Evaluation of Mechanical Defects in Power Transformer Windings Based on Frequency Response Analysis

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ABSTRACT— In-depth evaluation of mechanical defects of a 150 MVA, 330/132 kV power transformers windings was investigated in this study based on Frequency Response Analysis (FRA). The FRA, short circuit impedance and insulation resistances measurements were performed to determine transformer windings deformation, mechanical defects, and insulation conditions of the transformer's windings using Frequency Response Analyzer and Megger insulation tester. The attenuation in decibel (dB) of the transmitted signal was measured over a frequency range from 20 Hz to 2 MHz.

Results indicates that the transformer experienced axial and radial winding deformations; this affect leakage flux path, which differs significantly between phases of the measured short-circuit impedance of phases A, B and C. Insulation resistances failures between HV and LV winding to ground (HV - (LV+GND)) resulting to deterioration of insulation to 49MΩ at 60^0C; changes in the windings capacitance values of 14.43%; 13.69%; and 14.03% for winding combination of HV - (LV+GND); LV- (HV+GND); and (HV+LV)-GND at temperatures between 25^0C and 60^0C when compared with factory measured values. These results are dangerous for the bushings, indications of contamination and high dielectric stress in the insulation. The FRA is the most effective diagnostic tool for detecting mechanical deformation, electrical fault in core and in transformer windings without costly detanking and time-consuming visual inspection.

KEYWORDS—High Voltage, Frequency Response Analysis, Transformer, Mechanical Defects, Insulation Resistance, Radial Buckling, Winding Deformation.

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1.0 INTRODUCTION

Power transformers are in service in many diverse environmental, electrical and mechanical conditions [1] and are continually facing enormous hazards over the course of their operational life. The technical and economic significance of power transformers regarding electrical energy transfer efficiency and reliability in the power network is paramount. Supervision and diagnosis of power transformers, the heart of power systems networks, has been an important issue for a long time [2, 3]. Continuous information regarding the insulation system condition and the internal mechanical stability is vitally important for the system operation. Experience has shown that transformer failure especially at high voltage levels such as 330kV causes irrecoverable damage to the power system. In critical situations, the failure of a transformer can cause millions of Naira in damage to equipment owned by Electrical utility [3, 4, 5]. From technical point of view, faults in transformers are inevitable and thus requires the continual development of best practice monitoring. In this regard, one of the main common faults in transformers is mechanical displacement of core/windings. Mechanical defects can occur as a result of disturbances such as short circuit currents, severe explosion of combustible gases, or even unsuitable transportation and accidents. Experience has shown that each and every mechanical defect in an active part can make it necessary to take the transformer out of service for a considerable time because of the complexity and cost of removing windings and installing new ones [6-8]. Therefore, transformer diagnostic test methods have to be developed so as to recognize the type of transformer internal faults. In this study, a 150-MVA step-down transformer has been taken as a case-study for the evaluation of mechanical fault detection based on FRA.

Frequency response Analysis (FRA) is one of the most important test measurements that are performed during periodical maintenance tests or after fault occurrence [9, 10]. FRA is the measurement of the electrical transfer functions for a wide range of frequency for the evaluation of mechanical integrity of the windings, core and clamping structures within power transformers. It is also defined as the process of offline measuring the impedance of the transformer winding as the frequency's function [11, 12]. The motive behind the development of FRA was the detection of winding displacement and deformation in power transformer [13]. The internal mechanical defects or faults identified in transformer using FRA method include winding deformation in the axial and/or radial directions, hoop stress buckling, tilting, spiraling, displacements between high and low voltage windings, shorted or open turns, partial winding collapse, loosened clamping structures, core movement, faulty grounding of core or screens, broken clamping structures, or even problematic internal connections [14]. FRA consists of measuring the impedance of transformer windings on the same unit or identical ones or different phases of the same units over a wide range of frequencies and comparing the results of these measurements with previous results or results from identical transformer taken as reference. Any significant difference between the previous and new FRA measurements would indicate a mechanical fault in the winding like winding displacement or deformation [15-16]. Among all diagnostic tests, FRA has a high accuracy, is fast, economic and non-destructive in detecting winding defects, electrical and/or mechanical faults of a transformer for decision-making with regard to remedial action for a defective phase [17, 18]. Insulation resistance measurement on electrical equipment is perhaps one of the oldest techniques of testing. The purpose of this measurement is to determine the insulation resistance from individual winding to ground, between individual windings or between core laminations by applying DC voltage. This test is useful in revealing the conditions or indication of deteriorating trends in the insulation system. The insulation resistance values indicate the weakness of the insulation or its total dielectric strength [19]. It also indicate the contamination of the insulation and trouble ahead within the insulation system if a downward trend continued in the insulation resistance values [19, 20]. There are four factors that are responsible for insulation deterioration, these includes pyrolysis (heat); oxidation; acidity; and moisture. Moisture failures can be caused by leaking pipes and /or roofs, water entering the tank through leaking bushings and fittings, and confirmed presence of moisture in the insulating oil. The insulation resistance measured in the factory affords a useful indication as to whether or not the transformer is in suitable condition for application of other dielectric tests [21-22].

2.0 MATERIALS AND METHODS

2.1 Frequency Response Analysis Measurement Set-up Procedures

In this study, evaluation of pre-repair tests and measurement of a 150 MVA, 330/132 kV, failed three-phase power transformer in the field was performed to determine the causes of the transformer failure. From the operator's logbook report, the transformer was de-energized by emergency disconnection system actuated by gassing and differential protection systems as well as operation of two safety valves. Thus, in order to have detailed assessment of the transformer; full range of diagnostic tests were conducted. In this regard, the transformer was heated up to 60ºC by the oil circulating system and stop, allowing the transformer to cool down naturally before conducting the tests. The main technical specification of the transformer is presented in Table 1. All of the tests were performed according to IEC Standards and technical instructions indicated in the related drawings and operation manuals.

Table 1: Transformer Specifications

Type	Power Transformer, Step-down
Manufacture date	May 1987
Rated Voltage in kV	330/132
Rated power in MVA	150
Rated current in Amp	252/656
Vector group	Dy11
Number of coolers	12
No-Load current (%)	0.37
Number of phases	3
Number of limbs	5
S.C. voltage HV-LV (%)	11.81
Frequency (Hz)	50
Cooling system	OFAF, Detached

Base on Frequency Response Analysis measurement, there is a direct relationship between the geometric configuration of the winding and core within a transformer and the distributed complex network of resistances, inductances, and capacitances (RLC) parameter components of the transformer. The contributions to this complex mesh of RLC circuit are from the resistance of the copper winding, inductance of the winding coils and capacitance from the insulation layers between coils, between winding, between winding and core, between core and tank, between tank and winding as shown in Figure 1. Where L_{IK} = Primary inductance, L_m = Leakage inductance, C_n = Primary winding capacitance, C_s = Secondary winding capacitance, C_m = Inter winding capacitance, R_n = Primary winding resistance, and R_s = Secondary winding resistance.

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, i. e. any form of physical damage to the transformer results in the changes of the RLC network.

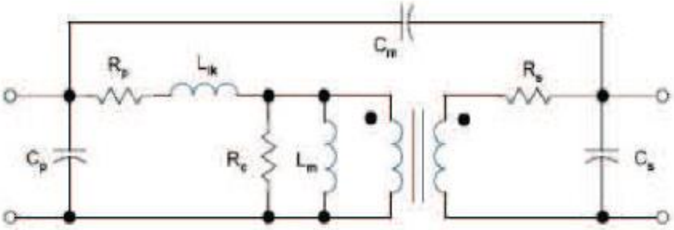


Fig. 1: Equivalent circuit model for two winding Transformer

The frequency response measurement was conducted by supplying a low-voltage (LV) signal to a winding terminal with respect to the tank as shown in Figure 2. The measured voltage at this input terminal is designated as the reference signal (V_s) and another voltage signal designated as response signal (V_r) was measured at a second terminal. In order to match the characteristic impedance of the connecting cables V_s and V_r were measured across an input impedance of 50 ohms. The ratio between V_r and V_s expressed in dB is designated as the amplitude of the frequency response. The basic principal that the geometry of windings is tightly related to the distributed capacitances and inductances between conductors and layers forms the basis of the sensitivity of the measurement for detecting winding displacement because these distributed capacitances and inductances characterize most of the series and parallel resonances in the recorded frequency response.

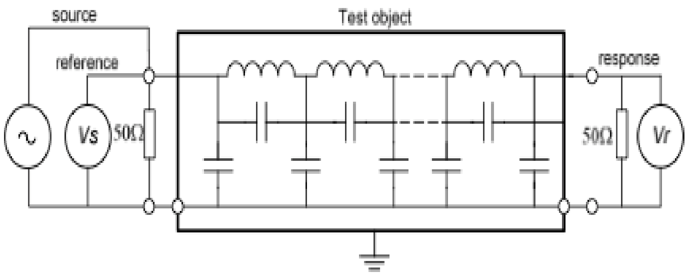


Figure 2: Frequency response measurement

FRA tests performed for each phase LV winding of the transformer involves measuring the frequency response of each phase winding. The frequency was measured by injecting a sine wave signal of 10 V AC to the winding for all possible connections with respect to earth at one end of winding of the transformer under test and measuring the signal amplitude there and at other end of winding. The attenuation (in decibel dB) of the transmitted signal relative to reference signal at the input terminal was measured over a frequency range from 20 Hz to 2 MHz. Fig 3 shows the frequency response analyzer measurement equipment used in this study. The frequency response analyzer is a powerful tool, quality control and maintenance toolkit which enables to look inside the transformer to detect even subtle changes in the mechanical structure of the core and windings without costly detanking before testing. This is the most effective diagnostic tool generally used on large HV power transformers because it is sensitive tests to detect winding distortion and deformation in coils, layers, turns, and leads in power transformers [12, 19-20].

Fig. 3: Frequency Response Analysis Analyzer with application software

2.2 Short Circuit Impedance

(a) Short-circuit impedance (also called leakage reactance) measurements are sensitive and probably the most widely accepted method to assess possible deformation or displacement of windings as prescribed in standard IEC: 76-5 for short circuit tests. The purpose of this test is to determine or detect winding movement that usually occurs due to heavy fault current, transformer winding deformation or mechanical damage. The measured short-circuit impedance of a power transformer can be compared to the nameplate value or to factory test results. Short circuit impedance is calculated using equation (1). Table 2 shows the transformer winding parameters while Fig.4 depicts the schematic of transformer active part.

$$V_K = \sqrt{V_R^2 + V_X^2} \qquad (1)$$

When, $$V_R = \frac{P_k}{S} \; x \; 100 \qquad (2)$$

Where P_k = Load loss (kW); S = Apparent power; and

$$V_X = 0.2976 \frac{S * C_x * D_x}{(V/N)^2 H_m * 2N_B} K_R\left(\frac{f}{50}\right) \qquad (3)$$

Winding deformation results in the change of V_x. Thus, the relative change in V_x can serve as an indication of deformation of the winding.

Table 2: Transformer winding parameters

N_B = Number of limbs having winding
K_R = Rogowsky Coefficient
f = Operation frequency
C_2 and DC_2 and B_{OW1} and B_{OW2}
$H_m = (H_{m1}+H_{m2})/2$: Average magnetic height of windings, $H_m = H_w$: for disc windings
S =Nominal apparent power (kVA)
$C_x = C_2 + (B_{OW1} + B_{OW2})/3$
$D_x = DC_2 + (B_{OW2} - B_{OW1})/3$
H_w = Height of winding
V/N = Volt per turn

The dissipation factor (tan δ), is calculated via the tangent of the angle δ between the measured current and the ideal current which would occur if no losses existed. The dissipation factor is an indication of the general condition of the insulation; it is useful for evaluation of dryness of the insulation system or aging and any oil contamination. The power factor on the other hand is the cosine of the angle (cos φ), between the output voltage and the measured current.

$$\text{Dissipation factor } \tan\delta = \frac{P_R}{Q_C} = \frac{I_R}{I_C} = \frac{X_c}{R} = \frac{1}{\omega C R} \quad (4)$$

$$\text{Power factor PF} = \text{Cos}\,\varphi = \frac{I_R}{I} = \frac{P_R}{S_C} = \frac{\tan\delta}{\sqrt{1+\tan^2\delta}} \quad (5)$$

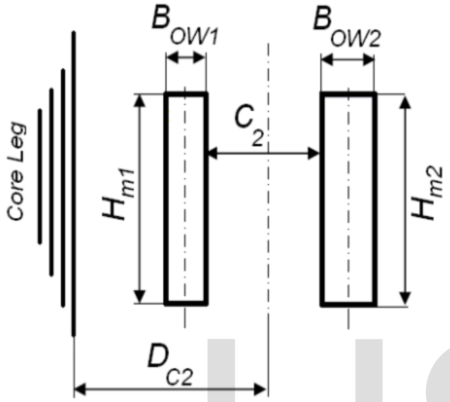


Fig. 4: HV and LV winding schematic

(b) Mechanical Failure due to Electromagnetic Forces

When a system short circuit causes high current to flow through a large power transformer, the windings and internal leads are subjected to extremely high mechanical forces. The total radial force and axial forces on a winding can be multiple of hundreds times of normal forces. The extremely high current during first peak of the fault current is a major source of mechanical displacements and subsequent transformer failures. The current flowing in transformer winding conductors sets up an electromagnetic field in and around the windings [12,19]. Any current-carrying conductor *(I)* which is linked by the field *(B)* experiences a mechanical force *(F)* which is perpendicular to the direction of the current and the field. The force of electrodynamics that acts on the winding of the transformer can be determined by equation (6) for the calculation of electromagnetic forces as

$$F = LBI \quad (6)$$

Where I is the current; L is the winding length and B is the magnetic induction

2.2 Transformer Windings Insulation Resistance Measurement

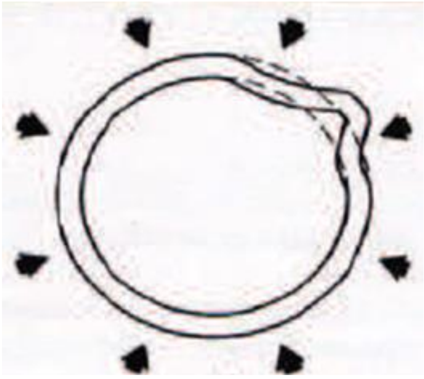
The insulation resistance measurements for a two-winding, three-phase transformers were made to determine the insulation conditions of the transformer's windings to ground (earth), or between HV winding to LV winding as a result of winding insulation deterioration. These measurement were conducted using the MEGGER insulation tester; Type: MIT 510 with a rated voltage of 5kV direct current (d. c.); and measuring range of 15 TΩ. The Megger insulation tester is a portable instrument that gives a direct reading of insulation resistance in megaohm.

Prior to performing the tests, first of all, short-circuited all high-voltage (HV) windings terminals and labeled (H) making sure that the short-circuits are clear of all metal and grounded parts; and secondly, short-circuited all low-voltage (LV) terminals labeled (L) and neutral bushings, making sure that the short-circuits are clear of all metal and grounded terminal, usually connected to transformer tank labeled (GND) in order to measure its insulation resistance in sequence as listed herein to include connecting the Megger leads (a) between high voltage winding and low voltage winding to ground; (b) connection between low voltage winding and high voltage winding to ground; and (c) connection between high voltage winding and low voltage winding to ground at three different temperatures of 25^{0}C, 40^{0}C and 60^{0}C respectively. Each measurement was maintained for a period of 60 seconds. It is unnecessary to perform insulation resistance test of transformer per phase wise in three phase transformer.

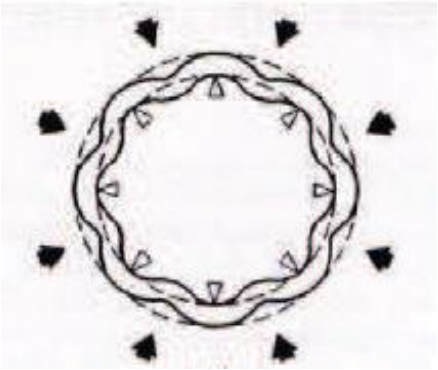
3.0 RESULTS AND DISCUSSIONS

3.1 Transformer Defects due to Radial Forces

Radial electro-dynamic forces cause winding buckling as illustrated in Fig.5 (a) and inward bending between axial strips as is shown in Fig.5 (b), leading to damage of conductor insulation and possible rupturing of conductors. The direction of the forces is perpendicular to the magnetic field lines which have components that cause both radial forces and axial forces. Due to the diversity of electro-dynamic forces acting on transformer active parts, only a number of defects related to these destructive forces are detectible.



(a) Buckling winding



(b) Inward bending between axial strips

Figure 5: Radial forces due to axial field

The radial forces are acting outwards on the outer winding tending to stretch the conductor, producing a tensile stress and acting inwards on the inner winding tending to collapse or crush it, producing a compressive stress called hoop stress. Radial collapse of inner winding is common, whereas outwards bursting of outer winding generally less take place; Forced buckling occurs when the winding cylinder has significant stiffness as compared to winding conductors; conductors bulge inwards as well as outwards at one or more locations along the circumference as indicated in Figure 5. Severe radial deformations of transformer windings, known as hoop buckling leads to bent winding, but not broken. These deformations occurred in LV windings and show significant decrease (shift to left) of the medium frequency resonance points.

Radial deformation of one side of the winding (degree 1) and deformation of three sides of the winding with 90^0 with respect to each other (degree 3) of the LV winding of the transformer was considered. The impedance of the windings measured considering different degrees of radial deformation as listed in Table 3 showing the relative deviations of the inductances, resistances and capacitances of the LV winding and between the HV and LV windings. As seen from the table, in general, the capacitances are much more influenced by the winding buckling than the inductances, showing less than 2% deviations. The deviation in inductances due to radial deformation (buckling) is negligible compared to the capacitance changes and was not accounted for during simulations; the same assumption can be applied to resistances, which also deviate insignificantly with less than 2% relative difference due to introduced radial deformations.

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Table 3: Relative percent deviations of lumped model parameters due to hoop buckling of the Low voltage windings of the three-phase transformer

Hoop Bucking Mode	Resistances		Inductances		Geometrical Capacitances	
	R_{LV}	R_{LVHV}	L_{LV}	L_{LVHV}	C_{HVLV}	C_{LV}
Degree 1	0.66	0.39	0.37	0.26	4.4	19.29
Degree 3	1.84	0.56	1.79	0.47	3.07	58.25

However, the capacitances between the LV winding and a core rapidly increase depending on the deformation degree, showing about 19% and 58% changes for the deformation degrees 1 and 3 respectively. This was due to the LV winding buckling towards the core, which reduces the distances between the corresponding surfaces of the LV winding and the core. Figure 6 depict short circuit plots of LV windings; the logarithmic amplitude ratio in (dB) is in y-axis against the frequency (Hz) in x-axis representing simulation of hoop buckling of the LV winding three-phase faults of **a-n** (brown color) **b-n** (blue color) and **c-n** (green color) with the deformation degrees 1 and 3 respectively.

It can be seen that at low frequency the difference in dB is around 0.4 dB, which was not so critical. However, there were significant deviations of resonance appearances from the middle toward higher frequencies spectrum.

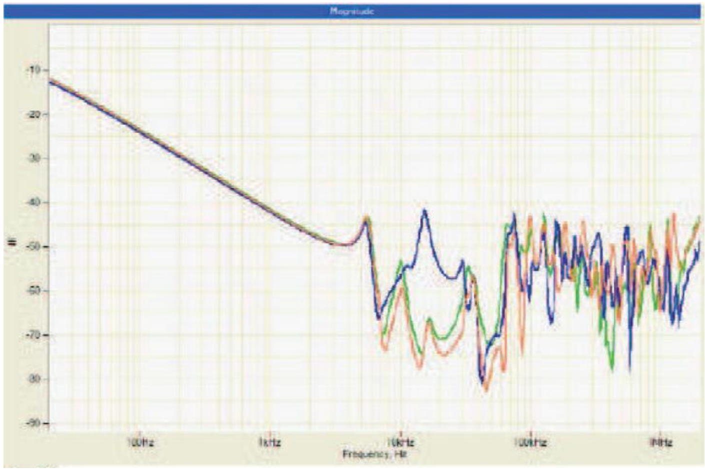
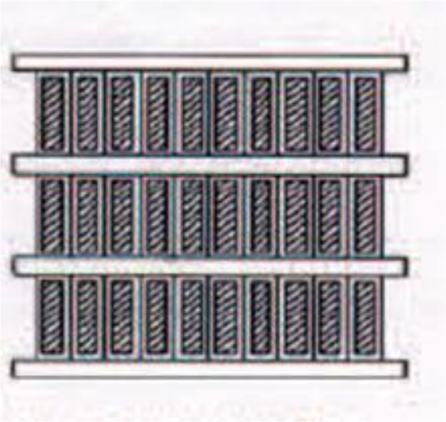


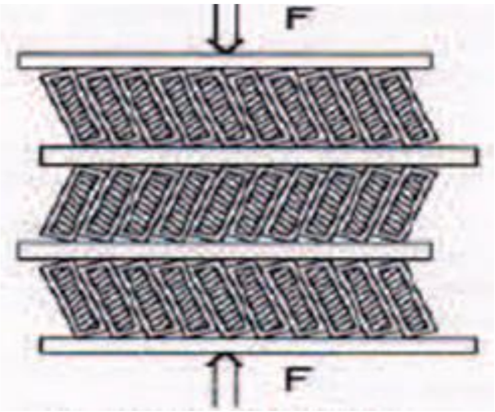
Fig. 6: Short circuit plot of LV winding with respect to HV due to Radial (buckling) deformation

3.2 Axial Displacement Forces

The axial forces due to radial fringing leakage field at winding ends are directed towards center of winding from both ends for uniform ampere-turn distribution in windings with equal heights under ideal condition as shown in figure 7 (a). When the compressive force was at maximum at the center of the windings, both the inner and outer windings also experience compressive forces. Low voltage winding conductors, which are subjected to the axial compressive load, failed due to bending between supports and tilting under axial load. When axial compressive forces exceed certain limit, failure due to tilting of conductors in a zigzag fashion occur as indicated in Figure 7 (b). The axial forces which were transmitted through the insulation structure gives rise to compressive force in the axial supports. For asymmetrical axial winding disposition, axial forces on two windings are in opposite direction and they tend to increase the asymmetry.



(a) Normal winding position



(b) Tilting core/windings

Figure 7: Axial forces due to radial field

In order to validate the tests, the transformer was de-tanked to examine the cores and windings physical appearance inside the transformer tank. De-tanking process is a procedure for taking out the core and winding from the main tank of transformer. This leads to the faults been identified more clearly. The de-tanking transformer was let uncovered until winding and core inspection was completed due to time constraint. From the visual inspection results shown in Figures 8(a) and (b), clearly indicates that the transformer had experienced axial winding deformation at HV windings. The HV winding move downward because of the large electromagnetic forces originated from short circuit current produced toward outer direction and make the upper layer of HV winding to disrupt downward.

(a)Axial defects of HV winding with H2-H3 phase moved downward

(b) Winding defects at H2-H3 phase affecting the tap leads winding

Fig. 8: Visual Inspection of Transformer Axial deformation at HV windings

Figure 9 illustrate the transfer function responses simulating upward and downward shifts of the LV winding with respect to the HV winding respectively. As seen from the figure there is clear shifts to right in resonance frequencies in both curves, which supports the above classification hypothesis.

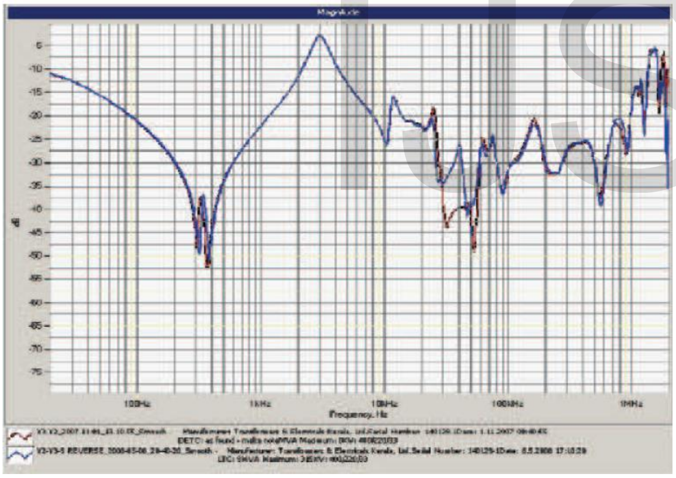


Fig. 9: Short circuit plot of LV winding with respect to HV showing major axial shift in winding movement

3.3 Short-circuit Impedance Measurements

The short-circuit impedance (also called Leakage reactance) measurements of concentric windings, were performed at rated frequency with sinusoidal voltage applied to the terminals of the delta connected HV windings with the three-phase terminals of the low voltage (LV) windings short-circuited. During these tests, the reluctance encountered by the magnetic flux is determined by the leakage channel. The leakage channel is the space confined between the inner surface of the inner winding, the outer surface of the outer winding, and the bottom and the top yokes. Due to windings distortion occurrences in the phases A, B, and C, it changes the reluctance of the magnetic flux path, resulting in a change of the measured leakage reactance as presented in table 4.

Table 4: Comparison of Measured and Rated short-circuit Impedances

Measurement Scheme	Measurement	measured impedances [Ω]	Rated impedances [Ω]	Percentage (%) Difference from rated
HV-LV	A-N	16.177	16.945	4.53
HV-LV	B-N	16.908	16.945	0.218
HV-LV	C-N	16.234	16.945	4.196

Results shown that the measured per-phase short-circuit impedance differs significantly between phases. The windings deformation affect the leakage flux path, which in turn results in the change of the measured short-circuit impedance of phases A, B and C as indicated in the table. The technique suffers the disadvantage that very small changes were detected. Even so, the main difficulty in making use of the technique appears to lie not with the repeatability of the measurements, but in the natural variation of the measured quantity.

3.4 Winding Insulation Resistances Measurements

Insulation resistance measurements are taken between the windings collectively as all the windings on HV side are internally connected together to form either star or delta and also all the windings on LV side are internally connected together to form either star or delta. By comparing the results obtained in insulation resistance of factory measurements with field measurements, the insulation conditions were evaluated. Table 5 represented factory measured winding insulation resistances before failure and field measured after failure at a temperature of 25^{0}C; while Table 6 present results of field measurement of winding insulation resistances after failure at temperatures of 40^{0}C and at 60^{0}C.

Table 5: Factory Measured Winding Insulation Resistances at 25^{0}C

Measured Between Terminals	Injected Voltage [kV]	Before Failure 25 ° C		
		tanδ (%)	C [pF]	IR [MΩ]
HV-(LV+GND)	5.0	0.42	2771.0	1050
LV-(HV+GND)	5.0	0.34	2801.2	1010
(HV+LV)-GND	5.0	0.35	2980.0	1020

Table 6a: Field Measured Winding Insulation Resistances at 25^{0}C

Measured Between Terminals	Injected Voltage [kV]	After Failure 25^0 C		
		tanδ (%)	C [pF]	IR [MΩ]
HV-(LV+GND)	5.0	0.62	2937.3	520
LV-(HV+GND)	5.0	0.44	2950.1	860
(HV+LV)-GND	5.0	0.45	3148.0	870

Table 6(b): Field Measured Winding Insulation Resistances at 40 ° C.

Measured Between Terminals	Injected Voltage [kV]	After Failure 40^0 C		
		tan δ (%)	C [pF]	IR [MΩ]
HV- (LV+GND)	5.0	0.65	3046.0	208
LV- (HV+GND)	5.0	0.45	3050.3	320
(HV+LV)-GND	5.0	0.55	3264.5	325

Table 6(c): Field Measured Winding Insulation Resistances at 60 ° C

Measured Between Terminals	Injected Voltage [kV]	After Failure 60^0 C		
		tan δ (%)	C [pF]	IR [MΩ]
HV- (LV+GND)	5.0	0.65	3171.0	49
LV- (HV+GND)	5.0	0.54	3184.7	80
(HV+LV)-GND	5.0	0.54	3398.3	81

The values of capacitance (cos φ), dissipation factor (tan δ) and their respective values of insulation resistance are presented in Table 5 and Table 6 respectively. The variation in the capacitance of the insulators as well as insulation resistances failures in Table 6 indicates abnormal conditions such as core or windings displacements between HV winding and LV winding to ground (HV - (LV+GND)) resulting to deterioration / breakdown of insulation to 49MΩ at 60^{0}C and subsequently short–circuited winding in the capacitance network. It was observed that good insulation has high resistance; while poor insulation has relatively low resistance values. The effect of temperature in measurement according to IEC Standard 60076-5 shown that for every 10 degree increase in temperatures, the insulation resistance is reduced to half; hence from the measurements, the insulation resistances decrease markedly with increases in temperatures. Also, there were changes in the windings capacitance values of 14.43%; 13.69%; and 14.03% for winding combination of HV - (LV+GND); LV- (HV+GND); and (HV+LV)-GND respectively at temperature of 60^{0}C when compared with factory base values of capacitance measured during Factory commissioning of transformer. These results are considered dangerous for the bushings which indicate contamination and high dielectric stress in the insulation. Similarly, the increase in dissipation factor accompanied by marked increases of the capacitance indicates excessive insulation thermal deterioration.

4.0 CONCLUSION

In this study, evaluation of mechanical defects on three-phase Power Transformer rated 150 MVA, 330/132 kV, in the field was conducted based on FRA. FRA tests performed for each phase LV winding of the transformer involves measuring the frequency response of each phase winding. FRA method of diagnosing the condition of transformer main mechanical parts such as core and winding was investigated. The attenuation (in decibel dB) of the transmitted signal relative to reference signal at the input terminal was measured over a frequency range from 20 Hz to 2 MHz using the frequency response analyzer instrument. Mechanical defects of windings such as buckling and tilting was considered. Radial electrodynamic forces causing winding buckling and inward bending between axial strips leading to damage of conductor insulation and rupturing of conductors was presented. Simulations of axial shift in winding movement as well as hoop buckling of the LV winding three-phase faults were also presented. Short-circuit impedance (also called leakage reactance) measurements test was also performed to determine winding movement due to heavy fault current, transformer winding deformation or mechanical damage. The insulation resistance measurements for a two-winding, three-phase transformers were conducted to determine the insulation conditions of the transformer's windings using the Megger instrument. The dissipation factor and capacitance (Tan δ / Cos φ) measurement of bushing/winding were also performed to determine the capacitances and power factor as well as the insulating condition of the transformer between the windings and the earthed parts and between different windings of the transformer.

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