SFRA ability in detection of Deformation in Transformers Windings: A field experience of 400kV 167MVA single phase unit

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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 comparative method and provides better information when evaluation of Transformer condition is done by comparing actual set of SFRA results with reference results. This field experience consists 400/220/33KV ICT bank, formed with three single phase unit with capacity of 167MVA each. A heavy fault current was fed by ICT due to failure of LA provided on delta winding formed outside. Mechanical defects ostensibly occur due to a short circuit current flowing through power transformer in case of terminal faults i.e. fault near to power transformer. To know the mechanical integrity of power transformer SFRA test is carried out and is supported by other tests i.e. DC resistance, Magnetic balance, Winding resistance, capacitance and tan delta etc. The test results reveals that SFRA is capable of providing more information about mechanical deformation about power transformers compared to other tests.

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

1. Introduction

Power transformers in service, agonize through excessive electrical as well as mechanical stresses throughout its life span. Power transformers are most costly, substantial and important equipment of power system and their failure may cause serious problems in order to feed 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 service forces arise from system faults which arises adjoining to Power Transformer. The electromagnetic forces generated by faults may be axial, radial or assorted, depending on natures 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 [3].

In our case- study overhauling (OH) of single phase unit of B phase was completed on date 07.01.2016 and transformer was put back to service. Due to failure of LA on date 04.07.2016 movement of tertiary winding noticed in SFRA. The same was supported by capacitance and tan delta test results as the change of capacitance only in tertiary winding was noticed and it was concluded that due to failure of LA, heavy fault current was fed by power transformer, lead to radial displacement in tertiary winding. Other winding found intact in SFRA test. The deformation of tertiary winding was undetected by other tests i.e. open circuit and short circuit tests and winding resistance test, hence it was recommended that internal inspection should be carried out of power transformer. However, nothing was found abnormal as it was known that tertiary winding is at innermost region and HV winding of power transformer is covered around it with hard board insulation and hence it was not possible to visualize the same.

After comprehensive testing, it was predicted that tertiary winding displacement should be there and its mechanical integrity reduced but all other test results found in order and within limit and hence it was decided to charge the transformer. However, after taking all safety precaution and testing of protection transformer charged. Transformer couldn’t withstand charging current and tripped with differential relay with buchholz relay at the time of charging. After that once again transformer was meticulously tested and now SFRA test very clearly indicated turn to turn short in tertiary winding [4].This was due to deformation and reduction of mechanical strength of tertiary winding at the time when heavy fault current fed by HV and LV source due to failure of Lighting Arrestor.

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, due to system faults or faults inside the power transformers, causes axial or redial electromagnetic forces and if transformer winding is not capable to withstand such forces then deformation taken place in winding and sometimes immense deformation may cause transformer failure [5].

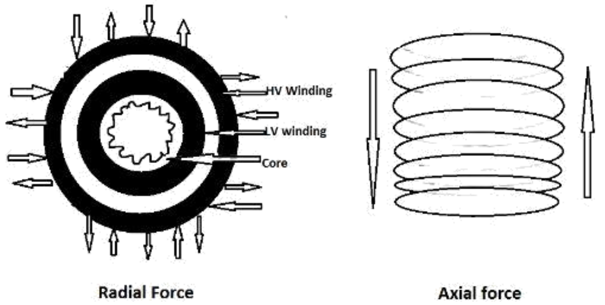

Fig. 1. (a) Radial Force (b) Axial force

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.

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 depend on impedance of particular winding that have with-stood test at particular frequency.

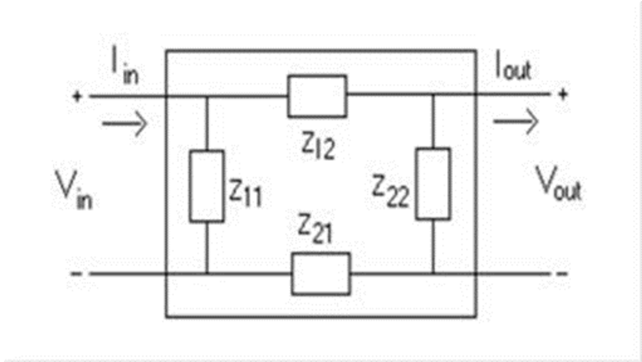

Fig. 2. Power Transformer as a two port network

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

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

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 involve comparison of two set of tests which is compared with base result and if base test is not available then compare it with sister unit, and if sister unit test is also not available then comparison is done with phase itself. If base available, then sound judgment can be taken with help of SFRA test.

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 the following purpose.

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-station, 500MVA interconnected power transformer (ICT) which consists bank of three single phase unit, each of 167MVA and tertiary winding with delta formation outside having adequate protection i.e. Lighting Arrestor (LA) and surge capacitor. 167 MVA B phase single unit over-hauling (OH) carried out and completed on date 07.01.2016, transformer charged and put in to service. On date 04.07.2016 due to failure of B phase, LA resulted into heavy fault current fed by said unit tripped with buchholz trip along with differential trip of bank. Suspected transformer of B phase, kept out of service for further investigation. 500MVA power transformer taken back in to service with utilization of spare single phase available unit, instead of suspected B phase. For to check healthiness of B phase unit all diagnosis test as well all routine tests carried out.

Overall test reports were normal and no any major fault inside the transformer was detected. It was decided to carry out internal inspection of power transformer as in DGA key gases were observed. After internal inspection nothing found abnormal inside the transformer and hence transformer oil filtration carried out and transformer cooled down naturally, and once again all tests carried out. Only SFRA test indicate deviation in tertiary winding and same was support by capacitance and tan delta test with change of capacitance in tertiary winding while tan delta test was performed. After necessary precaution checking of all the protection circuit and logic check, transformer was charged but it was tripped at an instance of charging with buchholz and differential relay. Outcome of all these test results discussed in following sections.

5.1 Capacitance and Tan delta Test

To know the condition of insulation of power 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 between the windings and different winding with respect to earth. The said power transformer overhauled (OH) and tan delta capacitance was measured and recorded after overhauled (OH). Also, capacitance and tan delta measurement was carried out after tripping of transformer with buchholz relay, due to failure of LA and compared with result taken after OH 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 was found i.e. There is no any 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 14.08.2016	
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			14.08.2016		
	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	2	1.7	2.4	1
HV to Tertiary	12	34	2.7	7.6	19.2	3	1.6	2.3	1
Tertiary to Earth	8.9	26	2.9	6.3	13	2	2.3	3.5	2

Table 2. Insulation Resistance and Polarization Index.

5.3 Open Circuit and Short Circuit Test

To check out electrical function 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 trans-former. From the table after failure Lightning Arrestor (LA), magnetizing current was found increased in L.V. winding and it was due to residual magnetic flux inside the transformer core and after demagnetization of the core, result was found normal. After tripping dated on 12.08.2017, all results were found abnormal particularly magnetizing current increased significantly, which indicate turn to turn short inside the transformer winding. Highest magnetizing current noticed in tertiary winding and it indicate turn to turn shorted in tertiary winding and same was confirmed by SFRA.

Routine testing	OH 07.01.2016	LA fail 05.07.2016	Trip 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 in tertiary (mili 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 ration of dc voltage measured across winding and current through winding will give the 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 in table 4. This test was performed with application DC source which cause flow of 10 Ampere current through the windings. Only value of DC winding resistance of OLTC tap position number 11 narrated in table for comparison as this transformer was tripped at tap number 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
Trip 14.08.2017	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 in transformer oil. The presence various key gases indicate the intensity and severity of fault inside the transformer. Oil samples are taken from the transformer and are send to test laboratory.

DGA was carried out at one of the well-known testing laboratory ERDA, Vadodara and DGA test results are mentioned in table no. 5 after overhauling (OH) for reference. After Lightning Arrestor (LA) failure, significant increase in key gases were observed, particularly in Hydrogen. It may be due to external fault current fed by power transformer. However, it was in limit, oil filtration was carried out before charging of transformer and all key gases were found normal. After tripping of date 12.08.17 again DGA test was carried out and it indicate heavy flashovers 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. Routine Tests and magnetizing current test.

5.6 Internal Inspection

As in above mentioned tests, results did not give any clear idea about the fault. As DGA indicated increment in key gases, capacitance and tan delta indicated movement in tertiary winding and SFRA indicated buckling in tertiary winding, it was decided to open the transformer using air dryer plant for inspection. As transformer was bell type, huge crane required for lifting of tank.

Fig. 3. Inspection of active part of transformer

After the removal of oil, main tank lifted at site, thorough inspection of winding was carried out and nothing found abnormal in the transformer. After completion of internal inspection oil filtration and drying out process for power transformer was carried out. All the required tests performed again to check whether the proper fitting and filtration was done or not. All the test results were found satisfactory. The distortion in tertiary winding which was noticed in earlier test i.e. SFRA, could not observed after opening of transformer, as winding was covered with hard board insulation and nothing can be visualized in inspection as shown in figure 3.

5.7 Sweep Frequency Response Analysis (SFRA) Test

SFRA is very important test to know the mechanical integrity of transformer winding. SFRA provides valuable in-formation regarding overall mechanical condition 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, source was injected from H.V. winding and its response was measured at neutral, comparison was done with its base is shown in figure 4.

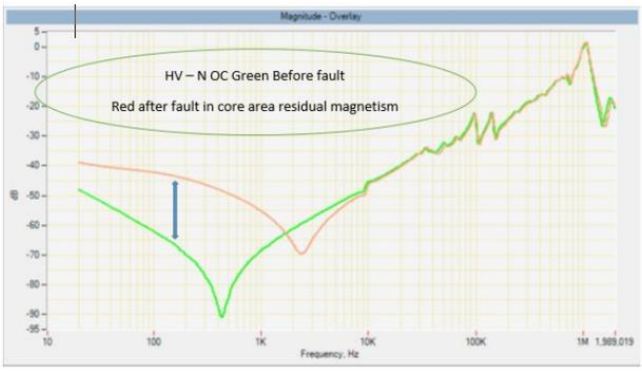

Fig. 4. SFRA of HV winding before OH and after LA fail

In SFRA test results, difference in core area (low frequency region) was noticed, while there was not any deviation in winding area (high frequency region). The difference in core area was due to residual magnetism.

To verify the effect of residual magnetism, SFRA was conducted again with shorting of tertiary winding 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.

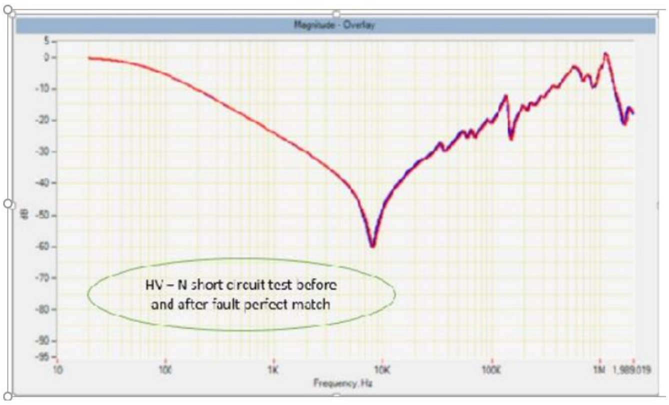

Fig. 5. SFRA of H.V. SC before OH and after LA fail.

SFRA test of L.V. winding was also done and compared with its available fingerprint, difference in core area (low frequency region) was observed which was due to residual magnetism, however, no deviation observed in winding area (high frequency region) as shown in figure 6. Hence L.V. winding was also found intact.

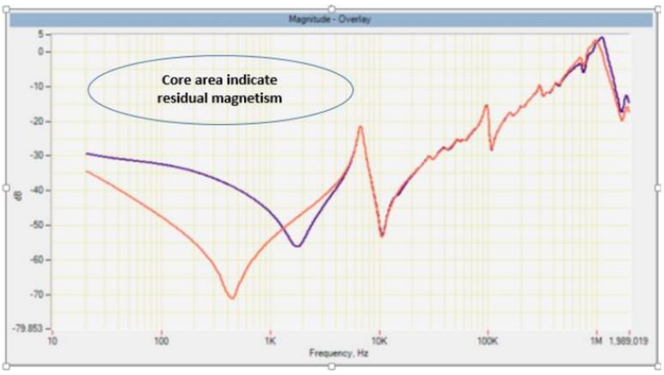

Fig. 6. SFRA of L.V. winding

SFRA test was performed on tertiary winding and its results was compared with its fingerprint and as usual, difference noticed in core area but as mentioned earlier the reason was residual magnetism, in addition deviation in winding area was also observed as shown in figure 7.

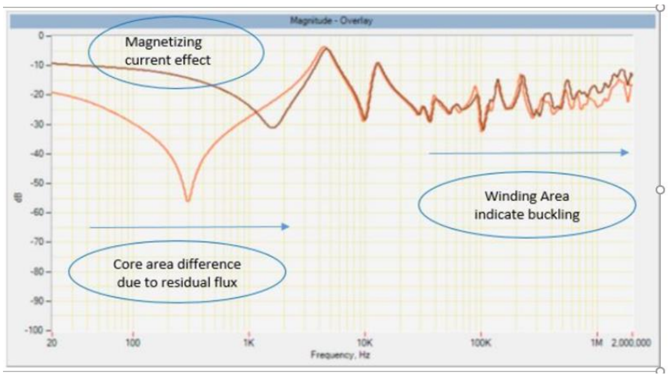

Fig. 7. SFRA of tertiary winding

As the deviation in winding area was noticed, and it was concluded that there could be buckling in tertiary winding and same was confirmed with tan delta test as there was change in capacitance of tertiary winding.

To re-verify the effect of residual magnetism it was decided to demagnetize the transformer by using demagnetizing technique and once again individual SFRA test on all windings were carried out .After demagnetizing, the trace of H.V. and neutral in low frequency area almost matched to the base fingerprint as shown in figure 8.

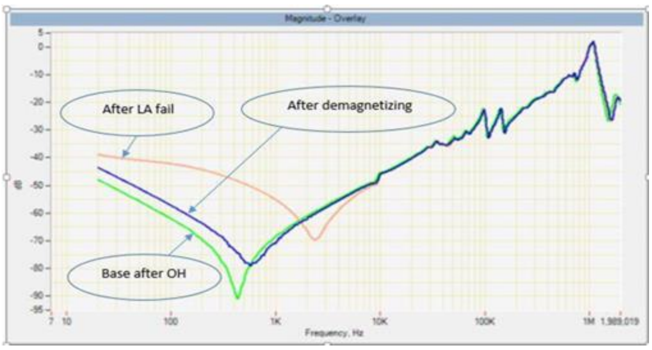

Fig. 8. SFRA of H.V. winding after demagnetization

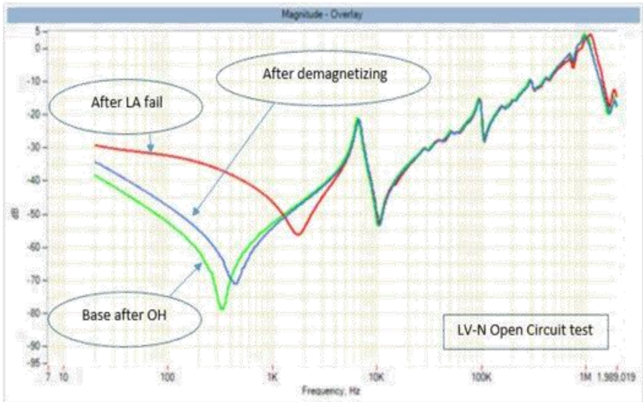

Fig. 9. SFRA of L.V. winding after demagnetization

In tertiary winding also the effect of residual magnetism was almost nullified, however, the deviation was noticed once again in winding area as shown in figure 10.

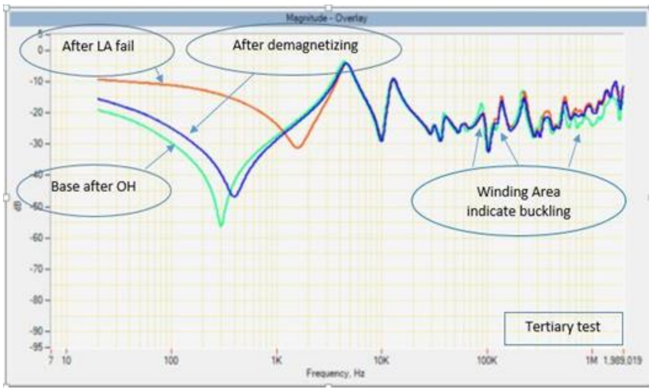

Fig. 10. SFRA of tertiary winding after demagnetization

So, now it could be said that there should be some deformation in tertiary winding.

After the analysis of all tests results, finally it was concluded that there was buckling in tertiary winding. The conclusion was supported by SFRA and tan delta results. The deviation SFRA results and tan delta results were permissible limit, which indicated that the deformation was minor.

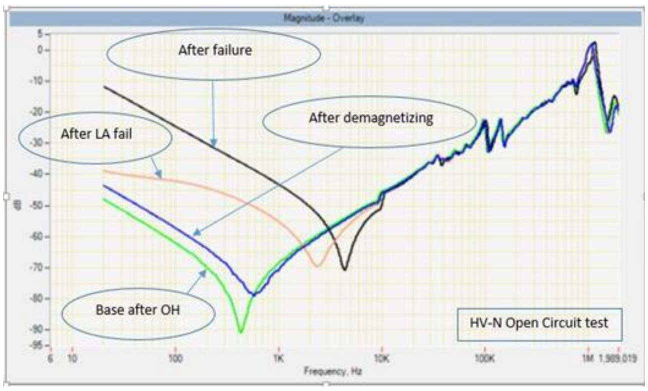

Fig. 11. SFRA of H.V. winding after tripping

Finally, the decision making authority has decided that to charge the transformer with all necessary safety precautions. At the instant of transformer charging, transformer was tripped. So, all tests i.e. Tan deltas, low voltage test , DGA, DC winding resistance and SFRA were performed again. All individual SFRA results of H.V. and L.V. windings were compared as shown in figure 11 and 12 respectively. As shown in figure 11 and 12, low frequency area indicated turn to turn short. However, there was no deviation in winding area which means that turn to turn short should be in tertiary winding.

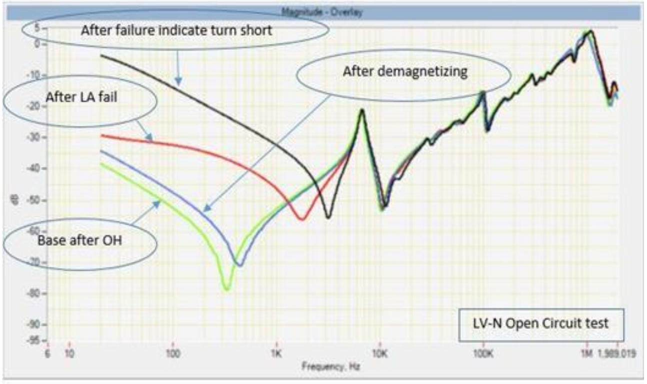

Fig. 12. SFRA of L.V. winding after tripping

All the SFRA results of tertiary winding were compared as shown in figure 13 and deviation in low frequency and high frequency are was Cleary observed, which indicated turn to turn short in tertiary winding.

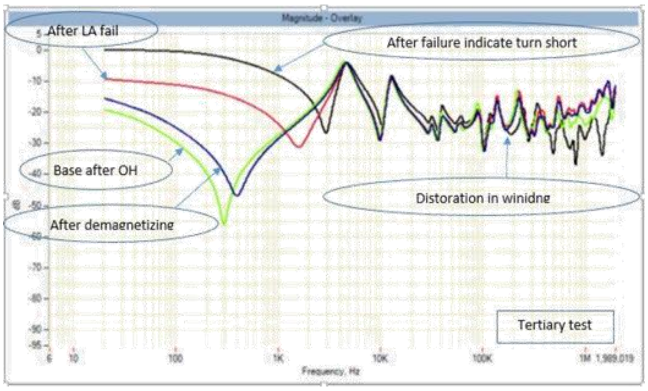

Fig. 13. SFRA of tertiary winding after tripping

Transformer was declared failed and to verify turn to turn short in tertiary winding, transformer was dismantled at site. H.V. and L.V. windings found intact and turn to turn short in tertiary was noticed as shown in figure 14.

Fig. 14. Buckled tertiary winding with turn to turn short

6. Conclusion

Sweep Frequency Response Analysis has proved that it provides valuable information about the condition of power transformers windings and its mechanical integrity. SFRA in aid with other tests provides clear information about winding deformation.

7. Acknowledgement

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8. References

[1] E.P.Dick and C.C.Erven," Transformer Diagnostics Testing by Frequency Response Analysis",IEEE Transaction on Power Apparatus and Systmes, Vol.97,pp. 2144 2153,Nov/Dec.1978.

[2] Asif Islam,Shahidul Islam Khan and Dr Aminul Hoque, "Detection of Mechnaical Deformation in Old Aged Power Transformer Using Cross Correlation Co-Efficient Analysis Method",Energy and Power Engineering, Vol.3, pp. 585–591,January 2011.

[3] M. Arul Sathya, Usa Savadamuthu," Prediction of Change in Equivalent Circuit Paramters of Transformer Winding Due to Axial Deformation using Sweep Frequency Response Analysis",Journal of Electrical Engi-neering and Technology, Vol.10, pp.983–989,May 2015

[4] Hormatollah Firoozi,Nami Mahmoodi,Mohammad Kharezi and M.I.Ghiyasi,"Frequency response analysis-

Low frequency character-istics and fault diagnosis on power transformers",IEEE International Conferense on Solid Dielectrics,Postdam,Germany,July2010.

[5] K.Ludwikowski,K.Siodla and W.Ziomek," Investigation of transformer model winding deformation using sweep frequency analysis", IEEE transaction on Dilectrics and Electrical Insulation, Vol.19. December 2012.

[6] S.D.Mayer,J.J.Kelly and R.H.Parrish, "A Guide to Transformer Mainte-nance",Transformer Maintenance Institute,USA,Second printing,1988.

9. Bibliography

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