New Methodology for Enhancement of Residual Life of Power Transformers

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Abstract— **The measurement of the frequency response of power transformers is a diagnostic methodology for detecting winding deformation and core displacement (along with other mechanical and electrical diagnostic methodology), which acts as the most important agents for the detection of mechanical failure in transformers. There are two different methods to carry out the measurement of frequency response: Sweep Frequency Response Analysis – (SFRA) and Low Voltage Impulse - LVI. SFRA has the upper hand over LVI such as: higher signal to noise ratio, higher repeatability and reproducibility and less measuring equipment required. It is based on comparison between; 1) earlier measurement on same transformer, 2) measurement on sister transformers, or 3) phase to phase comparison on same transformer with higher signal to noise ratio, higher repeatability and reproducibility and less requirement regarding measuring equipment. SFRA is an electrical test that provides information relating to transformers mechanical integrity. This paper details with use of sweep frequency response analysis (SFRA) as a diagnostic methodology to detect winding deformation and core displacement in power transformers. Practical case studies are presented that demonstrates the effectiveness of this methodology**.

Keywords- Sweep frequency response analysis (SFRA), Condition assessment, Power Transformers, Winding Deformation, core displacement.

I. INTRODUCTION

The most expensive apparatus in a high voltage AC power system network is power transformer. Appropriate monitoring and diagnosis techniques (AMDT) can help in reducing the failure rate and thereby enhancing system reliability. The AMDT [12-24] provide detailed information about the transformers condition and help to minimize the probability of an unexpected failure.

The high percentage of mechanical failures in power transformers are caused by core displacement and/or deformation of winding, which brings the necessity of the implementation of a sensitive technique for the detection of this type of catastrophic faults [12-16]. The loss of mechanical integrity in the form of winding deformation and core displacement in power transformers can be attributed by the large electromechanical forces due to fault currents, winding shrinkage causing the release of the clamping pressure and during transformer transportation and relocation. These winding deformation and core displacement if not detected early may typically manifest into a dielectric or thermal fault [1]. This type of fault is irreversible and are left out with the only remedy been rewinding of the phase or a complete replacement of the transformer. It is therefore imperative to check the mechanical integrity of aging transformers periodically and particularly after a short circuit event to provide early warning of impending failure; hence an early warning detection methodology of such phenomena is essential. The frequency response analysis (FRA) technique is widely used because of its high sensibility in the detection of this type of pattern changes [12-15]. It is based on the concept that windings deformation and displacement are reflected as a change of R, L, and C parameters of the equivalent circuit of the transformer, and which modifies its frequency response [3]. There are two methods to obtain the frequency response: SFRA and LVI (Low voltage Impulse test).

SFRA method uses a sweep generator to apply sinusoidal voltages at different frequencies to one terminal of a transformer winding. Amplitude and phase signals obtained from selected terminals of the transformer are plotted directly as a function of frequency.

During a LVI test, a low voltage impulse is applied to one end of the winding and the output voltage or current at the other end of the winding are registered. The Fast Fourier Transform is applied to both measurements in order to obtain the amplitude and phase of the transfer function [4].

SFRA presents some important advantages over LVI such as: higher signal to noise ratio, higher repeatability and reproducibility, and less measuring equipment required. An important disadvantage of the SFRA compared with LVI is the time required for the measurement. The necessary time for performing an SFRA test (typically several minutes) is related to the bandwidth and number of spot frequencies, which are not universally defined.

II. POWER TRANSFORMERS AND MECHANICAL INTEGRITY

Power transformers are designed to withstand the mechanical forces arising from both shipping and subsequent in-service events, such as faults and lightning. But during transportation, damage can occur if the clamping and restraints are inadequate; such damage may lead to core and winding movement. The most severe in-service forces arise due to system faults, and may be either axial or radial in nature. If the forces are above limit, radial buckling or axial deformation can occur. With the core form of design the principal forces are radially directed, whereas in the shell form units they are axially directed, and this difference is likely to influence the types of damage found. Once a transformer has been damaged slightly even, the ability to withstand further incidents or short circuit faults gets reduced. Therefore it is a clear need to effectively identify such damage. During a field inspection, the oil has to be drained out and confined space entry rules apply. So little of the winding is visible, like little damage is seen other than displaced support blocks. Often, a complete tear down is required to identify the problem. An alternative method is to implement field-diagnostic techniques that are capable of detecting damage, such as SFRA [5].

There is a direct relationship between the geometric configuration of the winding and core within a transformer and the distributed network of resistances, inductances, and capacitances that make it up [6]. This RLC network can be identified by its frequency dependent transfer function. Changes in the geometric configuration alter the impedance network, and in turn alter the transfer function. Changes in the transfer function will reveal a wide range of failure modes. SFRA allows detection of changes in the transfer function of individual windings within transformers and consequently indicate movement or distortion in core and windings of the transformer [7].

III. Diagnostic Significance of Frequency Ranges

Diagnostics of frequency ranges are discussed on two levels:

- Per-phase Open Circuit Measurement
- Short Circuit Measurement

A. *Per-phase Open Circuit Measurement*

As the name implies, the per-phase measurement targets the individual phase of a given transformer. At low frequencies, the influence of capacitance is negligible and the winding behaves as an inductor. Therefore, the attenuation (described by the magnitude of the transfer function) and the phase shift (described by the phase of the transfer function) of the low-frequency sinusoidal signals, passing through the winding, are determined by inductive and resistive nature of the network [8]. The inductive characteristics are determined by the magnetic circuit of the core and the resistive characteristics are dominated by the resistance of the output measuring cable. An example of transfer function magnitude and phase for a per-phase measurement is shown in Figure 1 and Figure 2. In Figure 2 the phase angle is around −80 degrees, indicating the inductive nature of the total impedance (in the region below 1 kHz). For a three-legged core-type unit, the magnetic flux coupled with the outer phase (H1-H3 or H3-H2 in Figure 1 faces a different reluctance than the flux coupled with the middle phase (H2-H1 in Figure 1). Therefore, the corresponding magnitude traces, in the low frequency range, differ as well, i.e., the traces for the two outer phases correlate very closely and are shifted from the middle-phase trace [4]. The presence of the residual magnetism may have an effect on relationship between the traces. This is the same phenomenon that, during exciting current and loss measurement, creates a pattern of two high similar and one lower reading under normal conditions and a slightly distorted pattern in the presence of residual magnetism.

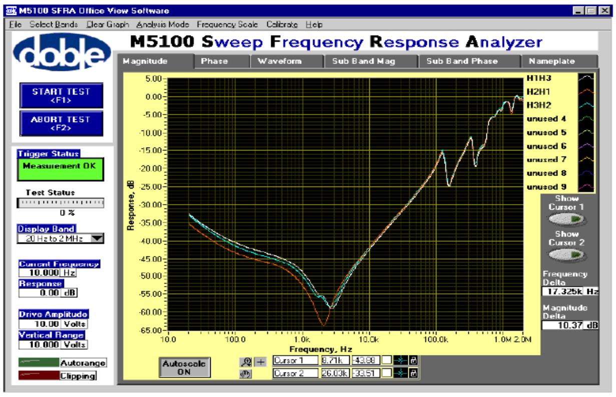

Fig 1. Per-Phase Measurements –Magnitude of the Transfer Function

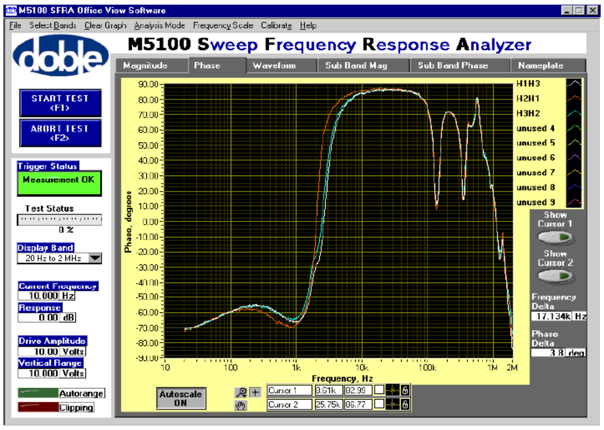

Fig 2. Per-Phase Measurements – Phase of the Transfer Function

As the frequency of the input signal increases, the capacitive effects begin to dominate and the phase angle quickly becomes close to +90 degrees (in the region above 1 kHz). Now, the attenuation and the phase shift of the high-frequency sinusoidal signals, passing through the winding, are determined by inductive and capacitive nature of the network. However, in high frequency region, the inductive characteristics are determined by the leakage flux coupling and the capacitive characteristics are determined by the various capacitance elements associated with individual turns [9]. The propagation characteristic of the winding becomes complex as a result of the many resonance frequencies found in the high-frequency range. However, since the winding responses become less dependent on the magnetic circuit of the core, the traces of the three phases converge and become quite similar. As the frequency increases even further (over 100 kHz in Figure 1), the sinusoidal signals travel mostly outside the winding and reflect the other elements found in the transformer, e.g., leads, support insulation, etc. The magnitude and the phase of the transfer function in that frequency region are influenced by the inductive-capacitive-resistive nature of these elements. Although most of the low-frequency magnitude responses exhibit a typical shape, there are no typical form responses in the high-frequency region. These vary greatly with design of the unit [1]. Therefore, the frequency ranges noted in description of Figure 1 and Figure 2, are different for different units.

B. Short Circuit Measurement

The aim of this measurement is to allow direct comparison between the three phases of a three phase transformer where no prior measurements exist. By making a measurement on one winding with another winding short circuited, the effect of the core at low frequencies is removed. The resulting response is that for a large inductor with no core. The responses for all three phases should be very similar at low frequencies. The theory behind the short-circuit measurement is straightforward. Any two winding transformer may be modeled at low frequencies by a simple T-model, as shown in Figure 3 [10].

Normal test on HVs - LVs float

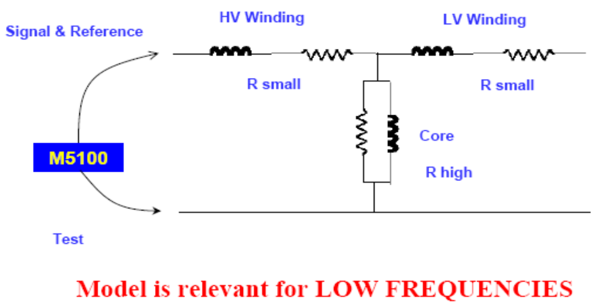

Fig 3. T Model of Transformer Winding

Normal test on HVs - LVs float

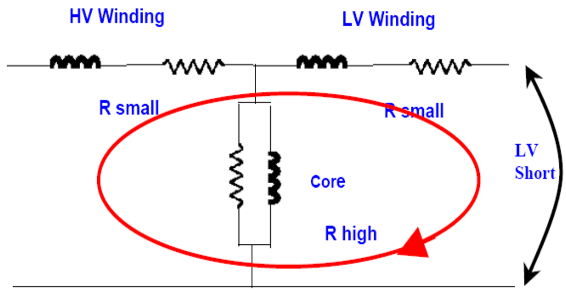

Fig 4. T Model with LV Short

The impedance of the windings is small, while the impedance of the core to ground is extremely high. This means that for any input signal, the response is dominated by the core [11]. By adding a short to the LV side as shown in Figure 4, the effect of the core is removed and the response is dominated by the windings, which are predominantly inductors at low frequency. The response of an inductor is to have a low db response at low frequency with an inductive roll off as frequency rises. All three phases of a transformer have similar winding inductances, which mean their responses should be very similar.

IV. Case Studies

SFRA Results: - Single-phase step-up transformer 26.67/33 MVA having current in HV winding 262.4A and current in LV winding 437.39A, make Crompton greaves. The Guaranteed Load Losses 67 KW and Guaranteed No Load Losses 13.5 KW.

As there are no signature signals and no sister unit is available for the comparison of the transformer, the analysis is done with phase to phase comparison of the transformers to know the mechanical integrity of the transformer.

A. Tests on high voltage winding and low voltage winding with all other terminals open

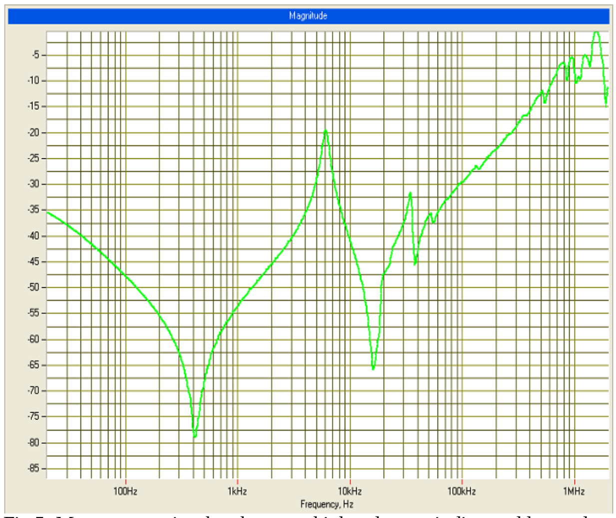

Fig 5. Measurement is taken between high voltage winding and low voltage winding

B. Test on high voltage winding and neutral with low voltage winding and neutral short circuited

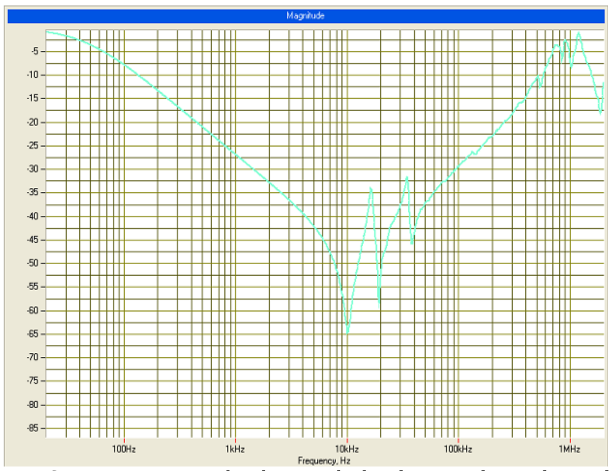

Fig 6. Measurement is taken between high voltage winding and neutral with low voltage winding and neutral short circuited

C. Test on high voltage winding and neutral with tertiary short circuited

Fig 7. Measurement is taken between high voltage winding and neutral with tertiary short circuited

D. Test on low voltage winding and neutral with tertiary short circuited

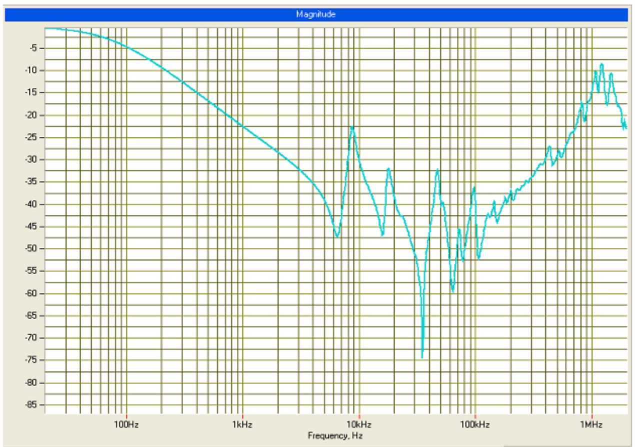

Fig 8. Measurement is taken between low voltage winding and neutral with tertiary short circuited

E. Test on low voltage winding and neutral with all other terminals open

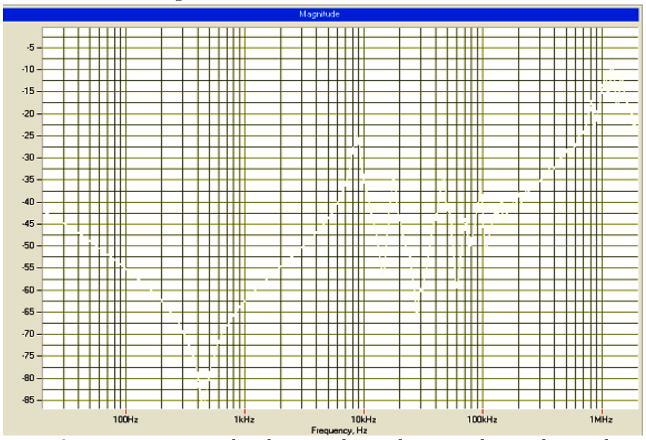

Fig 9. Measurement is taken between low voltage winding and neutral

F. Test on tertiary windings with all other terminals open

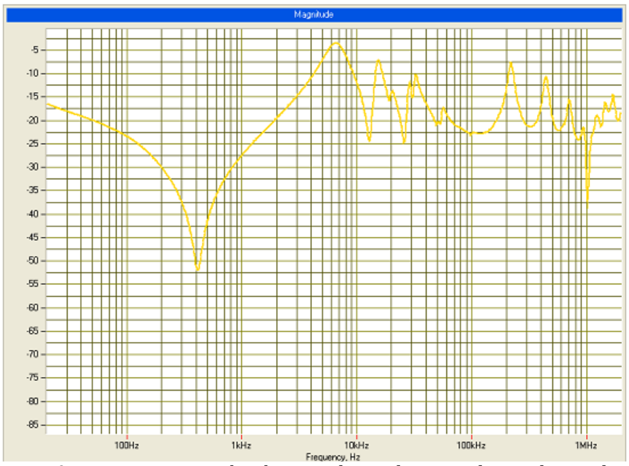

Fig 10. Measurement is taken between low voltage winding and neutral

G. Test on tertiary windings with all other terminals open

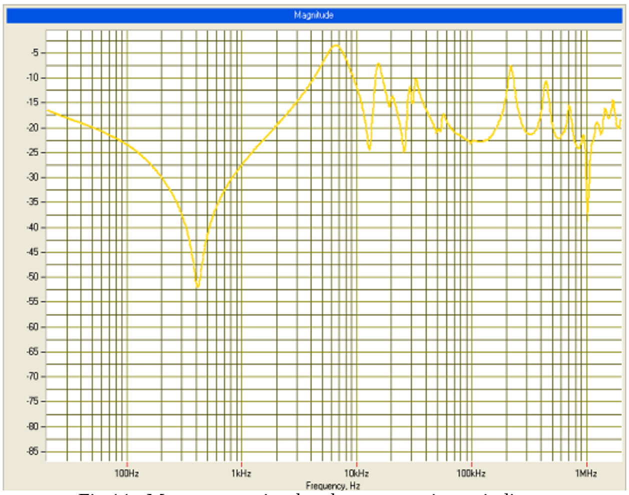

Fig 11. Measurement is taken between tertiary windings

V. Analysis of the Above Power Transformer

As there is no baseline and the sister unit is not available, the analysis is done with phase to phase comparison. The open circuit test results and the short circuit (test) results showing variations in higher frequencies. All phase responses are different at different frequency ranges. The analysis must be compared with the base line signature signals or the sister unit of this particular power transformer. It will be very difficult to comment about the mechanical integrity of the power transformer without baseline or sister unit comparison. All graphs taken from SFRA test equipment shows little variation at high frequencies may relate to some internal lead movement, but the results are acceptable.

SFRA showed over all good results and the transformer is OK as far as mechanical integrity of the transformer is concerned. SFRA results indicate consistent mechanical geometry of all units, obviously core movement or winding deformation is not present.

VI. CONCLUSION

Sweep Frequency Response Analysis (SFRA) has been applied successfully as a diagnostic method for detecting mechanical deformation in power transformer. In this paper we discuss the case of Power transformer and various SFRA signatures have been obtained. It has been shown that SFRA responses of different combination of transformer winding can highlight completely the mechanical integrity of power transformer by their careful comparison. Changes in frequency response as measured by SFRA techniques may indicate a mechanical deformation inside the transformer, the cause of which then needs to be identified and investigated, so that the appropriate action can be taken before outages occurs.

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