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Experimental Investigations to Aid Interpretation of Frequency Response Analysis Measurements for Diagnosing Transformers

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Frequency Response Analysis (FRA) is an emerging diagnostic tool to assess the mechanical integrity of the transformer. Proper guidelines on using FRA data for declaring the integrity of transformer windings or indicating the extent of displacement/deformations are not yet available. Interpretations of the Sweep Frequency Response Analysis (SFRA) data for diagnosing the condition of the transformer windings are not yet clear. Experimental investigations were carried out on a model transformer to obtain SFRA data for various simulated conditions like axial and radial displacements, winding displacements and deformation, core faults, etc. for different test configurations. The paper presents the results of these investigations and analyze them to form the guidelines in interpreting the SFRA data for various test conditions to detect various types of faults. It is observed from the analysis of results that SFRA with different test configurations needs to be applied to detect the type of fault and faulty phase winding. The information presented in the paper, from the simulated faults on transformers with SFRA measurements, will be useful in the interpretation of FRA results to assess and diagnose the condition of transformer windings and core.

1.0 INTRODUCTION

High-voltage power transformers are one of the most expensive elements in a power system and their failure is a very costly event. The monitoring and diagnostic techniques, which can evaluate the integrity of transformer, are essential to evolve optimum and better reliability of the equipment. In this regard, several techniques, such as thermal monitoring, oil analysis, partial discharge measurement, capacitance and tan delta measurements, recovery voltage measurements, etc., are applied for transformer, wherein each one is applied for a specific type of problem and have their own merits. These methods are not found to be suitable to monitor and diagnose winding deformations. When a transformer is subjected to high through fault currents, the mechanical structure and windings are subjected to severe mechanical stresses causing winding movement and deformations. It may also result in insulation damage and turn-to-turn faults are most likely. The deformation can also be due to aging of paper. As a transformer ages, the insulation shrinks and the clamping pressure may be lost which inturn reduces its withstand strength. Winding deformations in transformers are difficult to establish by conventional methods of diagnostic tests like ratio, impedance/inductance, magnetizing current, etc.

The main methods to detect winding deformation/displacements are Short Circuit Reactance Measurement (SCRM) method, Low Voltage Impulse (LVI) method and Frequency Response Analysis (FRA) method. In IEC Publication 76–5 [1], the short circuit reactance measurement is described as a diagnostics method to check the integrity of the windings. According to the standard, deviations of the reactance of more than 2 % are

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inadmissible with power transformer rated of 100 MVA and above. Deviations between 1 and 2 % are subject to an agreement between manufacturer and customer. But this reactance measurement is not applicable for detecting winding displacement of power transformers that are already in service due to its low sensitivity.

Many researchers [2–7] have been suggesting the FRA method to recognize the deformation in a transformer. These methods are based on the consideration that transformer is a linear, bilateral, complex and passive network that allows defining one input force and several output gates. Some researchers [2–5] use the time domain frequency response analysis to investigate the deformation; whereas, others [6,7] use frequency domain analysis. Deformation results in relative changes to the internal inductance and capacitance of the winding. These changes can be detected externally by low-voltage impulse method or FRA method. The displacements/deformation will change winding-distributed capacitance and inductance of the windings, and shift the corresponding resonant frequency that can be detected by measuring the frequency response at the terminals of transformer winding. As electrical changes, corresponding to mechanical deformations, can be observed in the measured frequency responses, many researchers have been involved in studies conducted on diagnostic and interpretation of FRA data for the last decades.

Although the FRA method or Transfer Function (TF) method is already commonly used [2–7], research on the optimum, efficient and unambiguous application method for predicting the geometric changes is still in progress. In LVI method, the stability and the repeatability of the impulse voltage are not always good enough. Also, the lower frequency range is limited by the tail time of the applied impulse voltage and the higher frequency range is limited by signal-to-noise ratio. Therefore, frequency range used is restricted between 10 kHz and 1 MHz, resulting in fault interpretation below as well as above this frequency range [2,4]. These drawbacks are overcome by FRA method and therefore it is widely used for detecting winding deformation/ displacements by power utilities [3,5,6].

In general, a small deformation/displacement of windings does not result in an immediate transformer failure, but it may increase the risk of insulation breakdown on next occasion of the overvoltage or short circuit stress and initiate an in-service failure. Therefore, the test of winding deformation/displacement is greatly valuable for the safe operation of transformers. Power utilities are employed to detect mechanical and electrical pre-damages of transformer that is in service in order to improve the reliability.

FRA is a comparative method which compares the measured present response with the reference fingerprints. This method is known as a time-based comparison. If there are any significant deviations in the results, the transformer is said to be faulty one and appropriate action has to be taken. In case reference fingerprints are not available, then other information has to be taken for comparison, i.e. type-based comparison, and construction-based comparison.

FRA results are sensitive to a variety of winding faults and are presumed to be less dependent on previous reference measurements. However, there are no guidelines on using FRA data for declaring the integrity on transformer windings, either for short circuit tests or indicating the extent of displacement/deformations.

In this paper, experimental work carried out on model transformer for various simulated faults like shortened turns, axial and radial displacements, winding displacements, core faults, etc. using Sweep Frequency Response Analyzer (SFRA) equipment for various test configurations is presented. Results are analyzed to investigate the possibility to form interpretation guidelines on various test conditions in framing SFRA method for its application in diagnosing the condition of the transformers.

2.0 DETAILS OF TEST SPECIMEN, TEST EQUIPMENT AND TEST PROCEDURE

In order to study the various aspects of FRA, 11 kV/433 V, 3 phase, 1 MVA core and coil assembly was selected. The HV winding is of disc type with 780 turns per limb suitably placed in 40 discs. The LV winding is spiral winding with 17 turns placed in two layers. Figure 1 shows a view of the test specimen used in this study.

FIG. 1 A VIEW OF THE MODEL TRANSFORMER

The SFRA instrument is provided with inbuilt processor for data storage, processing and display. The instrument has a frequency range of 10 Hz to 10 MHz with 1250 logarithmically spaced data collection. Figure 2 shows the schematic of the SFRA measurements on transformers.

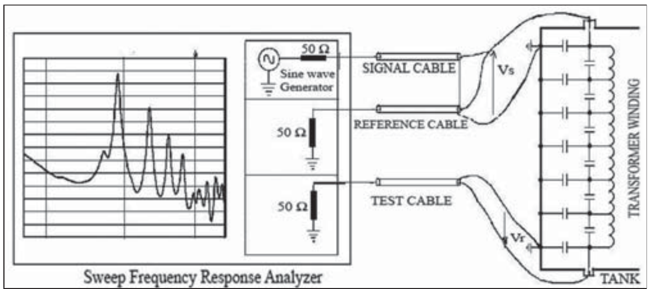

FIG. 2 SCHEMATIC OF THE EXPERIMENTAL SETUP FOR SFRA MEASUREMENTS

Some work has been done to compare the relative sensitivities of different connection techniques [8]. It is important to note that the variation in FRA responses introduced by different types of faults is detected by certain type of measurements with a greater sensitivity. There are varieties of measurements that can be made, viz., voltage transfer between windings, impedance/ admittance or attenuation across windings. Some of the common types of test connections, which are found to be very sensitive to different types of faults in a transformer, employed in SFRA measurements are listed below [8].

End-to-end (open) measurement: In end-to-end (open) test configuration, the input signal is applied to one end of the winding and the transmitted signal at the other end of the same winding is measured. All other terminals of the transformer are left open.

End-to-end (short circuit) measurement: In end-to-end (short circuit) test configuration, the input signal is applied to one end of the winding and the transmitted signal at the other end of the same winding is measured with all other terminals on the secondary side being short circuited.

Capacitive inter-winding measurement: In this test configuration, input test signal is applied to one phase terminal of a winding and the response is measured on the corresponding secondary terminal of the same limb. All other terminals of the transformer are left floating.

Inductive inter-winding measurement: In this test configuration, input test signal is applied to a terminal on the HV side and the response signal is obtained on the corresponding terminal on the LV side. Other end of both windings being grounded to measure the single phase turns ratio.

3.0 RESULTS AND DISCUSSION

Short circuits close to transformer terminals may cause displacement in transformer winding. The electromagnetic driving force exerted on the winding can be resolved into radial and axial components [9]. The radial forces act outwards on the outermost winding and reacted by tension in the conductors and inwards on the innermost winding. The axial forces will shift the winding axially or split the winding medially and even collapse some discs [9]. In addition, as transformer ages, the insulation shrinks and the clamping pressure may then getreduce reducing short circuit withstand strength. These severe mechanical stresses cause winding movements and deformations. As damaged windings are rarely available, effects of displacements/deformations have been investigated experimentally by simulating these faults to investigate and aid in the interpretation of the SFRA data. Various faults like axial and radial displacements, winding deformations like shorting of winding turns/disc and core-related faults were simulated in the investigations.

Number of frequency response measurements are possible with the above-mentioned type of terminal connections for a two-winding transformer. Magnitude response (dB) has been plotted for the frequency range of 20 Hz to 2 MHz. Various types of faults are created to study the sensitivity of these test configurations to detect and identify the fault. The results for each of the case are presented in the following section. In all the case studies, reference magnitude response is the response of the transformer winding without fault, shown with dotted line in all the frequency response plots, which is compared with magnitude response for a particular type of simulated fault, shown with solid line, for the same test connection.

3.1 Radial Displacements

Ocuring to the external through fault, the electromagnetic driving force acts on the winding in radial direction, i.e. this force acts outwards on the outermost windings and is reacted by tension in the conductors, and acts inwards on the innermost winding which causes radial deformation or displacements.

In order to simulate radial displacement of transformer windings, an aluminium foil of about half round was wrapped around B phase limb of HV winding and connected to earth. This arrangement will non-uniformly reduce the radial clearance of B phase of HV winding to the ground. Figure 3 shows the view of the transformer, showing the simulation of radial movement. Figure 4 shows end-to-end (open) frequency response for the HV-B winding, indicating the base response and response with radial movement. It can be observed that the frequency response with fault largely deviates from its base response from about 200 kHz to even up to 1 MHz throughout. It can also be said that radial displacement results in resonant frequency shifts in winding throughout in a mid frequency range for end-to-end (open) measurement responses. However, it was observed that responses for other phases with other test conditions did not show major deviations from their base reference responses.

Figure 5 shows the inductive inter-winding measurement response of B phase limb, indicating the insensitivity of these test conditions for radial displacement kind of faults.

FIG. 3 A VIEW TO SHOW SIMULATION OF RADIAL DISPLACEMENT

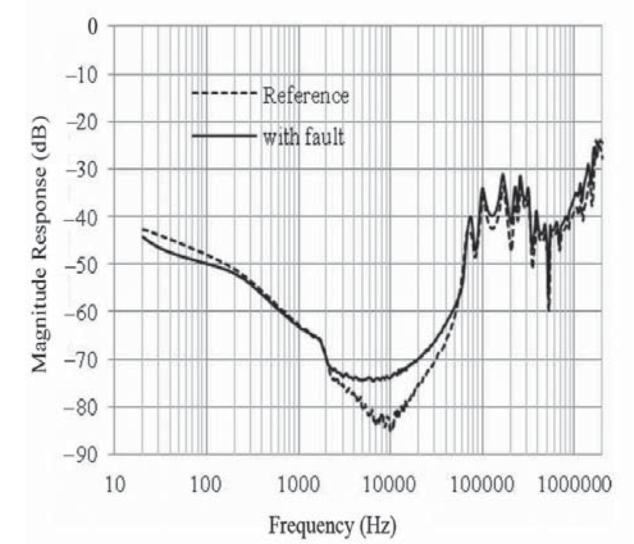

FIG. 4 END-TO-END (OPEN) FREQUENCY RESPONSE FOR THE HV-B WINDING WITH RADIAL MOVEMENT

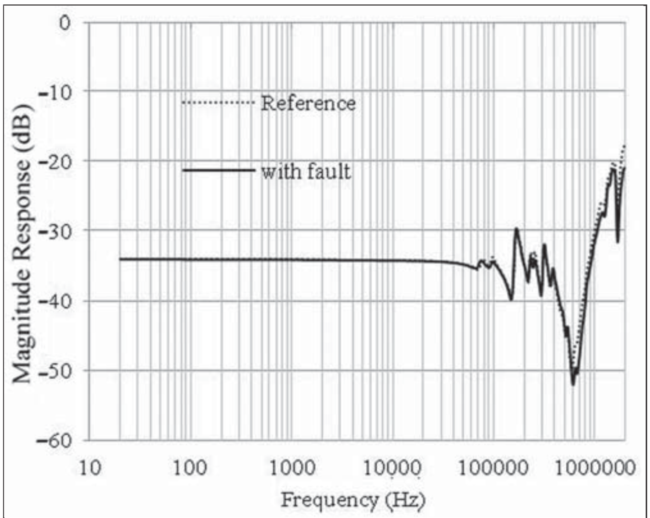

FIG. 5 INDUCTIVE INTER-WINDING MEASUREMENT RESPONSE OF W-PHASE LIMB FOR RADIAL DISPLACEMENT

3.2 Axial Displacements

Axial deformation may be caused due to the axial forces generated by the interaction of the current and the radial component of leakage flux in winding. These effects are studied by simulating change in the axial height of winding in the model transformer.

The mild steel clamping ring is placed at the top end of winding between the wooden ring and top clamping structure, and supported by insulating wooden stiffeners to give the axial mechanical strength. The clamping ring is earthed. Reduction in axial clearances for HV and LV winding was simulated by removing the earth connection to the clamping ring. This will result in a small reduction in ground capacitance. Figure 6 gives the end-to-end (open) HV-R winding response, indicating medium frequency range between 30 kHz and 300 kHz with a dominant shift in resonant frequencies and relatively small shift in resonant frequencies between 400 kHz and 600 kHz. Similar changes are observed in end-to-end other HV and LV winding responses. Variations in frequency responses for these test conditions for a small change in radial capacitive component resulted in a shift in certain resonant frequencies for these test configurations. The end-to-end (open) responses are found to be sensitive in medium frequency range for an axial displacement type of faults in a transformer.

3.3 Shorting of Winding Turns

A decrease in number of turns in practice can be due to damage to the insulation between two adjacent turns, thereby electrically touching each other. This can be due to the impact of large mechanical forces developed when the transformer sees through fault. Short-circuiting of a few turns at any point in the disc will reduce the inductance. In order to study the variation of inductance, change, which may be caused due to minor mechanical damage to the winding resulting in shorting of adjacent turn in the winding, experiments were conducted by short-circuiting a turn in various discs of the HV winding. Short-circuiting a turn will also change the inter-turn capacitance. However, the change in capacitance is small compared to the extent of change in inductance.

One turn fault was created by shorting two adjacent turns in the HV-R phase limb. Figure 7 shows end-to-end (open) measurement frequency responses for base response and with one turn fault. The frequency response with a turn fault deviates largely from the base response at low frequencies up to 40 kHz, indicating a certain fault. Lowering of inductance due to shorting of turns, thereby reducing the inductive impedance, increases the amplitude (lower attenuation of the signal), which resulted in a variation in frequency response at low frequencies.

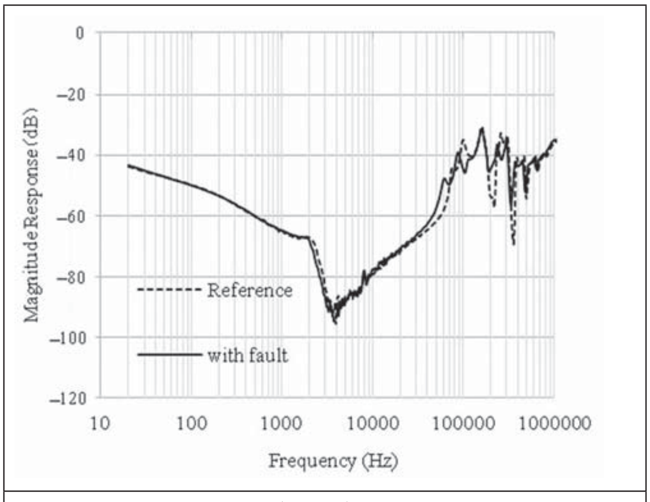

FIG. 6 END-TO-END (OPEN) WINDING RESPONSE OF R PHASE HV WINDING FOR AXIAL DISPLACEMENT

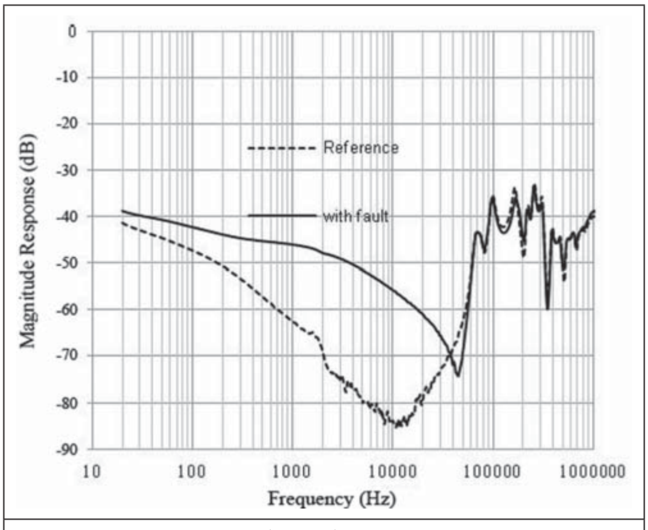

FIG. 7 END-TO-END (OPEN) SFRA WITH ONE TURN FAULT IN R-PHASE OF HV WINDING

It can also be observed from the reference magnitude plot (dotted line) with end-to-end (open) test configuration shown in Figure 7 that at low frequencies, the magnitude response decreases considerably as the frequency increases up to 1 kHz. The phase plots start (not shown due to limitation of space) with –90° as the winding behaves as an inductor and influence of capacitance is negligible. Therefore, the magnitude and phase (by the transfer function) response of the low-frequency sinusoidal signal, passing through the winding, are determined by inductive and resistive nature of the network. The magnetic circuit of the core determines the inductive characteristics, and the resistance of the output measuring cable determines resistive characteristics. As the frequency of the input signal increases, the capacitive effects begin to dominate in the region above 1 kHz. Beyond this, magnitude of the high-frequency sinusoidal signals, passing through the winding, is determined by inductive and capacitive nature of the network. In high-frequency region, the inductive characteristics are determined by the leakage flux coupling, and the capacitive characteristics are determined by the various capacitive elements associated with individual turns. The propagation characteristic of the winding becomes complex as a result of many resonance frequencies found in high-frequency range. As the frequency increases further (over 100 kHz), the sinusoidal signal travels mostly outside the winding and reflects from the other elements found in the transformer, e.g., leads, support insulation, etc. The magnitude and phase of the transfer function in that frequency region are influenced by the inductive/capacitive/resistive nature of these elements.

Similarly, it is also observed that the frequency responses of other two phases, viz., Y and B of delta-connected HV windings, also resulted in a deviation in frequency responses from the base response for the fault created in R-phase winding (these responses are not shown due to limitation of space). This is due to the fact that HV winding is connected in delta and shorting of a turn in R-phase also results in variations in response of other phases. However, deviation in R-phase response with a turn fault was much higher from the other two responses from their base reference responses, respectively.

Figure 8 shows end-to-end (short circuit) frequency responses for base response and with one turn fault in HV-R phase. These two responses closely match up to 40 kHz. However, it can be seen in Figures 7 and 8 that for frequencies beyond 40 kHz, responses with fault have negligible deviation from their base responses.

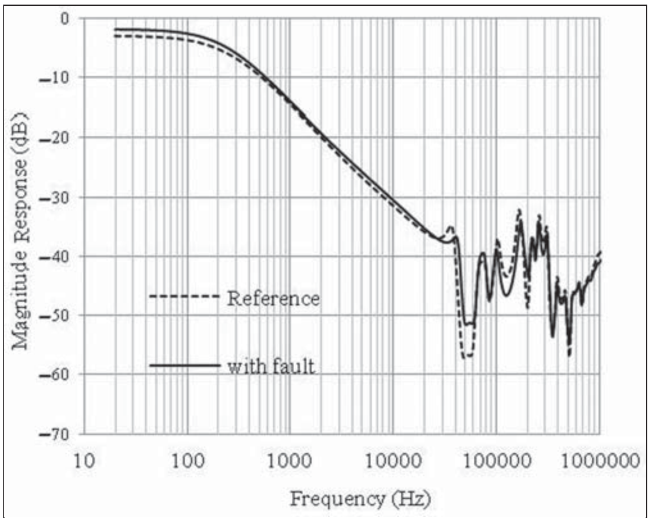

FIG. 8 END-TO-END (SHORT CIRCUIT) FREQUENCY RESPONSES WITH ONE TURN FAULT IN HV-R PHASE

It was also observed that the frequency responses with end-to-end (open) and end-to-end (short) responses fairly match beyond 40 kHz. This indicates that end-to-end (open circuit) measurements are sensitive to turn faults case and end-to-end (short circuit) measurements do not give any indication of turn faults in a transformer at frequencies below 10 kHz.

Figure 9 shows end-to-end (open) frequency response measurement for LV winding, indicating a base response and one turn fault in HV winding.

It can be seen from this figure that the response in LV winding also deviates from its base response largely at low frequencies up to about 20 kHz. By seeing the graph, it may be concluded that the fault is in LV winding which is not true. This is because of the delta-connected HV winding, resulted in corresponding deviation in frequency response for end-to-end (open circuit) responses of LV winding also. From above discussions it can be concluded that the fault in HV winding will also result in a considerable change in corresponding phase of LV winding for a delta-connected transformer.

Figure 10 shows capacitive inter-winding measurements for one turn fault in HV-R phase limb. It can be observed that for frequencies between 1 kHz and 20 kHz, there is a detectable deviation in the frequency response and fairly matches in other frequency range. However, for other capacitive inter-winding measurements, no appreciable deviation is observed.

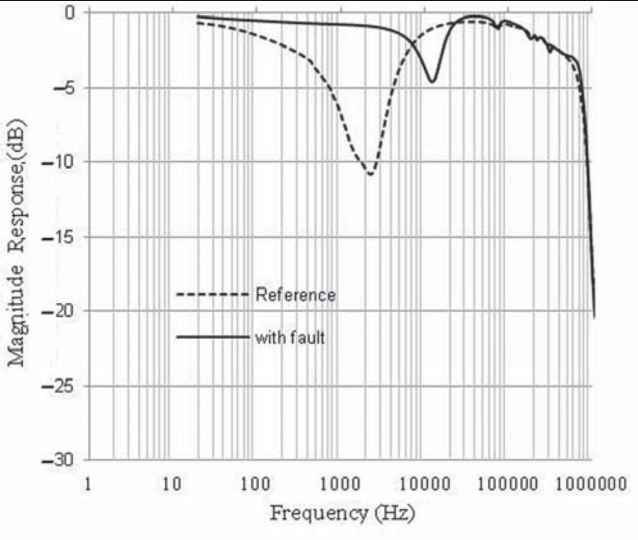

FIG. 9 END-TO-END (OPEN) FREQUENCY RESPONSES FOR LV-R WINDING WITH A TURN FAULT IN HV-R WINDING

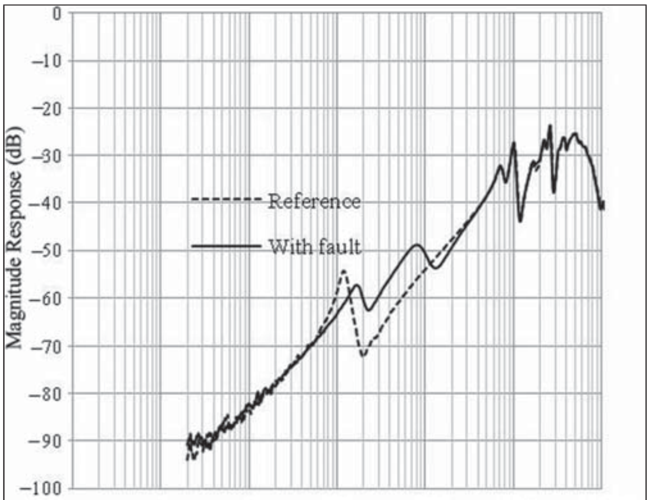

FIG. 10 CAPACITIVEINTER-WINDINGMEASUREMENTS FOR ONE TURN FAULT IN HV-R PHASE LIMB

3.4 Winding Deformations

In order to study the major mechanical damage to the winding structure resulting in a major deformation in the winding, two discs of a particular HV winding of the transformer were physically shorted. Short-circuiting a disc comprising of several turns will change the self and mutual inductance as well as the self capacitance of the winding.

Figure 11 shows end-to-end (open) measurement frequency responses for the reference and with one disc fault in R-phase of HV winding. It is observed that the frequency response with one disc fault deviates largely from its reference at low frequencies up to about 40 kHz. Similarly, responses for other test configurations were recorded, and it is observed that all are similar to the case of turn faults. It is observed that there are no much large deviations in respective responses when a single turn fault response is compared with a disc fault response. However, such type of faults can be easily identified with simple ratio tests.

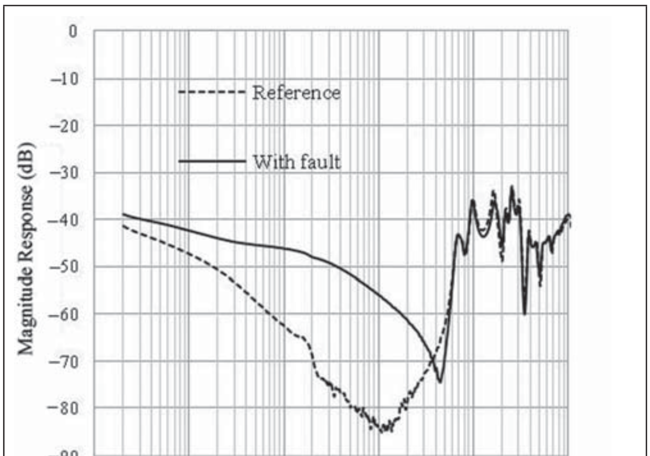

FIG. 11 END-TO-END (OPEN) MEASUREMENT FREQUENCY RESPONSES WITH ONE DISC FAULT IN HV-R PHASE

3.5 Winding Displacements

In order to study the minor displacements within the winding, a 2500 pF capacitor was connected across the first and second disc of R-phase of

HV winding to simulate the change in capacitance values of the winding. The influence on this change in winding on frequency responses was investigated. Figure 12 shows end-to-end (open) measurement frequency response for reference and capacitor connected across two discs. It is observed that there is a small change in low frequency around 10–40 kHz and considerably larger variations in the responses between 150 kHz and 650 kHz. The changes in low frequencies can be attributed to shorting, i.e. external connection of capacitor and significant changes in high frequencies can be attributed to capacitive changes in a transformer. It is also observed that the variations in response in other test connections are insignificant. Hence, end-to-end (open) test condition is found to be more sensitive for the capacitive changes, with observed changes are more significant beyond 150 kHz, for the transformer winding compared to other test conditions. All other test conditions, except LV winding responses (not shown), did not indicate any deviations in frequency responses. LV-R winding response indicated changes in the frequency response beyond 500 kHz for a capacitive change in HV-R limb. Impedance measurements at 1 kHz did not show deviation in values by more than 2 % for any of the test conditions, indicating the insensitivity of these measurements at 1 kHz to detect minor capacitive changes in the windings.

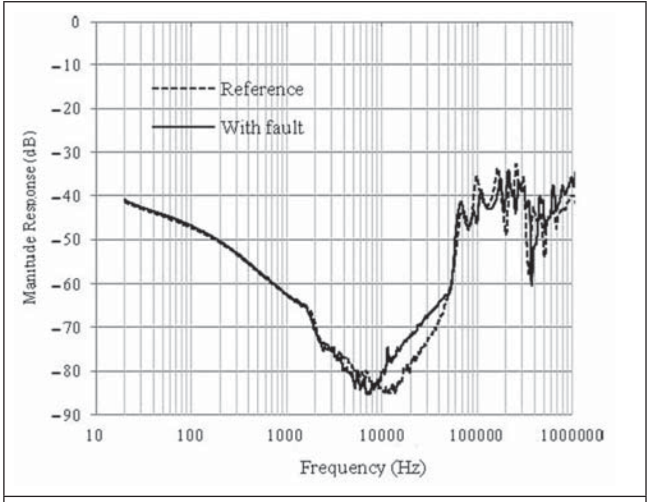

FIG. 12 END-TO-END (OPEN) MEASUREMENT FOR A CAPACITOR CONNECTED ACROSS TWO DISCS OF R-PHASE HV WINDING

3.6 Core-Related Issues

In order to study the sensitivity of frequency responses for identifying the improper core earth of the transformer, copper strip connection of core to earth was disconnected. Figure 13 shows end-to-end (open) frequency response measurement for and LV-R phase limb with a base reference and with a core earth disconnection. A small shift in frequency responses throughout up to 2 kHz can be observed. Beyond 2 kHz, there was no appreciable shift in the responses up to 1 MHz, indicating that the core earth irregularities will result in uniform shifting of frequency responses below 2 kHz in end-to-end (open) winding responses. Similarly, end-to-end (open) of HV side responses also resulted in similar shifts. From the above discussion, it can be observed that end-to-end (open) measurements resulting in shift of frequency response up to 2 kHz are indicative of improper core earth or core-related issue in transformers.

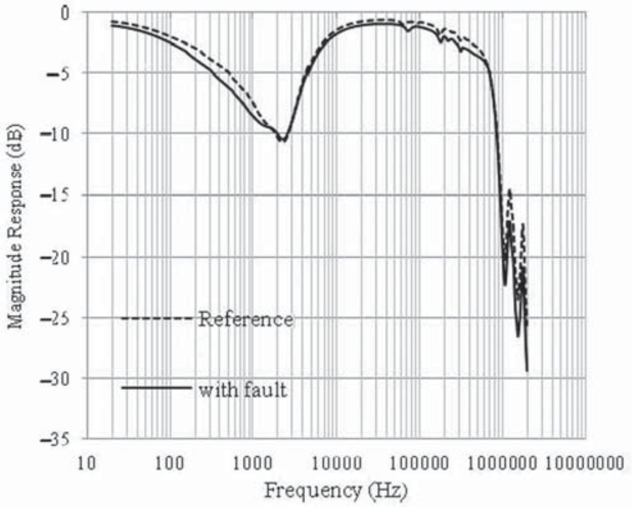

FIG. 13 END-TO-END (OPEN) FREQUENCY RESPONSE MEASUREMENT FOR AN LV-R PHASE LIMB

4.0 CONCLUSIONS

Experimental investigations were carried out on 1 MVA, 11 kV/433 V, Δ –Y, 3 phase transformer assembly. Various simulated faults like shorted turns, axial and radial displacements, winding displacements, core faults, etc., were created to obtain the SFRA data using SFRA equipment for various test configurations and analyzed.

The most obvious visibility of damages to the transformer can be detected in the characteristic of dominant resonant frequencies. If there is a deviation in one or more dominant frequencies from its reference, there will be satisfactory sensitivity for the damage according to the presented results.

The following conclusions are drawn from the results of the experimental investigations carried out.

For radial displacements, shift in the resonant frequencies is observed from about 200 kHz to even up to 1 MHz, suggesting a significant contribution of both inductive and capacitive component for end-to-end (open) test configuration. It is also observed that the frequency response with radial displacement fault largely deviates from its base response uniformly throughout from 2 kHz to 1 MHz for end-to-end (open) measurement responses. Frequency responses in inductive inter-winding and capacitive inter-winding test configurations were insensitive to detect the radial displacements.

Medium frequency response in the range from about 30 kHz to even up to 500 kHz is more sensitive to detect axial displacement faults for end-to-end (open) test configuration. A significant increase in the medium frequency resonance indicates axial movement in continuous disc winding.

Minor shorting of turns and major winding deformations results in a large variation in responses below 40 kHz with end-to-end (open) measurements. For delta-connected windings, the fault in HV winding will also result in variations in LV winding responses.

Change in winding self capacitances in a transformer due to winding displacements is found to have resulted in significant changes in frequencies between 150 and 650 kHz with end-to-end (open) measurements.

A small shift in frequency responses throughout up to 2 kHz was observed for end-to-end (open) test conditions, indicating its sensitivity to detect core earthing irregularities.

It was observed that the frequency responses with terminals floating, i.e. end-to-end (open), are very sensitive to detect the deformations within the windings. It is also observed from the analysis of results that under different simulated fault conditions, FRA with different test configurations can be applied to identify the faulty condition and can form a better tool in assessing the integrity of the transformer.

The results and information presented from these investigations will be useful in the interpretation of FRA results in condition assessment of the transformers. However, more work in this direction needs to be done to form an acceptance criterion on FRA measurements to identify the defect, assess the extent of damage and declare the integrity of transformer windings.

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