SFRA Capability for detection of deformation in Transformer windings: A field experience of 400kV 167MVA single phase ICT

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Abstract – Sweep Frequency Response Analysis has become very popular now – a - days due to its ability to provide comprehensive information regarding mechanical as well as electrical condition of power transformers. The SFRA is a signature test and provides better information when evaluation of Transformer condition is done by comparing actual set of SFRA results with reference results. This field experience refers to 400/220/33KV ICT bank, formed with three single phase units – each with capacity of 167MVA. Heavy fault current was fed through ICT due to failure of LA provided on external delta formation of Tertiary winding. Mechanical defects / deformation occur ostensibly due to short circuit current flowing through transformer winding in case of terminal faults i.e. fault adjacent to / on the power transformer. To ascertain mechanical integrity of power transformer, SFRA test is carried out and is supported by other tests i.e. capacitance and tan delta measurement etc. The test results reveal that SFRA is capable of providing more information about mechanical deformation of active parts of power transformers - compared to other tests.

Keywords: Sweep Frequency Response Analysis, Winding Deformation, Inter-connected Transformer ICT, Capacitance and Tan delta, Mechanical integrity.

1. Introduction

Power transformers in service, agonize through excessive electrical as well as mechanical stresses throughout their life span. Power transformers are most costly, substantial and important equipment of power system and their failure may hamper power supply to consumers, especially when sensitive industries are involved. SFRA test provides useful information about mechanical deformation of windings [1]. The most severe and predominant forces arise from system faults taking place adjacent to / on Power Transformer. The electromagnetic forces generated by faults may be axial, radial or assorted, depending on nature of fault. If the forces are excessive, radial buckling or axial deformation may occur [2]. Once a transformer is damaged either enormously or slightly, the ability to withstand further incidents or short circuit withstand ability is reduced proportionate to fault current supplied [3].

In present case- study, overhauling (OH) of single phase ICT unit of B phase was completed on date 07.01.2016 and transformer was put back in service. Subsequent to failure of LA on date 04.07.2016, movement of tertiary winding noticed in SFRA Traces. Same was supported by capacitance and tan delta test results, as change in capacitance value recorded for tertiary winding only. So, inference drawn that - due to failure of LA, heavy fault current was fed through ICT unit, leading to radial displacement in tertiary winding. No deviation noticed indicating any movement – in SFRA traces for other windings.

Other test results were found normal, they didn't indicate abnormality with Tertiary winding, and hence it was recommended to carry out internal inspection of ICT unit. However, nothing was found abnormal during internal Inspection at site.

Tertiary winding couldn't be inspected / visualized – as it was the innermost winding – surrounded by HV-IV winding - covered with hard board insulating cylinder.

Comprehensive SFRA testing and analysis thereof indicated tertiary winding displacement and led suspicion to mechanical integrity of same winding. However, all other test results were found in order; so it was decided to charge the transformer.

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After taking all safety precautions and confirming protection checks - transformer was charged. However, Transformer couldn't withstand charging current and tripped immediately on differential protection with buchholz relay. Once again transformer tested meticulously and now SFRA test results clearly indicated turn to turn short in tertiary winding [4]. This was due to development of deformation and reduction of mechanical strength of tertiary winding during heavy fault current feeding at the instant of L.A. failure.

2. Electromagnetic Forces

An electromagnetic force is generated in current carrying conductor when it is surrounded by magnetic flux, and its magnitude and direction depends on magnitude and direction of current flowing through conductor. In power transformer while in service, system faults or faults inside the power transformers cause axial or redial electromagnetic forces and if transformer winding is not capable to withstand such forces then deformation takes place in winding and sometimes immense deformation may lead to transformer failure [5].

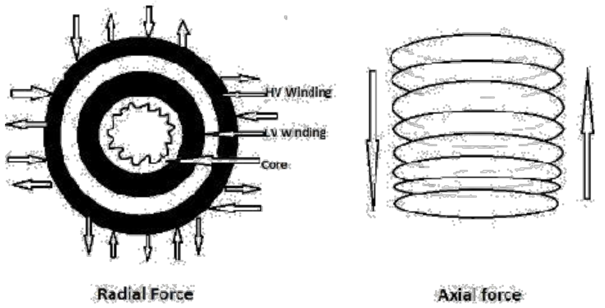

Fig. 1. (a) Radial Force (b) Axial force

Usually, transformer internal short circuits act on the transformer solid insulation system of paper and pressboard, while external through fault short circuits in power networks tends to subject transformer winding through radial electromagnetic forces. It acts on the external winding coil from within, and on the internal winding coil inwards and results in radial movement of the windings. The direction of the forces is perpendicular to the magnetic field lines which may have components that cause both radial forces and axial forces. Radial forces and axial forces cause winding buckling as narrated in figure 1(a) and figure 1(b) respectively.

3. SFRA

The first technical paper published on Frequency Response Analysis by Mr. E.P. Dick and Mr. C.C. Erven in 1978 [1]. Sweep frequency response analysis has been developed to detect winding movement and deformation in power transformers. High voltage power transformer can be represented as a complex electric system consisting bunch of inductances, capacitances and resistances in series and parallel formation. The complex structure of power transformers can be represented in simplified manner with two port network as shown in figure 2.

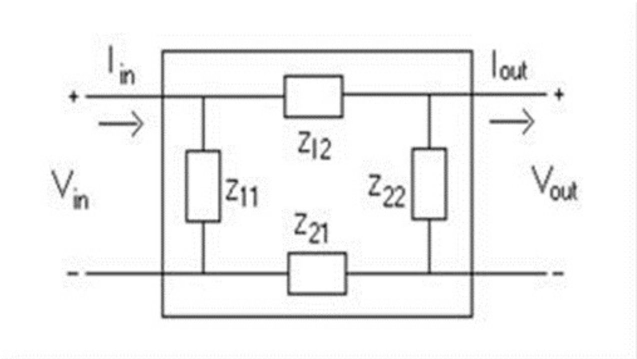

Fig. 2. Power Transformer as a two port network

The two port network, excited by the voltage signal, with variable frequency produces an electrical response which is dependent on the frequency of the input signal, and the value of output voltage depends on impedance of particular winding that have with-stood test at particular frequency.

Output voltage Vo and Input Voltage Vi are compared in the frequency domain, then the gain in dB as under

$$dB = 20\log 10 \frac{V_0}{V_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The values of RLC elements depend on the geometry and material used for each part of the transformer. Any change in geometry or change in material reflect significant change in the response. SFRA analysis involves comparison of two sets of test results: latest results are compared with base results; if base results are not available – comparison can be made with SFRA results of sister unit; and if SFRA results of sister unit are not available – comparison can be made with SFRA traces of other phases of same unit. If base results are available, then sound judgment can be drawn with the help of SFRA test results.

4. Tertiary Winding

It is an additional winding in a power transformer other than primary and secondary winding which is used to connect a synchronous condenser, a reactor and an auxiliary circuit for feeding power at a voltage level different from secondary voltage is known as a tertiary winding. If auxiliary load connected with tertiary winding then known as a loaded tertiary winding. Delta connected auxiliary winding used particularly in wye-wye connected three phase power transformers as a tertiary winding for following purposes:

1) To stabilize the neutral point of the fundamental frequency voltages.
2) To minimize third harmonics
3) To serve auxiliary load
4) To control the value of zero sequence impedance.
5) Use for testing purpose in Lab

5. Case Study

At one of the 400kv sub-stations, 500MVA interconnected power transformer (ICT) which consists bank of three single phase units, each of 167MVA and tertiary winding with outside delta formation having adequate protection i.e. Lighting Arrestor (LA) and surge capacitor - was in service. Overhauling completed for 167MVA B Ph. unit on date 07.01.2016, transformer was charged and put in to service. On date 04.07.2016, due to failure of B phase LA resulting into heavy fault current feeding - said unit tripped with buchholz relay along with differential protection of ICT-bank. Suspected ICT unit of B phase - kept out of service for further investigation. 500MVA ICT again taken in to service with utilization of spare single phase unit available - instead of suspected B phase unit. For checking healthiness of B phase unit - all diagnosis tests as well all routine tests carried out.

Overall test reports were normal and no any major fault inside the transformer was indicated. It was decided to carry out internal inspection of ICT unit, as in DGA - key gases were observed. During internal inspection, nothing found abnormal inside the transformer. So, transformer oil filtration carried out and transformer was allowed to cool down naturally. Once again all tests carried out. Only SFRA test indicated deviation in tertiary winding graphs and same was support by capacitance and tan delta test showing change in capacitance of tertiary winding. After necessary precautions, checking all protection circuits and logic checks, transformer was charged. But it tripped at the instance of charging - with buchholz and differential relay operation. Outcome of all these test results discussed in following sections.

5.1 Capacitance and Tan delta Test

To ascertain insulating properties of the Transformer - capacitance and tan delta test was carried out. It is one of the most common tests performed on power transformers. The purpose of the test is to determine the capacitances and tan delta values - between the windings and for each winding with respect to earth. The said power transformer was overhauled (OH), and tan delta capacitance measurement carried out after overhauling. Capacitance and tan delta measurement also carried out after tripping of the ICT unit on buchholz relay operation - due to failure of LA. Both results were compared as shown in below table 1. No any major change was noticed and change in capacitance was found particularly in tertiary winding, however it was less than 5 %. No significant change in tan delta value recorded indicating that - there is no flashover occurred inside transformer, though movement of tertiary winding in radial direction could be anticipated as change in capacitance was noticed in CT(capacitance of tertiary winding with respect to earth) and CHT (capacitance between H.V. winding and tertiary winding). This indicates buckling of tertiary winding and same was confirmed by SFRA.

Date of Test	After OH 07.01.2016		After LA fail 07.07.2016		After tripping 12.08.2017	
Test ID	Tan Delta	Capacitance	Tan Delta	Capacitance	Tan Delta	Capacitance
CH+CHT	0.33	7280	0.29	7224	0.44	7323.7
CH	0.36	3651	0.35	3669	0.36	3640.5
CHT	0.3	3624	0.26	3550	0.51	3678.1
CT+CTH	0.35	9469	0.32	9623	0.62	10117
CT	0.38	5834	0.36	6064	0.73	6438
CTH	0.3	3623	0.27	3549	0.52	3678.2

Table 1. Capacitance and Tan Delta Results.

5.2 Measurement of Insulation Resistance (IR) and Polarization Index (PI)

Insulation resistance(IR) taken at one minute and at 10 minutes with application of 5kV DC through insulation tester and Polarization Index (PI) value was derived [6]. Result found normal and no any significant change perceived. Insulation resistance (IR) and Polarization Index (PI) after OH and after tripping shown in Table 2.

IR (G Ohms)	07.01.2016			07.07.2016			12.08.2017		
	1min.	10 min.	P.I.	1min.	10 min.	P.I.	1min.	10 min.	P.I.
HV to Earth	8.3	15	1.8	4.7	8.97	1.9	1.7	2.4	1.4
HV to Tertiary	12	34	2.7	7.6	19.2	2.5	1.6	2.3	1.4
Tertiary to Earth	8.9	26	2.9	6.3	13	2.1	2.3	3.5	1.5

Table 2. Insulation Resistance and Polarization Index.

5.3 Open Circuit and Short Circuit Test

To check electrical functioning of transformer, all routine tests were carried out - with single phase variac to keep supply voltage constant. Three results were noted down which are shown in table no.3, first one was taken after overhauling(OH) of transformer, second one was taken after failure of Lightning Arrestor (LA) and third one was taken after failure of transformer unit. During testing after failure of Lightning Arrestor (LA), magnetizing current was found increased in L.V. winding. However, same was due to residual magnetic flux inside the transformer core, and after de-magnetization of the core, result was found normal. After tripping dated on 12.08.2017, all results were found abnormal – especially magnetizing current increased significantly - indicating turn to turn short inside the transformer winding. Highest magnetizing current noticed for tertiary winding indicating turn to turn short in tertiary winding - same was confirmed by SFRA.

Routine testing	OH 07.01.2016	LA fail 05.07.2016	Tripped 12.08.2017
Open Circuit Test			
Applied voltage across to H.V.and Neutral	220V	220V	220V
Measured Voltage across L.V. -Neutral	123.3V	124V	111.8V
Measured voltage across tertiary (Volt.)	31.7	32.3	23.35
Measured H.V. mag. Current in (mili Amp)	3.47	3.77	450
Short Circuit Test (L.V. and Neutral Short)			
Applied Voltage across H.V. and Neutral	220	220	220
H.V. Current in (Amp)	5.48	5.5	5.51
L.V. Current in (Amp)	10.3	10.3	9.96
Short Circuit Test (HV and Neutral Short)			
Applied Voltage across LV and Neutral	220	220	220
L.V. Current in (Amp)	17.48	17.57	19.6
L.V. Current in (Amp)	10.3	9.86	9.96
Measurement of magnetizing current in tertiary winding (applied voltage 33V)			
Magnetizing current for tertiary (milli Amp)	23.82	12	4560

Table 3. O.C & S.C. Test with magnetizing currents.

5.4 Winding Resistance Test

DC winding resistance test is performed with an application of dc low voltage and high current. The ratio of dc voltage measured across winding and current through winding gives value of DC winding resistance.

In this case, measurement of DC resistance of windings was performed at an ambient temperature of 36 °C, the temperature of winding taken form winding temperature meter and results were noted as shown in table 4. This test was performed with application DC source causing flow of 10 Ampere current through the windings. Only value of DC winding resistance with OLTC tap position number 11 narrated in table for comparison - as transformer was tripped with OLTC tap position at No. 11. Results show that there was not any significant change in winding resistance which means there are no short circuit turns, poor joints, bad contacts or opening of conductor.

Date of Test	Tap Number	H.V.	L.V.	Tertiary
OH 07.01.2016	11	325	155.5	15.35
LA fail 07.07.2016	11	330	154.3	16.62
Trippped 12.08.2017	11	329	170.3	16.7
*H.V.,L.V. and Tertiary winding resistances are in mili Ohms				

Table 4. Resistance Measurements for Windings.

5.5 Dissolved Gas Analysis (DGA)

Dissolved Gas Analysis (DGA) test is performed to measure the amount of dissolved gases' content in transformer oil. Presence and content value of various key gases indicate intensity and severity of fault inside the transformer. Oil samples were taken from the transformer and sent to test laboratory.

DGA was carried out at one of the well-known testing laboratories - ERDA, Vadodara and DGA test results are shown in table no. 5. DGA results for sample drawn after overhauling (OH) is also shown for reference. After failure of Lightning Arrestor, significant increase in key gases was observed- particularly in Hydrogen. It may be due to external fault current fed through ICT unit. However, it was within permissible limit. Oil filtration was carried out before charging transformer and all key gases were found normal. After tripping of date 12.08.17, again DGA test was carried out and it indicates heavy flashover inside the transformer with temperature rise of more than 700 °C - as Acetylene increased significantly.

DGA	OH 07.01.2016	LA fail 05.07.2016	Trip 12.08.2017
Hydrogen H_2	2	152	3058

Oxygen	4969	3998	3058
Nitrogen	13997	20371	9031
Methane	1	42	256
Ethylene	Nil	4	653
Ethane	Nil	4	45
Acetylene	Nil	2	727
Carbon Dioxide	66	554	1194
Carbon Monoxide	2	122	468
Routine Test			
PPM	8	8	12
Tan Delta	0.0015	0.0038	0.0077
Resistivity (Ohm-metre)	$70*10^{-12}$	$70*10^{-12}$	$7.6*10^{-12}$

Table 5. DGA test result comparison table.

5.6 Sweep Frequency Response Analysis (SFRA)

SFRA is a very important test to ascertain the mechanical integrity of transformer winding. SFRA provides valuable information regarding overall mechanical integrity of individual windings for power transformer.

SFRA for each winding was done and compared with its base which was available before overhauling (OH). For SFRA of H.V. winding, signal was injected from H.V. winding and its response was measured at neutral bushing and comparison was done with its base as shown in figure 4.

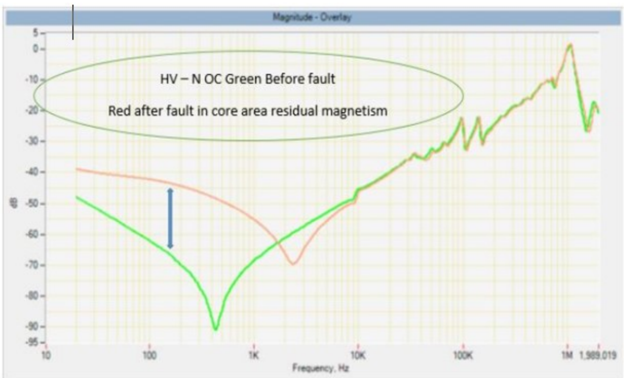

Fig. 4. SFRA of HV winding comparison with base result

In SFRA graphs for HV winding, difference was noticed in core area (low frequency region), while there was no any deviation in winding area (high frequency region). The difference in core area might be due to residual magnetism. SFRA carried out for LV winding with neutral bushing and deviation noticed in low frequency area - same as noticed in HV winding, and it may be due to residual magnetism. SFRA of tertiary winding also done and compared with base results - similar deviation noticed in SFRA traces of tertiary winding. Residual magnetism might have originated during fault condition. Effect of residual magnetism in LV and tertiary winding is shown in figure 5 and 6

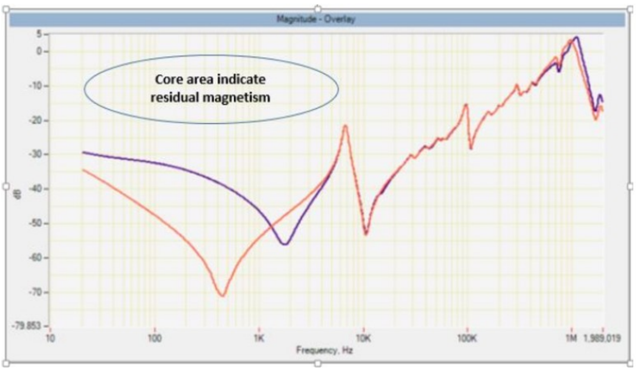

Fig. 5. SFRA of L.V. comparison with base

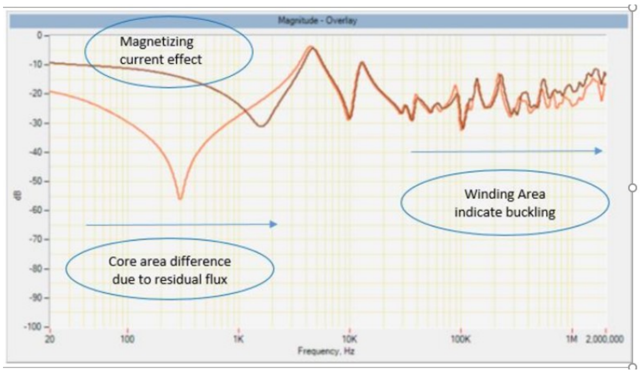

Fig. 6. SFRA of tertiary winding with base

For confirming that – deviation noticed in all three traces are attributed to residual magnetism, SFRA was conducted again for LV winding - after shorting tertiary winding terminals; and the response is shown in figure 5. The results clearly show that there is no any deviation in SFRA results which indicates that H.V. and L.V. both windings are intact.

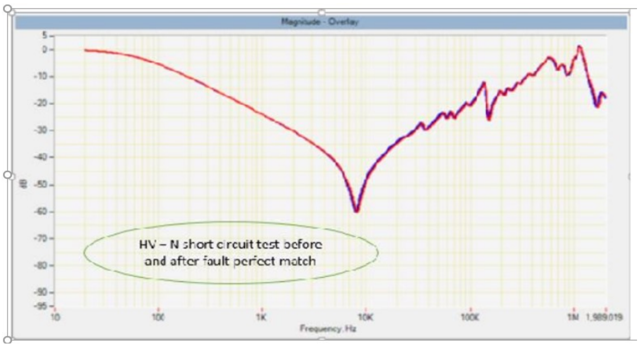

Fig. 7. SFRA of LV winding with tertiary short

For verification the effect of residual magnetism, demagnetization carried out for the transformer and once again SFRA test carried out for all windings individually. After demagnetizing, the SFRA trace of "H.V. – Neutral" in low frequency area almost matched to the base fingerprint as shown in figure 8.

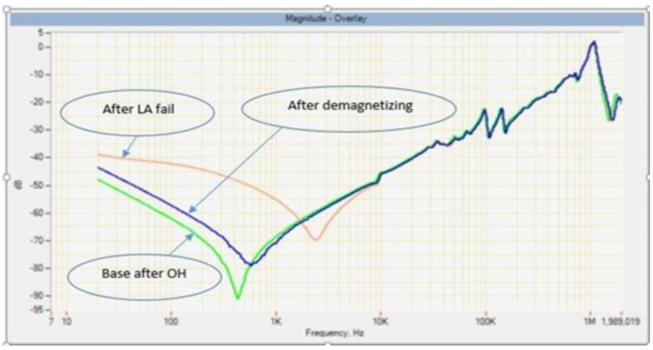

Fig. 8. SFRA of H.V. winding after demagnetization

After demagnetizing, the trace of "L.V.-Neutral" in low frequency area also matched to a great extent - to the base fingerprint as shown in figure 9.

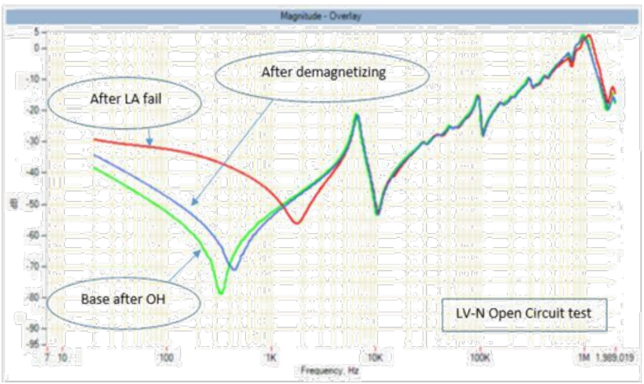

Fig. 9. SFRA of L.V. winding after demagnetization

After demagnetizing, the trace of "L.V.-Neutral" in low frequency area almost matched to the base fingerprint as shown in figure 10.

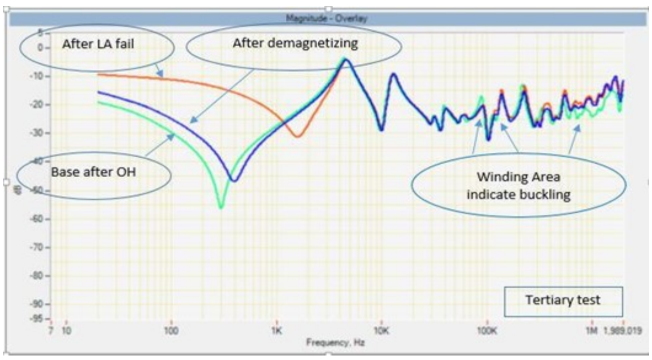

Fig. 10. SFRA of tertiary winding after demagnetization

5.6 Inspection

All test results found normal. Difference noticed in SFRA test results of tertiary winding indicated hoop buckling of tertiary winding, and same supported by capacitance and tan delta test, hence it was decided to inspect the transformer at site by lifting main tank. After removal of oil, thorough inspection of winding was carried out and nothing found abnormal in the transformer. No any black carbon particle or coper particle found inside main tank. After completion of internal inspection oil, filtration and drying out process for power transformer was carried out. All the required tests performed again. All the test results were found satisfactory or within permissible limit. The distortion in tertiary winding indicative from SFRA results - could not be observed / visualized after opening of transformer, as tertiary winding being innermost winding was surrounded by HV-IV winding - covered with hard board insulating cylinder. So nothing can be visualized for tertiary winding in inspection - as shown in figure 11.

Fig. 11. Inspection of active part of transformer

As transformer tank was bell type, huge crane required for lifting of main tank of power transformer. After analysis of all tests results and internal inspection, it was concluded that there was hoop buckling in tertiary winding. The conclusion was drawn from SFRA results and supported Capacitance and tan delta test results. The deviations recorded in SFRA and tan delta test results were within permissible limit, which indicated that the deformation was minor in nature. Deviation in SFRA and tan delta results had led to apprehension, however deviations were within permissible limits. Present available analytical tool of SFRA also didn't indicate any abnormality with Transformer windings.

5.7 Tripping of Transformer

Finally, it was decided to charge the transformer with all necessary safety precautions, as all results found within permissible limit. Transformer tripped at the instant of charging. So, all tests i.e. Tan delta, low voltage routine test, DGA, DC winding resistance and SFRA were performed again. All other test results after tripping shown in respective table. SFRA results of H.V. Winding were compared as shown in figure 12.

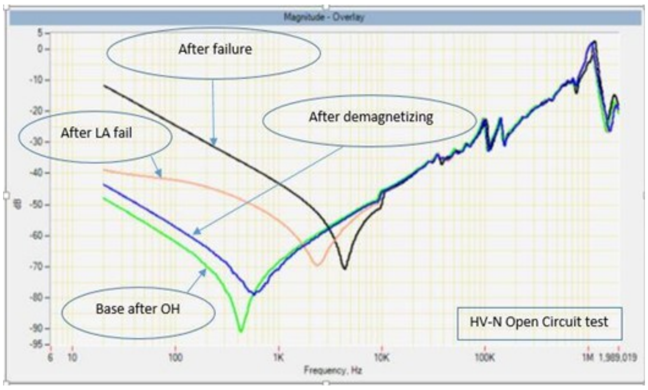

Fig. 12. SFRA of H.V. winding after tripping

As shown in figure 12 dB difference in low frequency area i.e. 10Hz to 100Hz, indicate turn to turn short. However, there was no any deviation in winding area which means that turn to turn short in other winding not in winding under tests i.e. HV winding. SFRA results of L.V. Winding were compared as shown in figure 13.

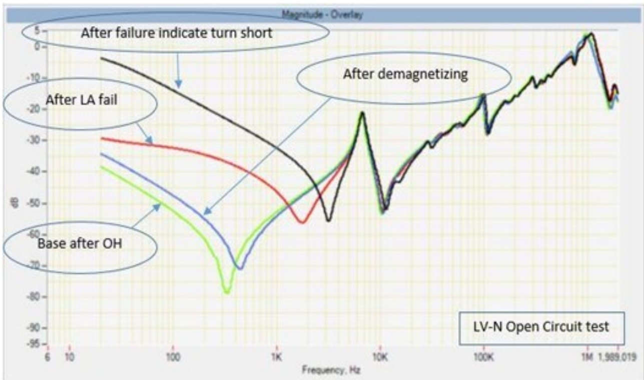

Fig. 13. SFRA of L.V. winding after tripping

As shown in figure 13 all four nos. of SFRA compared, in low frequency area i.e. 10Hz to 100 Hz, indicate turn to turn short. However, there was no deviation in winding area i.e. higher frequency and middle frequency which means that turn to turn short in other winding not in LV winding.

All four results of SFRA results of tertiary winding were compared as shown in figure 14 and deviation in low frequency as well as in middle and high frequency area was Cleary visible, which indicated turn to turn short in tertiary winding.

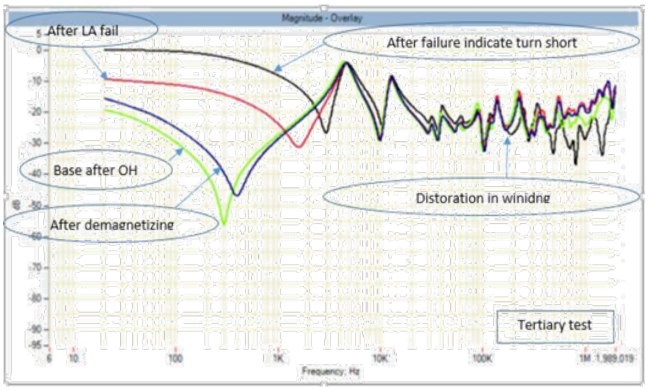

Fig. 14. SFRA of tertiary winding after tripping

Transformer was declared failed with base of SFRA and other test results, for verification of turn to turn shorting in tertiary winding, transformer was decided to open again and inspect the tertiary winding. After opening of transformer at site. H.V. and L.V. windings found intact and turn to turn shorting observed in tertiary as shown in figure 15.

Fig. 15. Buckled tertiary winding with turn to turn short

Transformer scraped and declared fail. To confirmed analysis of SFRA result for turn to turn shorted in tertiary winding proved with physical inspection at field level.

6. Conclusion

Sweep Frequency Response Analysis has proven that it provides valuable information about condition of power transformer windings and their mechanical integrity. SFRA in aid with other tests provides clear information about winding deformation, which cannot be visualize in physical inspection. Present available analytical tool of SFRA didn't indicate any abnormality with Transformer winding. With experience and expertise, proper judgements can be taken as to condition of the Transformer - even from Minor deviations recorded in SFRA traces. Information received with all test carried out will help to decision making authority to take quick and sound decision for transformer for further course of action , like expenditure for inspection, oil filtration required or not. With help of SFRA one can judge the internal condition of power transformer and take sound decision for replacement of transformer, repairing of transformer at site or sent at works etc.

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9. Bibliography

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