budapest Colloquium, it is reported that some interpretations of FRA results are not so clear and failure criteria are uncertain [15]. In order to correlate mechanical displacements with deviation of FRA measurements and to study its sensitivity, a lot of measurements have to be performed [20, 25]. Because the damaged windings are rarely available, the present work discusses special experimental investigations carried out on model transformer winding with and without core to study the various aspects of winding displacements and deformations using SFRA test. Frequency response measurements were made for different axial and radial displacements on transformer windings by considering uniform as well as partial/sectional winding displacements. The experimental results for various mechanical defects on winding are presented and analyzed, which will help in understanding the health of an actual transformer and diagnosing it for any impending fault with respect to winding deformation/movement.

2.0 SFRA Instrument, Test Specimen and Methodology

FRA measurements were carried out using Sweep Frequency Response Analyzer (SFRA) instrument. The instrument has a frequency range of 10 Hz to 10 MHz with 1250 logarithmically spaced data collection instants. The instrument is provided with automatic scaling of the range based on the input magnitude level and gives a very good dynamic range. The voltage ratio transfer function data is displayed as magnitude in decibels (dB) and phase in degrees versus frequency in hertz (Hz).

The experimental setup to carry out SFRA measurements is shown in Figure 1. The SFRA test requires a 3-lead approach, with the leads providing signal, reference and test. Voltage ratio transfer function (TF) was obtained by simultaneous measurement of the test response and reference signals. All other non-test terminals were either kept open or connected to common earth. The frame/tank is always earthed.

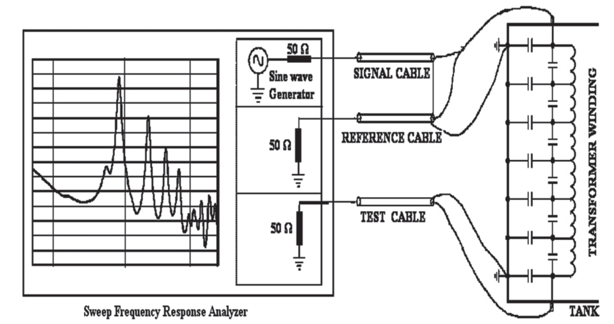

FIG. 1 EXPERIMENTAL TEST SET-UP

A few views of the test transformer windings considered in the investigations are as shown in Figure 2. The transformer-winding model is of continuous disc type, consisting of sections with two discs in each section and ten turns per disc. Its axial height (AH) is 280 mm with internal diameter of 127 mm and radial depth of 50.5 mm. The gap spacing between sections of a disc is 1.5 mm and 3 mm between two alternate sections throughout the winding. Bare conductor cross-section is 11 mm × 4.4 mm with paper insulation thickness of 0.4 mm. Totally, eight such windings are considered with differing radii in order to study the radial deformation. Each section is independent and can be joined so as to make it a continuous winding. Any section can also be replaced with another section of different dimension. This arrangement gives the flexibility to change the axial and radial dimensions of the winding. For radial displacement, a total of eight windings of different internal radii, ranging from 130 mm to 160 mm, are considered. For axial displacement, spacers are introduced between sections, thereby increasing the overall height of winding.

FIG. 2 VIEWS OF MODEL TRANSFORMER WINDINGS

Frequency response measurements covering 10 Hz to 10 MHz range were carried out using Sweep Frequency Response Analyzer. Frequency response measurements were carried out with non-test terminals floating. In FRA, the frequency range 10 Hz to 3 MHz is used which plays a great role in identifying the faults with maximum selectivity and sensitivity. The frequencies beyond 3 MHz are not considered, as these are influenced by measuring cable capacitance and stray capacitance.

Figure 1: A view of SFRA instrumenFrequency responses were measured for various displacements of the winding with or without core and used for analysis. Reference fingerprint is obtained without introducing deformation/ displacements in the model transformer. The magnitude response is used as reference fingerprints/base for comparison with different displacement/deformation. The phase responses are not discussed since they are reported as not to be giving additional information. To compare frequency response measurements, the relative deviation of magnitude and shifting of frequency hae been defined as follows:

Percentage change of frequency comparing with

$$\text{with base} = \left(\frac{f_{k.i} - f_{b.i}}{f_{b.i}}\right) \times 100$$

Percentage change of magnitude comparing with

$$\text{with base} = \left(\frac{M_{k.i} - M_{b.i}}{M_{b.i}}\right) \times 100$$

where

$f_{k.i}$ → i^{th} Resonance/anti–resonance frequency with axial displacement of *k* or radial displacement of k,

$f_{b.i}$ → i^{th} Resonance/anti-resonance frequency in base response,

$M_{k.i}$→i^{th} Magnitude of i^{th} resonance/anti-resonance frequency with axial displacement of *k* or radial displacement of *k* and

$M_{b.i}$→Magnitude of i^{th} resonance/anti-resonance frequency in base response.

3.0 Experimental Results and Discussion

3.1 Radial Displacement

Due to external through fault, the electromagnetic driving force acts on the winding in radial direction. These forces act outwards so as to create tensile hoop stress in the outermost windings as well as inward compressive hoop stress on the innermost winding. The forces act in the same direction on each half cycle and therefore pulsate at 100 Hz on a 50 Hz transformer, which causes radial deformation or displacements [2]. This effect simulated by using the different internal diameter (ID) disc sections in model transformer winding.

3.1.1 Effect of Radial Stress to Complete Winding

The response of ID-140 mm winding is used as base or reference fingerprint. All the windings used for this analysis have same axial height (AH) of 280 mm. ID of the winding increases from 145 mm to 165 mm, i.e. 3.5% to 18% with respect to base. Figure 3 shows the comparison of magnitude response of windings of different radii to illustrate the radial displacement.

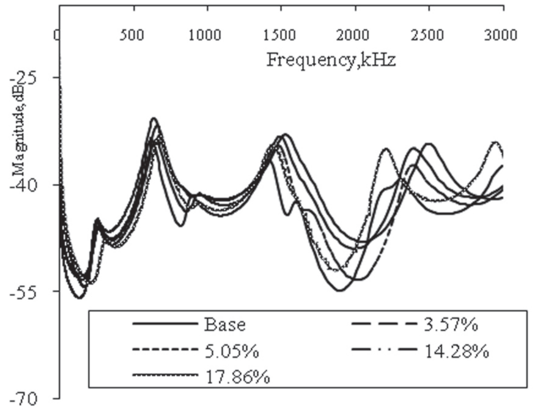

FIG. 3 MAGNITUDE RESPONSE OF RADIAL DISPLACEMENT WITH CORE

It can be observed that the resonant frequency starts from 275 kHz onwards when the windings were placed on core, which otherwise happen at much higher frequency without the influence of core. As the ID increases from 3.5% to 18%, the changes increase in all resonant and anti-resonant frequencies over the entire range. The frequency signature pattern shifts from right to left, i.e. there is decreasing of both resonant and anti-resonant frequencies except the second, which increases from their base value. Moreover, if change of ID is greater than 5.0% the, there is one new resonance as well as anti-resonance frequency created between 800 kHz and 1 MHz range. This indicates the severity of the winding damage. As far as the magnitude deviation is concerned, the overall damping rates, i.e. decrease in the magnitude as compared with reference values, increase at resonant and anti–resonant frequencies.

3.1.2 Sectional Winding Displacement at Different Locations

Radial movement is a winding that may occur on one or all the sections. In this work, the consequence of the displacement fault on one disc section is considered. In addition to that, the position of the displacement is moved along the axial height (AH) of the winding. This is used to study the influence of position of displacement on frequency response, with an objective of observing the trends for the possible location of the displacement.

The radial displacement fault is experimentally simulated on a model transformer winding ID 156 mm without core. One of the disc section is replaced by another section having ID 164 mm at various positions such as 1st, 2nd, 3rd, 4th, 7th, 8th, 9th and 10th section of the original winding. The corresponding frequency responses are obtained, which is shown as in Figure 4. The overall effect of changes in resonant, anti-resonant and magnitudes for radial displacement at different locations without core is summarized in Table 1. It is observed that frequency signature changes as the movement of location is changed. However, similar responses were obtained for 1st and 10th, 2nd and 9th, 3rd and 8th, 4th and 7th, and 5th and 6th sections. The changes in the frequency responses were observed only in few resonance as well as anti-resonance frequencies for all the cases except 3rd and 8th section displacement; whereas, the changes occur in almost all the resonance as well as anti-resonance frequencies. The overall changes in the magnitudes are observed but there are no general trends in the damping rate. It is observed that there is no discernible pattern, to the changes in frequency responses, as the location of the movement of winding is changed to suggest the possibility of locating the position.

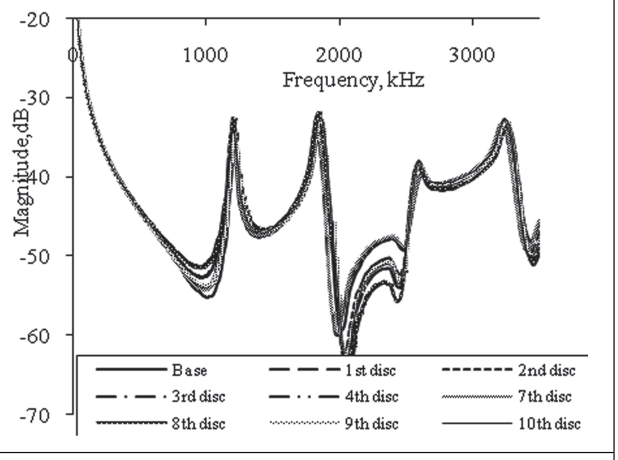

FIG. 4 PARTIAL/SECTIONAL WINDING DISPLACEMENTS WITHOUT CORE AT DIFFERENT LOCATIONS

TABLE 1

SECTIONAL WINDING RADIAL DISPLACEMENT AT DIFFERENT LOCATIONS WITHOUT CORE

Base response		% Change of resonant frequency comparing with base								% Change of magnitude comparing with base							
Res. Freq (Hz)	Mag (dB)	Replaced section								Replaced section							
		1st	2nd	3rd	4th	7th	8th	9th	10th	1st	2nd	3rd	4th	7th	8th	9th	10th
1.21E+06	–36.53	–0.83	0.00	–0.83	–0.83	–0.83	–0.83	0.00	–0.83	–7.25	–4.11	–10.70	–2.57	–2.41	–10.46	–5.50	–7.09
1.86E+06	–34.4	0.00	0.00	–1.08	–2.15	–2.15	–1.08	0.00	0.00	–4.91	–3.40	–6.83	0.41	–0.12	–7.35	–5.09	–5.06
2.40E+06	–47.79	–2.08	–1.25	–2.08	0.00	0.00	–2.08	–1.25	–1.25	7.89	5.17	11.78	–0.10	–0.71	11.36	6.07	6.82
2.62E+06	–39.45	–1.15	–1.15	–1.15	0.00	0.00	–1.15	–1.15	–1.15	–3.55	–1.29	–1.67	0.81	0.25	–2.92	–2.56	–3.37
3.24E+06	–33.26	0.00	0.00	0.93	0.00	0.00	0.93	0.93	0.00	–1.56	0.03	0.51	1.02	0.54	0.75	–0.30	–1.80

Base response		% Change of Anti- resonant frequency comparing with base								% Change of magnitude comparing with base							
Anti. Freq (Hz)	Mag (dB)	Replaced section								Replaced section							
		1st	2nd	3rd	4th	7th	8th	9th	10th	1st	2nd	3rd	4th	7th	8th	9th	10th
1.01E+06	-55.17	-4.04	-2.98	-6.14	-2.98	-2.98	-5.10	-2.98	-4.04	-4.68	-2.16	-7.09	-2.16	-1.54	-6.69	-2.68	-4.22
1.41E+06	-47.51	1.42	0.00	2.13	-0.71	-0.71	2.13	0.00	1.42	-0.88	-0.51	-1.60	0.19	-0.19	-1.94	-1.05	-0.88
2.01E+06	-59.49	2.49	1.00	2.49	-1.00	-1.00	2.49	2.49	2.49	6.89	4.40	9.48	0.81	0.10	8.59	4.45	6.10
2.48E+06	-49.21	-1.21	-1.21	-2.02	0.00	0.00	-2.02	-1.21	-1.21	9.51	6.30	13.01	-0.20	-0.85	13.21	7.70	8.47
2.71E+06	-40.84	2.21	1.11	2.21	0.00	0.00	2.21	2.21	2.21	0.00	0.73	2.06	0.61	0.17	1.52	0.22	-0.07

3.2 Axial Displacement

The electro-magnetic driving force exerted on the winding can be resolved in radial and axial components. Axial displacement may be caused due to the axial forces generated by the interaction of the current and the radial component of leakage flux in winding. Short-circuits close to transformer terminals may cause displacement in transformer winding. In addition, as transformer ages, the insulation shrinks and the clamping pressure may then be lost causing a reduction in withstand strength. These severe mechanical stresses will cause the winding to shift axially, split the winding centrally or even collapse some discs. These effects of axial displacement have been investigated experimentally by changing axial height of winding by introducing spacers, i.e. pressboard paper in between the sections.

3.2.1 Effect of Clamping Pressure Changes

The winding of ID 127 mm and AH 280 mm with core are used in this experimental work. The response without any displacement is used as reference fingerprints. The effect of clamping pressure changes is studied by increasing the overall axial height by 5%, 10%, 15% and 20% using spacers of different widths, i.e. 1.5 mm, 3 mm, 4.5 mm, and 6 mm between two sections uniformly throughout the winding. Figure 5 indicates the magnitude response due to effect of clamping pressure changes. Because of the core parameter influence, the resonance and anti-resonance frequencies occur earlier than without core response. There is no deviation of frequency responses for all cases below 600 kHz. It can be observed that the shifts in all the resonance and anti-resonance frequencies from right to left, i.e. there is a decrease in resonance frequency for all the cases of 5%, 10%, 15% and 20% change of AH except in the first resonance and anti-resonance

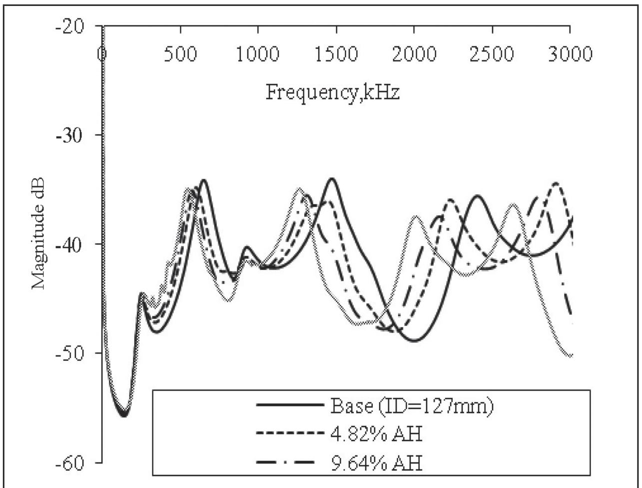

FIG. 5 THE EFFECT OF CLAMPING PRESSURE CHANGES

frequency in 5% change, where shifting is from left to right and non-uniform damping rate for entire frequency range was observed.

3.2.2 Sectional Winding Displacement

This effect of axial displacement has been investigated experimentally by changing axial height (AH) of winding by introducing spacers, i.e. pressboard paper in between the sections. Model transformer winding having ID-127 mm, AH-280 mm along with core is used in this study. The width of the pressboard paper/spacers is increased from 3 mm to 26 mm with an increment of 3 mm at one particular location, thereby increasing overall axial height of winding from 0.54% to 5.36%. The simulations have been carried out at various winding locations i.e. between 1st and 2nd, 3rd, 4th, 6th, 7th, 9th and 10th sections along the height of winding. The corresponding frequency response is taken at each displacement. Figure 6 illustrates magnitude response of sectional winding displacement between 6th and 7th sections. Similarly, magnitude responses for all other sectional displacements were plotted but not shown here for space constraints. The observations made from all the magnitude response plots are outlineds as under:

(a) Between 1st and 2nd sections

- There is no deviation in the magnitude as well as shift in the frequency below 700 kHz for all the cases of displacement. The shifts are clearly visible beyond 700 kHz onwards.
- There is no shift in the first and second resonance frequency (RF) and anti-resonance frequency (ARF). The remaining signature pattern shifts from right to left, i.e. decreases from their respective base frequency. As the displacement increases from 3 mm to 26 mm, the percentage of shifting of frequency increases.
- As far as magnitude deviations are concerned, no change at the first and second RF and ARF is observed. Thereafter, a decreasing damping rate was observed for all the RF and ARF except at fourth and fifth RF.

(b) Between 3rd and 4th sections

- The deviations and shifting are observed clearly beyond 300 kHz onwards for all the cases of displacement.
- There is no shift at first RF and ARF. The remaining signature pattern shifts from right to left, i.e. decreases from their respective base frequency. As the displacement increases from 3 mm to 15 mm, the percentage of shifting of frequency increases.
- As far as magnitude deviations are concerned, no change at first RF and ARF is observed. Thereafter, increasing damping rate for all the RF except fifth and decreasing damping rate for all ARF except fifth were observed.

(c) Between 6th and 7th sections

- The deviations and shifting are observed clearly beyond 300 kHz onwards for all the cases of displacement.
- There is no shift at first RF and ARF. The remaining signature pattern shifts from right to left, i.e. decreases from their respective base frequency. As the displacement increases from 3 mm to 15 mm, the percentage of shifting of frequency increases.
- As far as magnitude deviations are concerned no change at first RF and ARF is observed. Thereafter increasing damping rate for all the RF and ARF except the second ARF where decreasing damping rate was observed.

(d) Between 9th and 10th sections

- There is no deviation in the magnitude as well as shift in the frequency below 600 kHz for all the cases of displacement.
- There is no shift in the first, third and fourth RF and first, second, third ARF. From fifth RF onwards, signature pattern shifts from right to left as well as the percentage of shifting of frequency increases.
- As far as magnitude deviations are concerned no change at first, fourth RF and first, second ARF is observed. The remaining parts of signature pattern have decreasing damping rate.

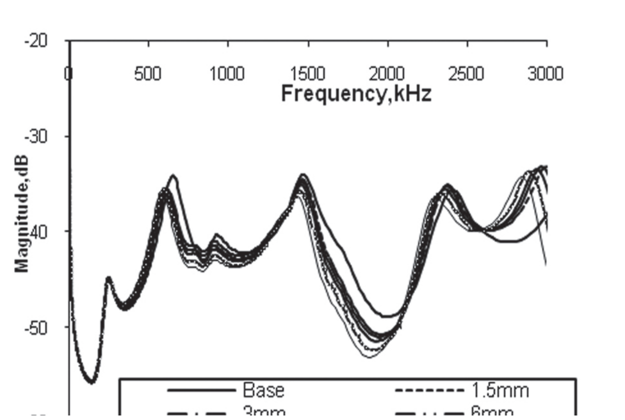

FIG. 6 SECTIONAL WINDING AXIAL DISPLACEMENT IN BETWEEN 6th AND 7th SECTIONS

3.2.3 Comparison of Sectional Winding Displacement at Different Locations

In this study, for the first case, some displacement is introduced using pressboard paper in between first two sections. For the second case, the same displacement is introduced but in next two consecutive sections. The location of displacement is moved along the height of the winding and the corresponding frequency responses are recorded. The objective of this simulation is to study whether it is possible to locate the displacement or not. A displacement of 6 mm is introduced in each case on the transformer winding of ID-147 mm with core. Figure 7 illustrates the magnitude responses of axial displacement at different locations. The overall effect of changes in resonant, anti–resonant and magnitudes for axial displacement at different locations without core is summarized in Table 2. It can be observed that for all the cases, there are no deviations in the responses up to 400 kHz and both the resonance as well as anti-resonance frequency shift from right to left. In other words, the resonance and anti-resonance frequency decreases from their base value irrespective of locations of the displacement. As the location of displacement is moved along the height of the winding, there is no discernible pattern of signature changes. If there displacement at 60% of AH location, there is one eliminating frequency of 4.08 MHz. As the location of displacement is moved along the height of the windings there is no discernible pattern of signature changes. With regard to the magnitude deviations, there is non-uniform damping rate, i.e. increasing and decreasing trends are obtained. Also, the above – said procedure is repeated using 6 mm and 9 mm thickness pressboard paper and similar characteristic signature patterns are obtained.

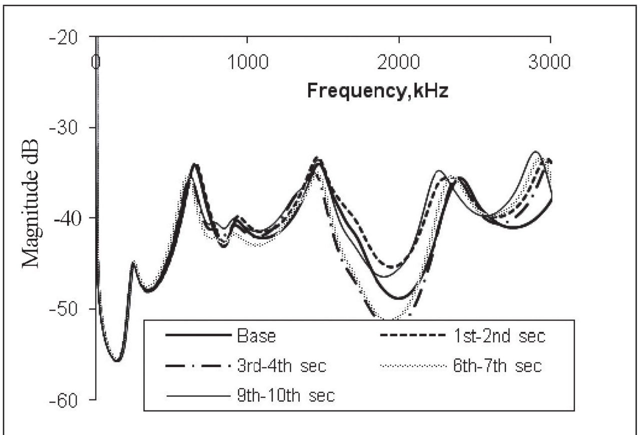

FIG. 7 MAGNITUDE PLOT OF PARTIAL OR SECTIONAL WINDING DISPLACEMENT WITH CORE AT DIFFERENT LOCATIONS IN ID 147 mm (6 mm)

TABLE 2

SECTIONAL WINDING AXIAL DISPLACEMENTS AT DIFFERENT LOCATIONS WITHOUT CORE

Base response		**% Change of resonant frequency comparing with base**								**% Change of magnitude comparing with base**							
Res. freq (Hz)	**Mag (dB)**	**Spacers 3 mm width introduced between the sections**								**Spacers 3mm width introduced between the sections**							
		1st-2nd	**2nd-3rd**	**4th-5th**	**5th-6th**	**6th-7th**	**7th-8th**	**8th-9th**	**9th-10th**	**1st-2nd**	**2nd-3rd**	**4th-5th**	**5th-6th**	**6th-7th**	**7th-8th**	**8th-9th**	**9th-10th**
1.14E+06	–36.28	1.75	–4.39	–5.26	–5.26	–1.75	0.00	1.75	0.00	–3.78	–16.70	–9.73	–10.23	–2.37	–2.56	–3.22	–2.04
1.76E+06	–35.19	–1.14	–4.55	–2.27	1.14	–1.14	–3.41	–2.27	0.00	–5.46	–5.60	1.93	1.59	3.50	–1.42	–4.66	–6.34
2.57E+06	–41.06	–4.67	–5.45	–2.33	–4.67	–1.17	0.00	–4.67	–2.33	–2.02	1.05	–1.92	–1.95	–1.97	–1.85	–0.68	–1.07
3.13E+06	–35.93	–3.19	–2.24	–4.47	1.28	–3.19	0.00	–2.24	–2.24	1.28	7.10	0.17	–3.09	0.25	0.28	5.37	–6.37

Base response		% Change of resonant frequency comparing with base								% Change of magnitude comparing with base							
Anti. Freq (Hz)	Mag (dB)	Spacers 3 mm width introduced between the sections								Spacers 3mm width introduced between the sections							
		1st-2nd	2nd-3rd	4th-5th	5th-6th	6th-7th	7th-8th	8th-9th	9th-10th	1st-2nd	2nd-3rd	4th-5th	5th-6th	6th-7th	7th-8th	8th-9th	9th-10th
9.38E+05	–55.49	–2.19	–11.46	–8.47	–8.47	-2.19	–2.19	0.00	0.00	0.83	–11.41	–8.40	–8.97	–3.28	–1.80	–2.69	–1.21
1.35E+06	–48.03	0.00	0.00	–0.74	–0.74	-0.74	–0.74	–0.74	0.00	-2.23	–3.14	0.58	1.23	1.33	–1.17	–1.81	–2.60
1.90E+06	–59.27	0.00	–1.05	–2.11	1.05	-1.05	–1.05	–2.11	0.00	4.72	10.04	1.72	3.17	–0.57	1.92	5.84	2.83
2.40E+06	–47.91	–3.33	–4.17	–1.25	–2.08	0.00	0.00	0.00	-3.33	8.29	13.92	4.13	10.71	1.31	1.67	9.48	3.40

4.0 Conclusions

Experimental investigations were carried out on model transformer windings specially designed to investigate the sensitivity of frequency responses to various winding movements. Experimental simulation of both axial and radial-winding movements emphasized that even very minor changes are also easily detectable using FRA. Different combinations of readings are taken in order to analyze the FRA response clearly.

- From the experimental results, it was observed that movements in the windings can be observed by the shifts or creations or eliminations of resonant as well as anti-resonance frequencies and magnitude variations, i.e. damping rate in the measured frequency response. The creating or eliminating of one or more resonance as well as anti-resonance frequencies indicates that there were severe faults in the transformer winding.
- For radial displacements, shift in the resonant frequencies is observed in the frequency range 200 kHz to 2.5 MHz, suggesting, significant contribution of both inductive and capacitive components. Radial deformations in the windings shift the resonant frequencies uniformly in the entire range.
- Axial displacement of the windings resulted in shift in a few resonant frequencies beyond 600 kHz and may be attributed to slight change in series capacitance of the windings. For partial/sectional winding axial displacement of windings, it is observed that for every 0.5% increase in axial height,' the shift in resonance frequencies observed is about 1.0%.
- From the case studies of comparison of partial/sectional winding axial displacements at different locations and partial/sectional winding radial displacements at different locations, it was observed that the change of frequency signature as the movement of the locations is changed. There is no discernible pattern to the changes, it is difficult to locate the displacements in the winding. However, it may be possible to use pattern recognition techniques software to provide an identification of the failure location.

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