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SFRA Ability to Find out Fault Inside The Winding: A Practical Case Study

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Abstract — **Sweep Frequency Response Analysis (SFRA) has become very popular now – a - days due to its ability to provide much more information regarding mechanical as well as electrical condition of power transformers. SFRA has ability to provide information about inner winding which cannot be visualized in internal inspection of power transformer. SFRA is 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 220/66KV 160MVA, power transformer tripped in differential relay. 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 compared to other tests.**

Keyword - Sweep Frequency Response Analysis, transformer, differential relay, terminal fault, mechanical integrity, Winding Deformation, capacitance and tan delta.

I. 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 cater 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 are arising adjoining to Power Transformer. The electromagnetic forces generated by faults may be axial, radial or assorted, depending upon the 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 [3]. In our case- study one 220/66kV 160 MVA power transformer has fed through fault 8500A currents for 360milisecond. Due to high current through the faulty transformer, inner winding shifted axially or radially and this turned up into transformer inner fault and transformer tripped by differential relay after through fault. In SFRA, distortion has been noticed in LV winding in middle frequency range [4]. Hence it was recommended to go for internal inspection of power transformer. But, nothing found abnormal as the low voltage windings are at inner most region and HV windings are covered around it with hard board insulation and hence it was not possible to visualize the same. However, carbon particle at lower part of R phase found. After comprehensive testing, winding displacement was predicted at low voltage i.e. 66kV side and flashover also took place between turn to turn, all test results found in order and within limit. Only SFRA indicated distortions in LV windings and carbon presence in bottom of R phase winding indicated issue in R phase. Hence transformer sent back to works for repairing. Supporting test winding resistance indicated increase in resistance compared with previous one. It didn't provide much more information. In Dissolved Gas Analysis, presence of key gases indicated abnormality in the transformer.

II. ELECTROMAGNETIC FORCES

An electromagnetic force is generated in current carrying conductor when surrounded with magnetic flux and its magnitude and direction depend on magnitude of current and its direction of flow. In power transformers while in service due to through faults, terminal faults or faults inside the power transformers generate axial or redial electromagnetic forces and if transformer winding is not capable to withstand then deformation take place in winding and immense deformation may cause transformer failure. 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 tend to subject transformer winding through radial electromagnetic forces. They act on the external winding coil from within, and on the internal winding coil inwards and result 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 cause winding buckling as narrated in figure 1 (a) and axial forces as is shown in Figure 1(b)

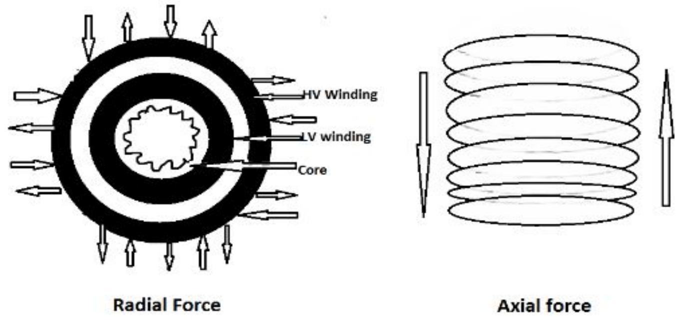

Figure. 1. (a) Redial force (b) Axial forces

III. SFRA

The first technical paper published on Frequency Response Analysis was 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 of inductances, capacitances and resistances. The complex structure of power transformers can be represented with two port network as shown in figure.

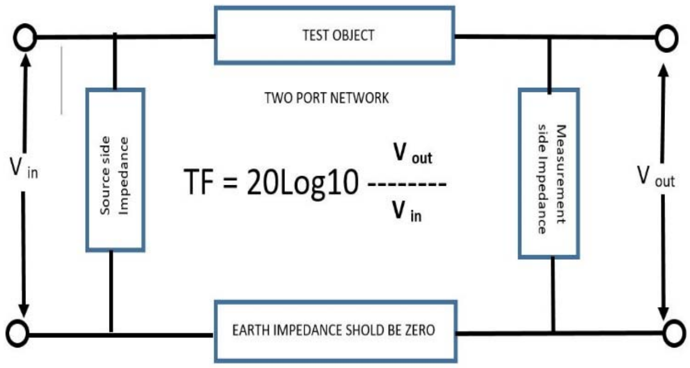

Figure. 2. Power Transformer as a two port network

The two port network, excited by the voltage signal, 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 withstood test at particular frequency. Output voltage Vout and Input Voltage Vin are compared in the frequency domain, the gain in dB as under

$$A\ dB = 20 \log 10\ \frac{V\ out}{V\ in} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

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

VI. THROUGH FAULT

In power system due to overhead construction of bus bars and lines, chances of through fault is much more, and if fault occurred near to transformers known as a terminal fault, fault current fed by the transformer is very high. Through fault passed through transformer for longer time as compared to transformer fault, as back up protection take longer time. Higher magnitude fault for more time create mechanical stresses inside the transformer and transformer windings may shift and any minor movement of active part may lead to the transformer failure.

V. CASE STUDY

At one of the 200kv sub-station, 2 nos. 160MVA power transformer were in service. During its service and normal functioning on date 16.06.2019 at 6.13Hrs, bus fault took place. It was due to heavy wind which caused conducting material fall on 66kv bus. Both transformers tripped with LV side, however transformer no. 1 tripped with differential relay and buchholz relay. Said transformer kept out of service for further investigation.

Disturbance Recorder (DR) extract from both numerical relay, differential as well as back up. From the disturbance recorder it was noticed that transformer has cleared the fault successfully at 6.13 as shown in fig.

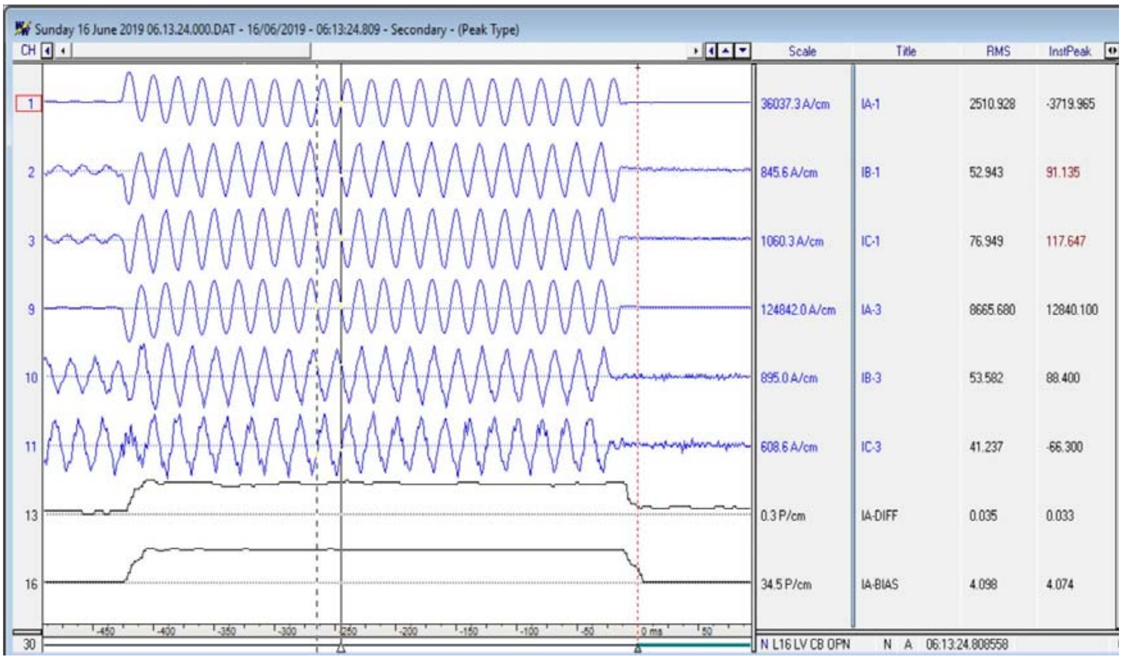

Figure. 3. Through fault fed by transformer in LV R phase

Transformer tripped with backup relay and LV breaker trip, hence fault current stopped and transformer charged from HV side. After 14 second fault took place again inside the transformer and transformer tripped with differential relay. Transformer HV side breaker kept off with differential relay and magnitude of differential fault current was very low i.e. 450 Amp in R phase and differential fault cleared within 75 milliseconds including all i.e. fault detecting and fault cleared and breaker off as shown figure .

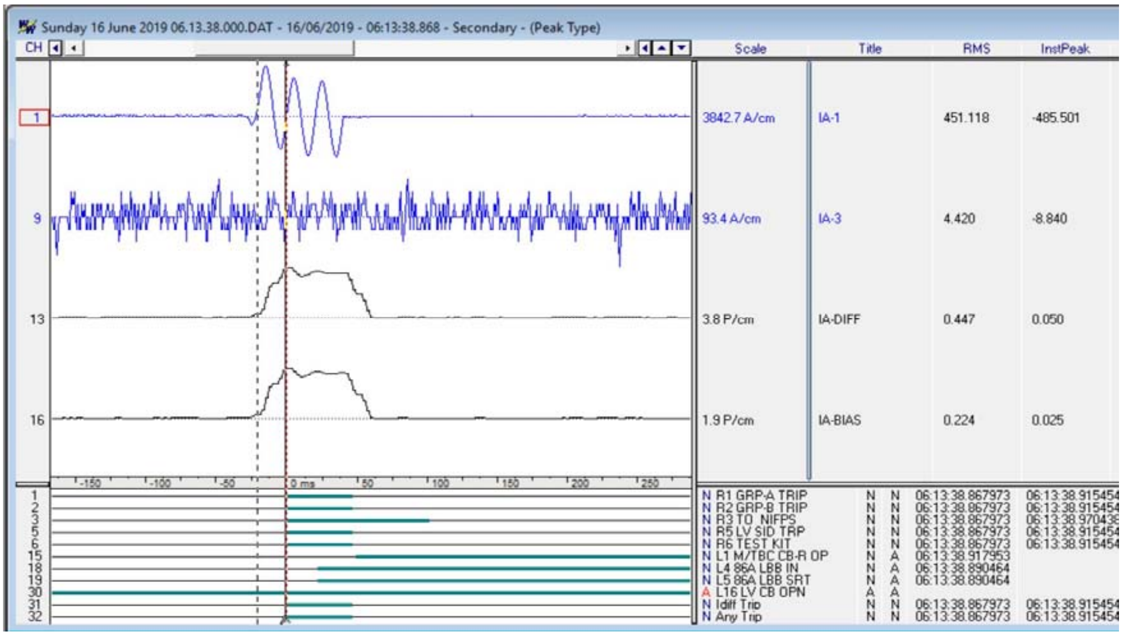

Figure 4. Differential fault occurred in HV R phase

A. *Capacitance and Tan delta test*

To know the condition of insulation of power transformer, capacitance and tan delta test was carried out. This test provide information regarding watt loss through insulation if watt loss more than previous results than it means insulation going to aging faster. Any change in capacitance value indicate change in mechanical integrity of winding or change in dielectric constant of insulation material used.

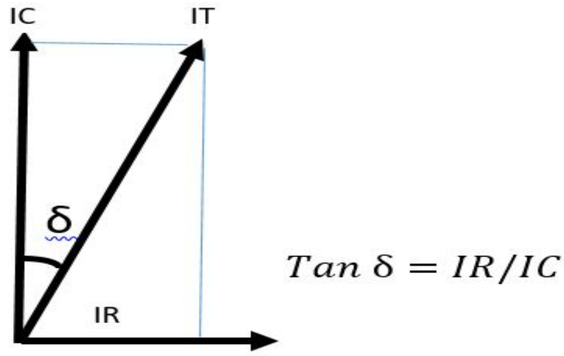

Figure. 5. Tan delta of insulation

It is one of the most common test performed on power transformer to know the healthiness of insulation system in our case tan delta value found within limit and value of capacitance also in permissible limit as shown in table. It indicate that there is no major change in insulation system, change in capacitance and tan delta noticed in LV winding, however it is in permissible limit.

TABLE I. Tan delta and Capacitance comparison

	Tan Delta Corr. @ 20 °C		Capacitance	
Date ---->	**12-03-2015**	**17-06-2019**	**12-03-2015**	**17-06-2019**
HV - Earth	0.2	0.26	3708	3657.08
LV - Earth	0.19	0.42	19560	19892.59
HV - LV	0.12	0.18	7800	7980.15

B. *Insulation resistance and polarisation index*

IR Value test is carried out for a Transformer to determine insulation resistance from individual windings to ground or between individual windings. PI (Polarization Index) value is ratio between 10 Minutes' IR value to 1 Minute IR value. Polarization Index test along with IR value test is carried out to determine service condition of the Insulation. Insulation resistance taken at one minute and at 10 minute with applied 5kv DC through insulation tester known as IR tester and Polarization Index PI value was derived. Result found normal and no any significant change perceived. Insulation resistance and Polarization Index before and after tripping shown in Table II.

TABLE II. Insulation Resistance and Polarization Index

	12.03.2015			**16.06.2019**		
	HV to E	**LV to E**	**HV to LV**	**HV to E**	**LV to E**	**HV to LV**
1 min.	8020	7800	6160	5500	4750	13000
10 min.	14700	14300	17800	12250	7500	25000
P.I.	1.83	1.83	2.89	2.22	1.578	1.923

C. ***Low Voltage or Routine test***

To check out electrical function of transformer all routine test carried out with low voltage. This all test known as a non-destructive test and provide information about overall healthiness of transformer. In this section all test are narrated one by one with its significant and results compare with base available, before fault and after fault.

Magnetic balance test is carried out for 3-Phase Transformers to identify inter turn faults and healthiness of magnetic circuit.

1) HV magnetic balance test

Three phase power supply applied to HV winding and measure the magnetizing current. This test indicates about magnetic circuit created by core.

Any shorted turn may result into high magnetizing current in particular phase. In our case all results found normal as shown in table.

TABLE III. HV Magnetizing current

Date: 12.03.2015			
Applied Voltage	RY	YB	BR
	428	413	411
	Current in mile Ampere		
Tap No.	HV R	HV Y	HV B
13	2.90	1.65	2.92
Date: 19.06.2019			
Applied Voltage	RY	YB	BR
	421	405	410
	Current in mile Ampere		
Tap No.	HV R	HV Y	HV B
13	3.40	2.05	3.04

2) LV magnetic balance test

LV magnetic balance test with application of three phase voltage LV side and note down LV magnetizing current at all taps. As our transformer in doubt having two winding hence both HV as well as LV magnetizing current required to be checked and nothing found abnormal in LV magnetizing current as shown in table IV.

TABLE IV. LV Magnetizing current

Dt	**12.03.2015**			**19.06.2019**		
App Voltage	RY	YB	BR	RY	YB	BR
	428	413	411	421	405	410
Tap No.	**Current in milli Amp.**			**Current in milli Amp.**		
	LV R	**LV Y**	**LV B**	**LV R**	**LV Y**	**LV B**
1	13.00	7.7	13.2	19.60	12.9	14.7
2	13.20	7.9	13.5	20.00	13.3	14.96
3	13.50	8	14	20.40	13.6	15.22
4	13.70	8.1	14.3	21.00	13.9	15.5
5	13.90	8.3	14.2	21.40	14.2	15.78
6	13.90	8.5	14.4	22.00	14.5	16.08
7	14.40	8.6	14.6	22.60	14.9	16.38
8	14.40	8.8	14.9	23.20	15.3	16.71
9	14.70	9.1	15.1	23.90	15.8	17.07
10	15.00	9.2	15.4	24.60	16.3	17.4
11	15.30	9.4	15.8	25.30	16.7	17.77
12	15.60	9.5	16.1	26.00	17.2	18.15
13	16.20	9.7	16.8	26.80	17.7	18.52
14	16.20	9.9	17.2	27.70	18.3	18.95
15	16.50	10.1	17.5	28.70	18.9	19.37
16	17.20	10.3	17.8	29.70	19.5	19.85
17	17.60	10.5	18.2	31.20	20.3	20.37

3) WINDING RESISTANCE TEST

Winding resistance measurement is carried out at site as routine or after fault tripping to check for abnormalities due to loose connections, broken strands of conductors, high contact resistance in tap changers, high voltage leads and bushings. Measurement of DC resistance of windings was performed at an ambient temperature, the temperature of winding taken form winding temperature meter and results noted as below in table. From the winding resistance test one cannot conclude about transformer winding condition as there is no any change in winding resistance

3.1) *HV Winding Resistance*

TABLE V. Winding Resistance test for windings.

12-03-2015	**Ambient Temp. 37°C , Winding Temp.: 43°C**					
	Measured Resistance. in mΩ			**Resistance Value at 75°C**		
Tap No.	RN	YN	BN	RN	YN	BN
13	261.6	261.80	262.00	291.71	291.94	292.16
16-06-2019	**Ambient Temp.: 35°C, Winding. Temp.: 35°C**					
	Measured Resistance. in mΩ			**Resistance Value at 75°C**		
Tap No.	RN	YN	BN	RN	YN	BN
13	275.4	276.2	275.4	316.20	317.12	316.20

3.2) LV Winding Resistance

LV winding separate as this transformer constructed with two winding not auto hence as tap in LV winding resistance taken at each tap. And shown in below table no.5 there is difference in winding resistance and it is due to temperature difference, however increasing and decreasing trend with very of tap position is same i.e. there is no change in winding resistance.

TABLE VI. Winding Resistance test for Low Voltage windings.

Date	**12.03.2015**			**16.06.2019**		
	Oil 31°C / Wdg. 35°C			**Oil 41°C / Wdg. 45°C**		
Tap No.	**Measured Resi. in mΩ**			**Measured Resi. in mΩ**		
	rn	**yn**	**bn**	**rn**	**yn**	**bn**
1	22.55	23.00	22.44	24.34	23.58	23.58
2	22.17	22.63	22.05	23.89	23.12	23.11
3	21.75	22.2	21.63	23.67	22.72	22.77
4	21.34	21.8	21.22	23.01	22.26	22.26
5	20.93	21.37	20.78	22.8	21.82	21.89
6	20.47	20.97	20.39	22.1	21.41	21.37
7	20.05	20.57	19.96	21.9	20.96	21.03
8	19.63	20.14	19.53	21.2	20.51	20.48
9	19.08	19.58	18.98	20.63	19.93	19.91
10	19.66	20.17	19.57	21.24	20.56	20.54
11	20.06	20.55	19.96	21.83	20.96	21.01
12	20.46	20.94	20.36	22.09	21.39	21.35
13	20.86	21.35	20.78	22.64	21.85	21.86
14	21.26	21.75	21.19	22.93	22.27	22.2
15	21.74	22.16	21.59	23.53	22.67	22.72
16	22.14	22.58	22.02	23.84	23.07	23.07
17	22.55	23.00	22.45	24.36	23.59	23.58

4) *SHORT CIRCUIT TEST*

In this test three phase applied to HV winding and LV winding shorted with coper conductor. In this test current measured in HV and LV winding and as per ratio calculate results compare with previous results nothing found abnormal in this test also.

TABLE VIII. Short circuit test

Date	12.03.2015						16.06.2019					
Applied Voltage	RY 425		YB 423		BR 428		RY 421		YB 405		BR 410	
Phase TapNo	HV R Amp	LV R Amp	HV Y Amp	LV Y Amp	HV B Amp	LV B Amp	HV R Amp	LV R Amp	HV Y Amp	LV Y Amp	HV B Amp	LV B Amp
1	6.2	17.6	6.1	17.6	6.1	17.6	6.1	17.8	6.2	17.8	5.9	17.2
2	6.1	17.7	6.1	17.7	6.1	17.7	6.1	17.6	6.1	17.7	5.8	16.9
3	6.1	17.9	6.0	17.9	6.1	17.9	6.1	17.7	6.1	17.8	5.8	17.2
4	6.1	17.9	6.0	18	6.1	18	6.0	17.8	6.1	18.1	5.8	17.3
5	6.0	18.1	6.0	18.2	6.0	18.2	6.0	18	6.0	18	5.8	17.4
6	6.0	18.2	6.0	18.3	6.0	18.3	6.0	18.2	6.0	17.9	5.8	17.6
7	6.0	18.4	5.9	18.4	6.0	18.4	6.0	18.2	6.0	17.9	5.8	17.8
8	6.0	18.5	5.9	18.4	6.0	18.4	6.0	18.2	6.0	18.1	5.8	17.9
9	5.9	18.6	5.9	18.6	5.9	18.6	5.9	18.2	5.9	18.2	5.7	18
10	5.9	18.7	5.8	18.7	5.9	18.7	5.9	18.2	5.9	18.3	5.7	18.1
11	5.8	18.8	5.8	18.8	5.8	18.8	5.8	18.2	5.8	18.5	5.6	18.1
12	5.8	18.8	5.8	18.8	5.8	18.8	5.8	18.2	5.7	18.5	5.6	18.2
13	5.8	18.9	5.7	18.9	5.8	18.9	5.8	18.2	5.7	18.6	5.6	18.2
14	5.7	19	5.6	19	5.7	18.9	5.7	18.2	5.7	18.8	5.5	18.2
15	5.7	19	5.6	19.1	5.7	19.1	5.6	18.2	5.6	18.8	5.4	18
16	5.6	19	5.5	19.1	5.6	19.1	5.6	18.2	5.6	18.8	5.4	18.4
17	5.6	19	5.5	19.1	5.5	19.1	5.5	18.2	5.5	18.6	5.3	18.4

5) *VOLTAGE RATIO TEST*

Voltage ratio or turn ratio test provide conformation about proper function of power transformer at for which it design actually. Voltage ratio measured with applied primary side three phase AC supply voltage and measured the LV side voltage at each tap. Where in turns ratio applied voltage kept constant primary side and measured the voltage at secondary to avoid any change in AC supply in measurement. In our case turn ratio test carried out with kit and all results found within permissible limit, as shown in below table.

TABLE IX. Voltage Ratio test

Tap. No.	% Ration Deviation (less than 0.5% allow)		
	R phase	Y phase	B phase
1	0.40	0.45	0.49
2	0.35	0.46	0.47
3	0.31	0.43	0.42
4	0.29	0.39	0.39
5	0.23	0.33	0.33
6	0.22	0.31	0.31
7	0.18	0.25	0.26
8	0.13	0.22	0.26
9	0.09	0.18	0.19
10	0.03	0.16	0.15
11	0.01	0.13	0.10
12	0.04	0.07	0.08
13	0.06	0.01	0.02
14	0.13	0.03	0.01
15	0.17	0.05	0.06
16	0.08	0.12	0.11
17	0.27	0.16	0.16

D. *Dissolved Gas Analysis (DGA)*

Dissolved Gas Analysis carried out after fault in transformer and compare with previous results. DGA indicate increasing in key gases in oil present it may be due to heavy fault current fed by transformer not clear indication of fault and key gases can be removed with oil filtration and in many case study such type phenomena observed most of the all test carried out on transformer and

TABLE X. Dissolved Gas Analysis

Date/ Gas	Hydrogen	Oxygen	Nitrogen	Methane	Ethylene	Ethane	Acetylene	carbon dioxide	Carbon Monoxide
4.10.18	11	6738	32711	4	Nil	Nil	NIL	1182	405
17.6.19	13	8073	46807	12	23	2	24	1282	209

E. *Sweep Frequency Response Analysis (SFRA)*

Sweep frequency response analysis carried out after differential trip and compare with base signature available and all test results found normal. However, in LV and HV R phase in winding area deformation notice and it indicated that there is shift in LV winding and same reflected in HV windings. Distortions in LV winding shown in below figure blue trace is before fault and consider as base and red trace after fault and in mid frequency area clear deviation noticed.

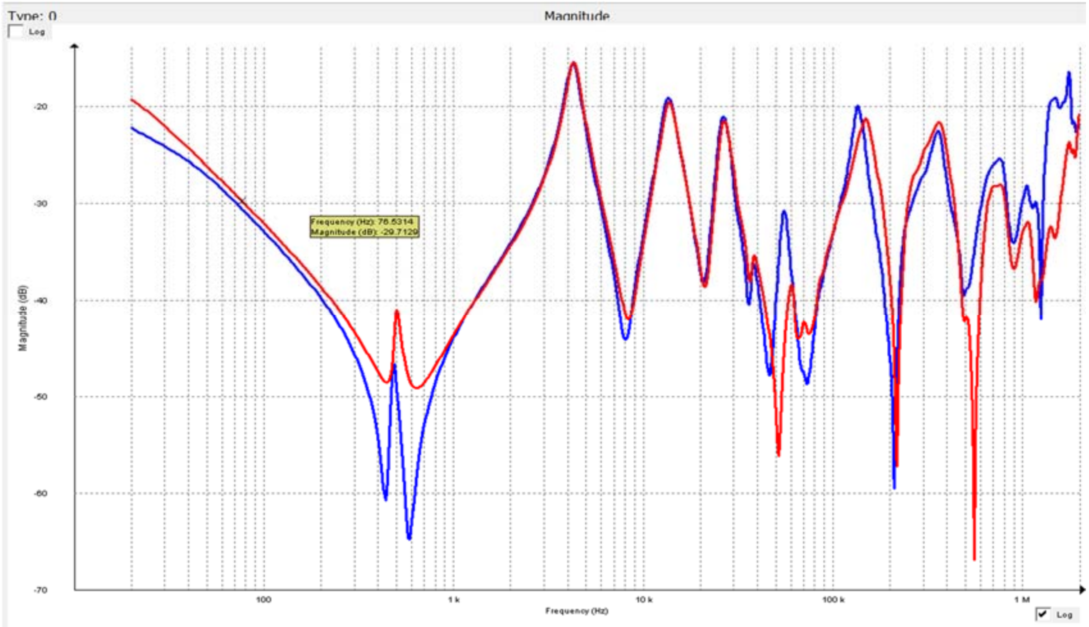

Figure 6. LV R-N Blue before fault and Red after fault comparison

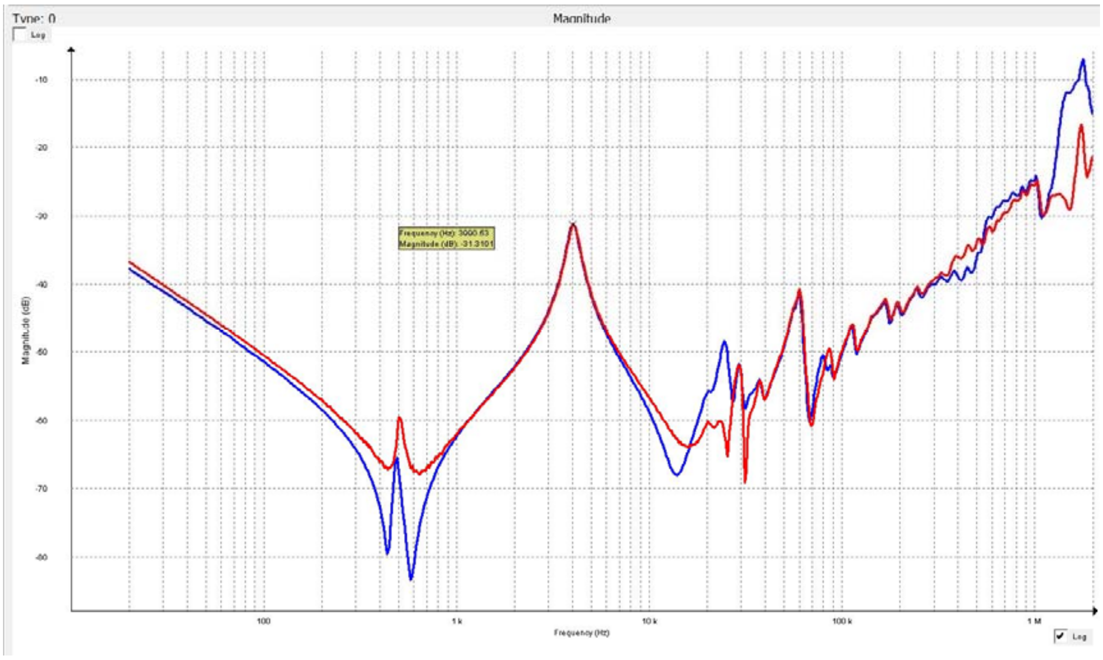

Figure 7 . HV R-N Blue before fault and Red after fault comparison

H. *Internal Inspection*

After the study of all test results with analysis of SFRA, it was concluded that LV winding was deformed which cannot be visualized in internal inspection. However, to find out any other damaged caused due to deformation of LV winding, internal inspection was carried out. In internal inspection, at bottom part of R phase winding carbon particles were noticed as shown in figure 8.

Figure 8. In internal inspection minor carbon particle find out

VI. CONCLUSION.

This is a case where in we can state that in the event of bus fault, due to metallic object fall in bus heavy through fault current fed by the transformer. After successfully clear the fault by transformer, transformer cannot with stand more voltage stress and trip with differential relay and buchholz relay. Fault created in transformer is not major, hence detection is not easy. SFRA test in such situation provide more information about mechanical as well as electrical integrity of transformer windings. There is no any major fault inside the transformer only displacement in HV and LV winding of R ph. it is difficult to know about geometric changes would have occurred in the transformer, can be ensured by carrying out SFRA test post failure it can be matched with base SFRA test. The same is done in this case, in winding area creation of new resonance point and elimination of old resonance point indicate displacement in winding. While in internal inspection nothing found abnormal, as fault in winding and winding covered with hard insulation one cannot find anything, however SFRA clearly indicate movement in winding.

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