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Detecting Winding Displacement and Deformation in Transformers

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ABSTRACT: The paper presents experimental studies carried outon a three phase transformer to investigate the sensitivity of Sweep Frequency Response Analysis (SFRA) measurements for detecting faults in transformers. Number of test conditions were applied to obtain the frequency responses of a transformer for different type of faults simulated in a particular phase. The frequency responses were analyzed for the sensitivity of different test conditions to detect and identify the fault. It is observed that the different test conditions need to be employed to identify the type of fault and faulty winding. The experimental results presented in the paper will help in understanding the sensitivity of SFRA measurements in detecting various types of faults in the transformer.

I. INTRODUCTION

Large power transformers belong to the most expensive and strategically important components of any power generation and transmission system and their failure is a very costly event. Deformation / displacement of winding assemblies are caused by stresses originating from mechanical vibrations during transport or by magnetic forces evoked by external short-circuit currents and ageing [1]. Prediction of winding movement/deformation is very valuable for the safe operation and better planning of maintenance of transformer in service and to improve its reliability. In IEC 76-5 standard [2] short circuit reactance measurement is described as a diagnostic method to check the mechanical integrity of the winding. Main methods used for detecting winding deformation/ displacements are frequency response analysis (FRA) method [1,3] using sweep frequency voltage source and transfer function (TF) method [4] using a low voltage impulse source. 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 [5].

All the conventional FRA techniques are based on graphical analysis for diagnosis, which requires trained experts to interpret test results in order to identify both the failure and failure tendencies in the transformer. Therefore, conclusions will differ depending on the personnel experienced in interrupting the FRA data. In CIGRE SC-12 Budapest Colloquium, it is reported that some interpretation of FRA results are not so clear and failure criteria is uncertain [6]. 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 systematic guidelines for interpretation of theFRA results and more needs to be studied, collect field data by conducting measurement at site and analyze them for an objective and systematic interpretation methodology.

Attempts have been made and are being continued to develop an evaluation method that can be applied by inexperienced personnel using numerical methods [7,8]. The paper presents FRA measurement work carried out on number of power transformers at various sites involving problems like Shorted turns, Sister Units comparison, Influence of bushing, Core magnetization, Core related problem, OLTC problem and winding displacements.. Numerical evaluation techniques to compare different phase windings of the same transformer or sister units for interpreting frequency response measurement data is also attempted. The results presented in the paper will help in interpreting the FRA data based on the phase comparison/sister unit comparison, even in the absence of fingerprints, in order to assess the condition of the transformer.

II. DETAILS OF TEST EQUIPMENT AND TEST PROCEDURE

FRA measurements were carried out using Sweep Frequency Response Analyzer (SFRA) instrument. The experimental setup to carry out FRA measurements is shown in Fig.1. Different type of test conditions with tested and non tested terminals are applied to obtain various frequency responses in order to detect the faulty winding and type of fault. Some work has been done to compare the relative sensitivities of different connection techniques [9]. It is important to note that the variation in FRA results is introduced by different type of faults which are detected by certain type of measurement with greater sensitivity. Some of the common type of test connections, which are found to be very sensitive to different type faults in a transformer, employed in SFRAmeasurements are listed below are explained in [9].

a) End-to-end (open) measurement
b) End-to-end (short-circuit) measurement
c) Capacitive inter-winding measurement.
d) Inductive inter-winding measurement

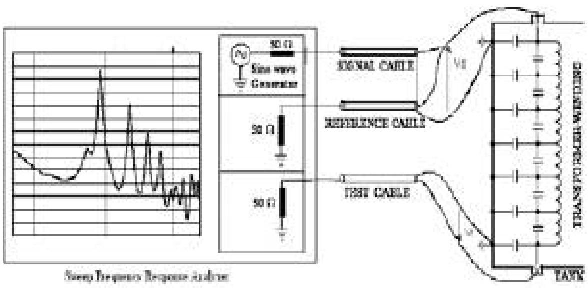

Figure1: Twse Schematic diagram for SFRA measurements

III. NUMERICAL TECHNIQUES USED

Interpretation of the frequency responses on graphical display requires experts to locate a problem in the transformer. For inexperienced personnel, numbers come in handy to detect the problem based on some criterion given to them. Recent literature survey indicates three important numerical techniques [for the detection of a defect. They are Correlation Co-efficient (CC), Standard Deviation (SD) and Absolute Sum of Logarithmic Error (ASLE) computed by using equations 1, 2 and 3 respectively given below.

$$CC_{(X,Y)} = \frac{\sum_{i=1}^{N} X(i)Y(i)}{\sqrt{\sum_{i=1}^{N}[X(i)]^2 \sum_{i=1}^{N}[Y(i)]^2}} \qquad \text{.........(1)}$$

$$SD_{(X,Y)} = \sqrt{\frac{\sum_{i=1}^{N}[Y(i)-X(i)]^2}{N-1}} \qquad \text{.........(2)}$$

$$ASLE_{(X,Y)} = \frac{\sum_{i=1}^{N}\left|20\log_{10} Y(i) - 20\log_{10} X(i)\right|}{N} \qquad \text{.........(3)}$$

Where X(i) and Y(i) are the i^{th} elements of reference fingerprint and measured frequency response, respectively using SFRA. 'N' is the total number of samples in the frequency response. Ideally for the perfect match of frequency responses, the ASLE shall be 0, SD shall be 0 and CC shall be 1.

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IV. CASE STUDIES

FRA results presented in the following cases is based on the comparison of frequencyresponses of different phases of the same transformer and comparison of frequency responses of sister units wherever they were available. In all the case studies, terminations designations indicated in the figures are uniformly indicated as: H or U/V/W for HV, X for LV and Y for tertiary. SC denotes short circuit (end to end short circuit response) and E denotes earthed (inductive inter winding response). Terminals are designated as ‘1’ for ‘A’, ‘2’ for ‘B’ and ‘3’ for ‘C’ phase terminal. Numerical parameters are computed in three free frequency bands - Band 1 (10Hz–10kHz), Band 2 (10kHz- 100kHz) and Band 3(100kHz-1MHz). In case of three phase transformers middle limb frequency response is considered as reference.

Case 1: Shorted turns

One turn fault was created by shorting two adjacent turns in the U limb of HV winding. Figure 3 gives end to end (open) measurement frequency responses for base response & with one turn fault. It can be observed that the frequency response with turn fault deviate largely from the base response at low frequencies up to about 40 kHz indicating certain fault. Lowering of inductance due to shorting of turns, there by reduction in inductive impedance, increases the amplitude (lower attenuation of the signal) which resulted in variation in frequency response at low frequencies.

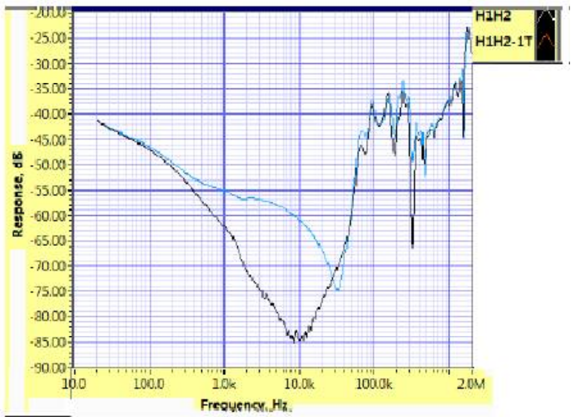

Figure 2: End to end (Open) frequency with one turn fault in U phase of HV winding.

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

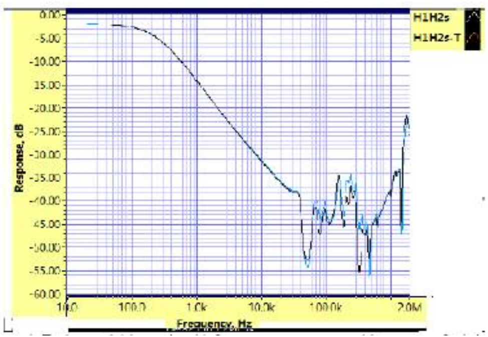

Figure 3: End to end (short-circuit) frequency responses with one turn fault in U phase of HV winding.

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Fig (4) gives end to end (short-circuit) frequency responses for base response & with one turn fault in U phase of HV winding. These two responses closely match up to 40 kHz. However, it can be seen in Fig. 3 & Fig. 4 that for frequencies beyond 40 kHz, responses with fault deviate marginally from their base responses. It was also observed that the frequencyresponses with end to end (open) & 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 & end to end (short circuit) measurements does not give any indication of turn faults in a transformer at frequencies below 10 kHz. It is also observed that capacitive winding measurement & inter inductive winding measurement responses with turn fault fairly match with their base response, thus indicating the insensitivity of these test configurations to indicate small faults.

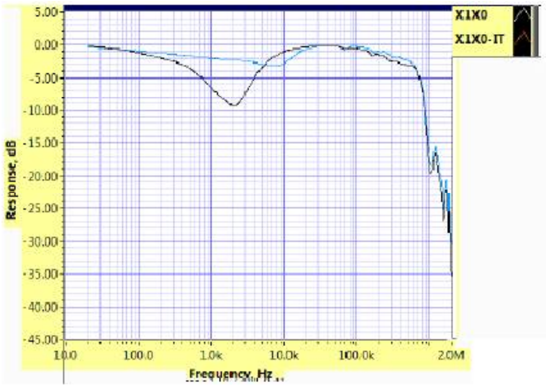

Figure 4: End to end (open) frequency responses for LV winding with turn fault in HV winding

Figure 5 gives end to end (open) frequency response measurement for LV winding indicating base response & one turn fault in HV winding. It can be seen from Fig.5 that, the response in LV winding also deviates from its base response largely at low frequencies up to about 40 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 considerable change in corresponding phase of LV winding for a delta connected transformer.

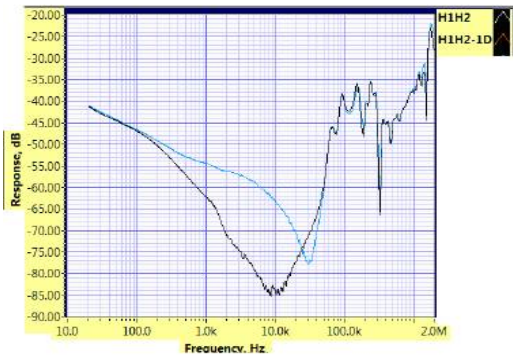

Figure 5: End to end(open) measurement frequency responses with one disc fault in U-phase of HV winding

Case 2: Disc faults

Figure 6 gives end to end (open) measurement frequency responses for the reference & with one disc fault in U – 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. Hence, similar observations as given for the case with one turn faults do hold good for disc faults. Comparison of single turn fault response & disc fault response with their base responses, it is observed that there is no much large deviations. Hence difficulty in identifying the extent of shorted turn fault.

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Case 3: A Capacitor connected across two discs

A 2500 pF capacitor was connected across 1st and 2nd disc of U phase of HV winding to simulate change in capacitance values of the winding and study the influence on frequency responses. Fig (7) gives end to end (open) measurement frequency response for reference and capacitor connected across I & II discs of U-phase HV winding. It is observed that, there is a small change in low frequency around 10 to 40 kHz and considerably larger variations in the responses between 150 kHz to 650 kHz. The changes in low frequencies can be attributed to shorting ie external connection of capacitor & 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 sensitivefor the capacitive changes, with observed changes are more significant beyond 150 kHz, for the transformer winding as compared to other test conditions.

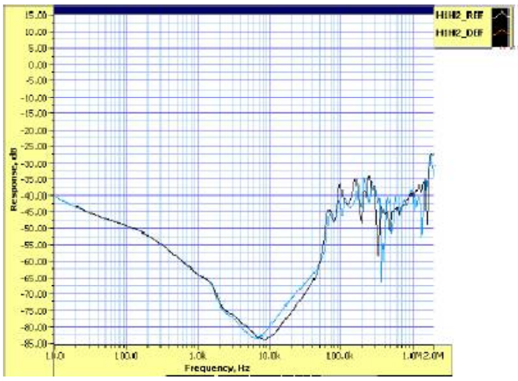

Figure 6: End to end (open) measurement for capacitor connected across I & II discs of U-phase HV winding

Case 4: Radial displacements

In order to simulate radial displacement of transformer windings, an aluminum foil of about half round was wrapped around W phase limb of HV winding and connected to earth. This arrangement will reduce the radial clearance of W–phase of HV winding to the ground. Figure 8 shows the view of the transformer, showing the simulation of radial movement. Figure 9 gives end to end (open) frequency response for the W-limb of HV winding indicating base response & response with radial movement. It can be observed that the frequency response with fault largely deviates from its base response about 2 kHz up to 1 MHz uniformly throughout. However it was observed that responses for other phases with other test conditions did not show major deviations from their base reference responses.

Figure 7: A view to show simulation of radial displacement.

Figure 10 gives the inductive inter winding measurements response of W phase limb indicating the insensitivity of these test conditions for radial displacement kind of faults. 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.

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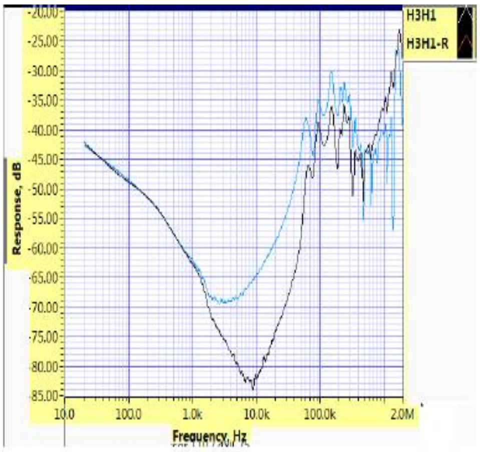

Figure8: End to end(open) frequency response for the W-limb of HV winding with radial movement

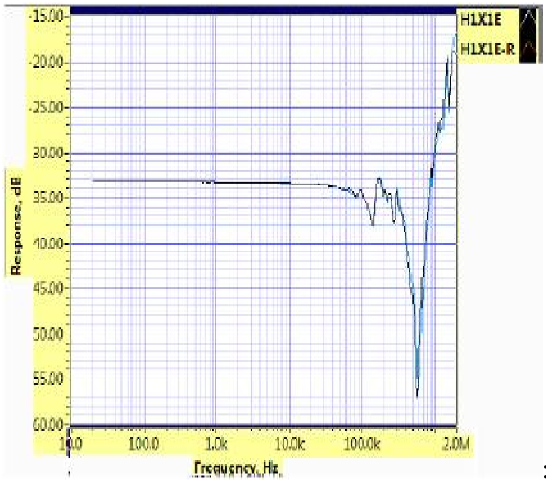

Figure 9: Inductive inter winding measurement response of W-phase limb for radial displacement.

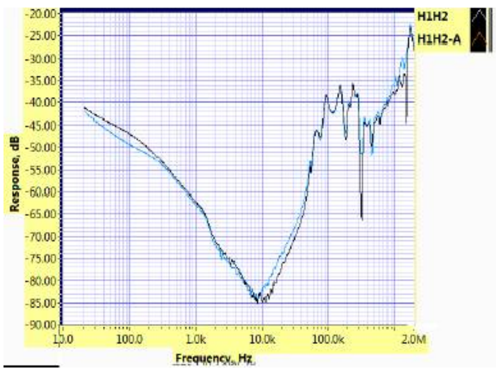

Figure 10: End to end (open) winding response of U phase HV winding for axial displacement.

Case 5: Axial displacements

Reduction in axial clearances for HV & LV windings was simulated by removing the earth connection to the clamping rings. This will result in a small reduction in ground capacitance. Figure 11 gives the end to end (open) winding

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response indicating small changes in the low frequency up to 30 kHz & relatively small changes between 400 kHz to 600 kHz frequency. Similarly Figure 12 shows capacitive inter winding measurement for U-phase limb. It can be observed that, the frequency responses vary from its base response up to 200 KHz. The variations for frequency responses for these test conditions for a small change in capacitance component resulted in a shift in certain resonant frequencies for these test configurations. The end to end (open) responses are sensitive in medium frequency range and capacitive inter winding responses are sensitive up to 200 kHz for axial displacement type of faults in a transformer.

Figure 11: Capacitive inter winding measurement for U-plane limb for axial displacement.

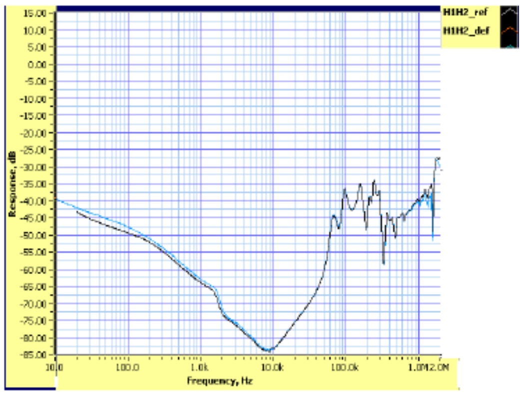

Figure12: End to end(Open) frequency response measurement for U-phase limb with core earth disconnection

Case 6: Improper core earth

In order to study sensitivity of frequency responses for identifying the improper core earth of the transformer, copper strip connection of core to earth was disconnected. Figure 13 gives end to end (open) frequency response measurement for U – phase limb with base reference and with core earth disconnection. A small shift in frequency responses throughout up to 10 kHz can be observed in Fig. 13. Beyond 10 kHz, there was absolutely no change in the responses up to 1 M Hz indicating that, the core earth irregularities will result in uniform shifting of frequency responses below 10 kHz in end to end (open) winding responses. Similarly end to end (open) of LV also resulted in similar shift. From the above discussion, it can be observed that end to end (open circuit) measurements resulting in shift of frequency response up to 10 kHz are indicative of improper core earth or core related issue in transformers.

IV. CONCLUSION

Experiments were carried out on 1000 kVA, 11 kV/433V, Delta/star, three phase transformer core and coil assembly to investigate the sensitivity of frequency responses for various test configurations. Number of test conditions was applied to obtain the frequency responses of a transformer for different type of simulated faults. The sensitivity of frequency responses obtained and analyzed for their sensitivity to detect and identify the faulty winding.

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It was observed that, end to end (open) frequency responses are very sensitive to detect the faults within the windings. Shorted turns and disc faults result in 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 is found to have resulted in significant changes in frequencies between 150 to 650 kHz. It is also observed that the frequency response with radial displacement fault may largely deviates from its base response uniformly throughout up to 1 MHz It is also observed that, end to end (open) responses are sensitive in medium frequency range and capacitive inter winding responses are sensitive up to 200 kHz for axial displacement type of faults in a transformer. A small shift in frequency responses throughout up to 10 kHz was observed for end to end (open) test conditions indicating its sensitivity to detect core earth irregularities. Hence, to identify the particular winding, it is found essential to analyze all the traces of frequency responses. The frequency response of the winding giving higher degree of variation from the reference can be confirmed as a faulty winding. The data and information provided will be useful in the interpretation of FRA data that in turn help in the condition assessment of the transformers. However, more data on the onsite FRA measurements are needed with different faulty conditions correlated withphysical verifications of the transformers to identify the problem and validate the interpretation.

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