Chapter 6

Variation in SFRA plot due to design and external parameter

6.1 Introduction

As the experience grows with Sweep Frequency Response Analysis in world, it is useful to discuss the measurements and results in context of the practical application where SFRA has been used for decision support . It is important to highlights the various aspects of SFRA plot variation due to design and external parameters . By understanding these points, it will be easy to understand the good practice in taking measurements and making conclusions which is supported by evidence from other test data also. SFRA is now accepted , as part of routine test for new transformer at manufacturer place and as a post-fault investigation test for aged transformer.

It is observed that although the detailed form of a frequency response depends on the winding design used, usually the basic overall form of the response is surprisingly similar for the same type of winding, even for significantly different winding arrangements, and therefore is presumably determined by some essential distinguishing property of the type of winding involved, rather than the details of its construction. The method of interconnection used, e.g. LV delta connection, also results in very characteristic forms.

This chapter discusses SFRA data from several cases in the field in context of variation in plots which is not due to fault in transformer, along with discussion of results and lessons learned .

6.2 Effect of Oil-Comparision of SFRA plot for Sister unit with full and partially filled oil

Two nos. of single phase transformer were tested for SFRA and they were sister units with following details.

132 kV/ 33 kV, 25 MVA Power Transformer

ON LOAD Tap changer

Winding configuration - HV/LV

Year of manufacturing - 2006

Serial No.: T-1 (With Full oil) and T-2 (Partially filled oil)

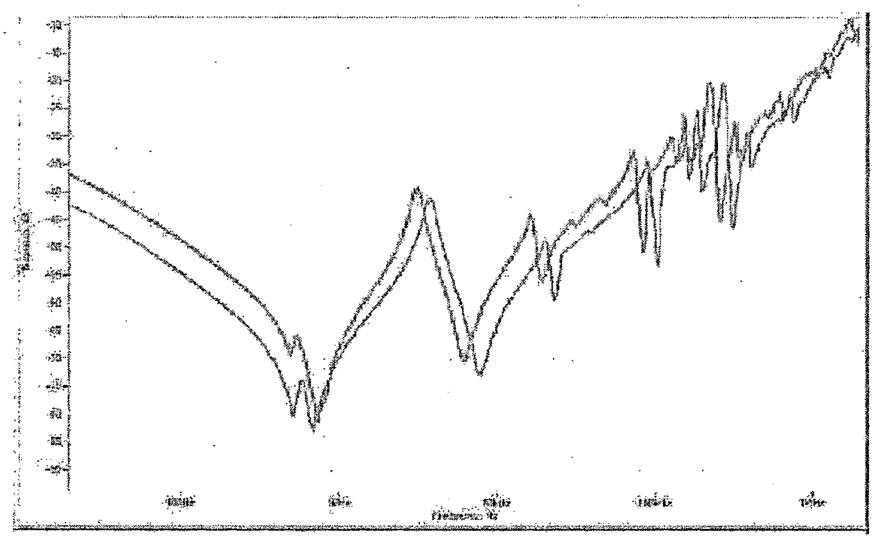

Figure 6.1: Open circuit SFRA plot of HV winding for both the sister unit (with oil-Red color)

When SFRA measurement were carried out with full oil in tank, the relative permittivity from air to oil ($\epsilon_r = 2.2$) increases the overall capacitance of transformer and shifted the resonant frequency to lower frequency for full oil filled transformer as shown in Figure 6.1 and Figure 6.2. The overall trends of SFRA variation corresponds well for the SFRA plot of with oil and without oil measurement. The identical low frequency region of SC plot (Figure 6.1) indicate that effect of capacitance is null and it is dominated by resistive and inductive parameter of the winding.

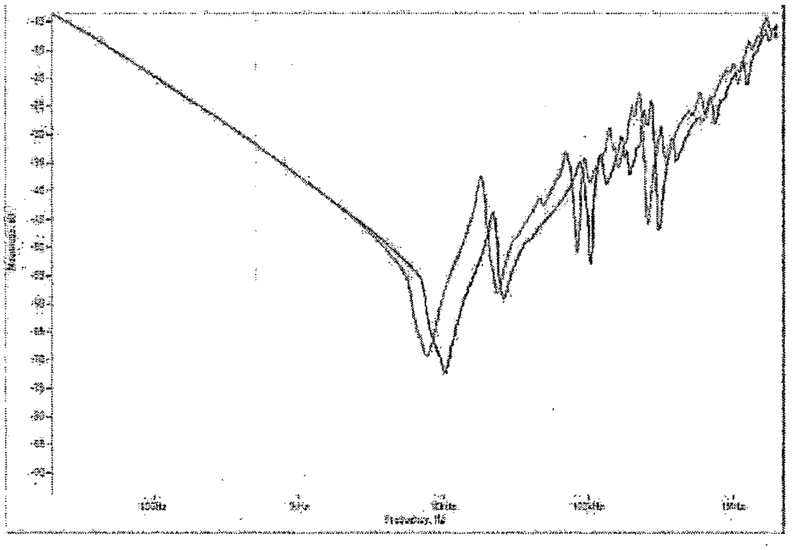

Figure 6.2: Short circuit SFRA plot of HV winding for both the sister unit (with oil-Green color)

The inter winding plot is shown in Figure 6.3, which is mainly capacitive in nature at low frequency due to the fact that circuit element of transformer which act is the intertwining capacitance of insulation mainly.

6.3 Variation in SFRA due to Residual Moisture of Winding

The effect of excessive moisture content, on the SFRA signatures, is identified by a practical example of the application of SFRA to 17 years old, 16MVA transformer which was having high moisture content[56]. No maintenance was carried out on the transformer since it was commissioned. No history available with the customer. However, major observations made in visual inspection were:

- Leakages at various points on tank body.
- Breather completely pink.
- Huge water logging below the transformer, this gave an idea that transformer was

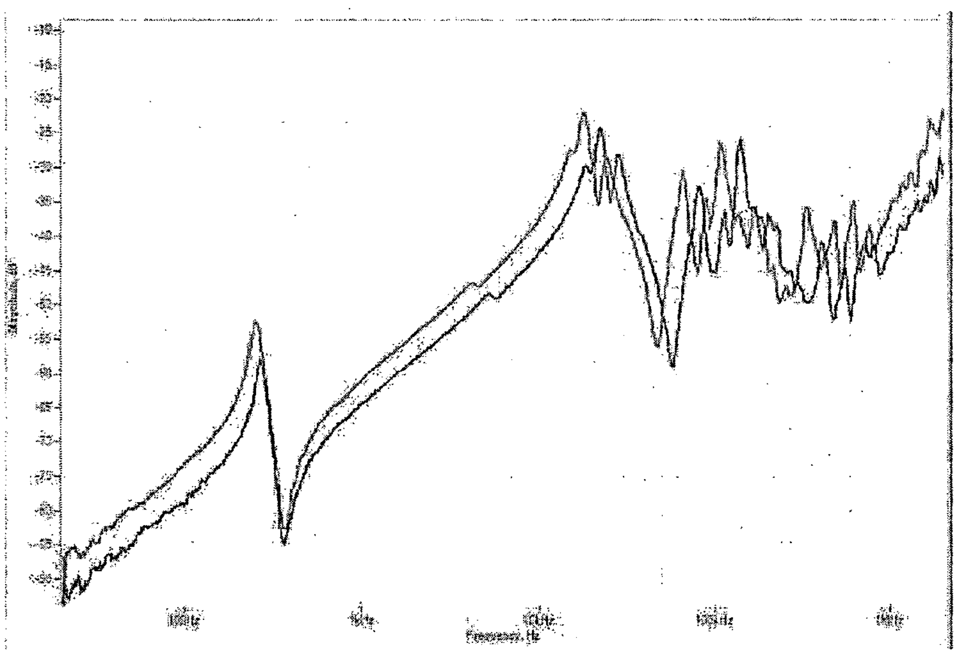

Figure 6.3: Inter winding SFRA plot of HV-LV winding for both the sister unit (with oil-Red color)

exposed to moisture as indicated in the Figure 6.4 below.

Figure 6.4: Water accumulation at the base of transformer

All the low voltage routine tests were carried out to verify the electrical parameters.

Observationsa:

1. Tan delta values too high (> 3.8 percent) indicating high moisture content.
2. Polarization Index was low (< 1.1 percent) indicating high moisture content.
3. Moisture content of oil was too high (73 ppm)
4. SFRA was conducted to determine mechanical integrity of transformer. In absence of reference signature, phase to phase comparisons were made as seen in Figure 6.5. Phase to phase comparison showed good correlation indicating that transformer is mechanically intact.

Recommendations

Based on visual inspection and the results of off -line tests recommendations given were:

1. To arrest oil leakages.
2. To replace gaskets.
3. To dry out transformer.

For drying out transformer on-site, Low Frequency Heating system was preferred. Around 17 liters of water was removed from the transformer during the application of Low frequency heating(LFH.)

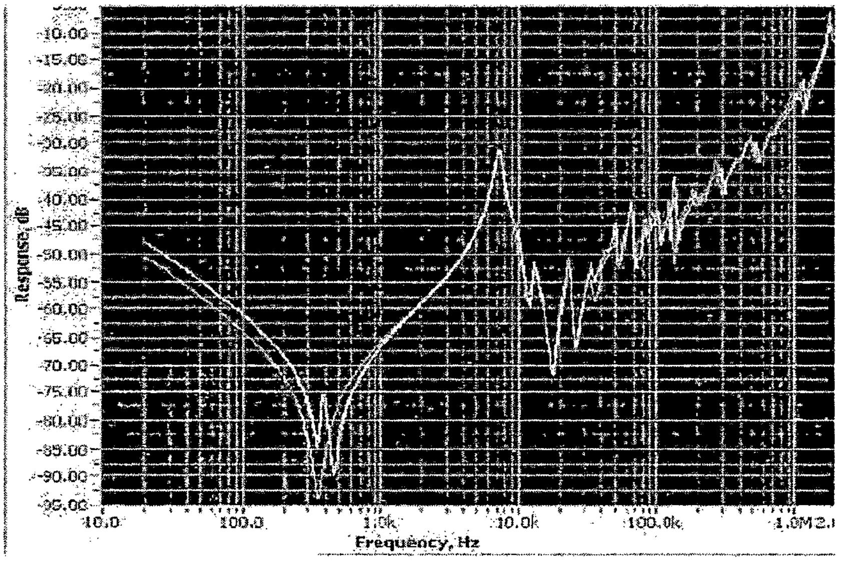

Figure 6.5: Comparison of three phase Open circuit Base SFRA plot before drying out

After the drying out the three phase SFRA plot were compared and it was identical as shown in Figure 6.6. However , when the SFRA plot before and after drying out was compared, above first resonance, frequency shift in the Plot is observed as shown in Figure 6.7. Variation is mainly due to change in effective capacitance of the transformer circuit [5]. As the resonant peak frequencies has increased for the SFRA plot after drying out, the effective capacitance must have decreased. Since the geometrical parameters of the transformers were unchanged, change in effective capacitance is mainly due to change in moisture content as explained below.

Notations:

Before LFH drying out,

- F_{r_1} = Ref resonant freq
- C_1 = Effective capacitance
- L_1 = Effective inductance

Table 6.1: Improvement in the parameters of transformer after drying out process.

	Before LFH	**After LFH**
BDV	3.4	68
Water content of oil (ppm)	73	10
$\tan\delta$ of oil	0.0237	0.00015
% $\tan\delta$ of winding		
HV-LV	3.350	0.722
HV-GND	2.699	0.886
LV-GND	3.854	0.654
HV-LV+GND	3.839	0.789
Capcitance in pF		
HV-LV	3887.38	3583.23
HV-GND	2960.41	2785.03
LV-GND	6939.32	6419.69
HV-LV+GND	6849.41	6369.1
Insulation Resistance 60 Sec	(in M ohms)	(in G ohms)
HV-LV	57.5	4.07
HV-LV+Earth	47.8	3.89
LV-HV+Earth	40.0	2.38
Insulation Resistance 10 min	(in M ohms)	(in G ohms)
HV-LV	61.5	6.6
HV-LV+Earth	49.8	4.78
LV-HV+Earth	42.0	3.68
PI		
HV-LV	1.07.	1.6
HV-LV+Earth	1.04	1.23
LV-HV+Earth	1.05	1.55

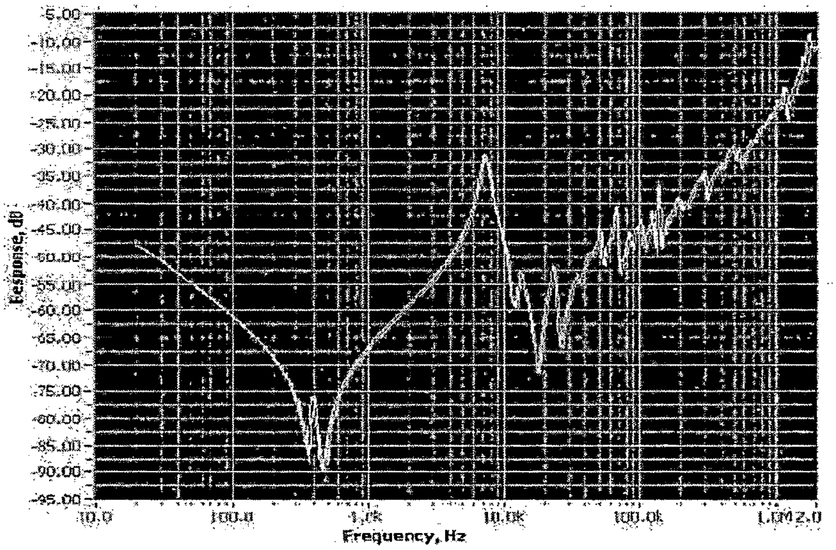

Figure 6.6: Comparison of three phase Open circuit Base SFRA plot after drying out

After LFH drying out,

- F_{r_2} = New resonant freq
- C_2 = Effective capacitance .
- L_2 = Effective inductance

$F_{r_1} = 13.41kHz$ and $F_{r_2} = 13.86kHz$ (from Figure 6.7).

General formula for resonant frequency

$$F_r = \left(\frac{1}{2\pi\sqrt{LC}}\right)$$

For two different cases, i.e. before and after LFH as indicated in Figure6.7,

$$F_{r_1} = \left(\frac{1}{2\pi\sqrt{L_1C_1}}\right) \tag{6.1}$$

$$F_{r_2} = \left(\frac{1}{2\pi\sqrt{L_2C_2}}\right) \tag{6.2}$$

Dividing equation (8.1) by equation (8.2)

$$\frac{F_{r_1}}{F_{r_2}} = \frac{\left(\frac{1}{2\pi\sqrt{L_1C_1}}\right)}{\left(\frac{1}{2\pi\sqrt{L_2C_2}}\right)} \tag{6.3}$$

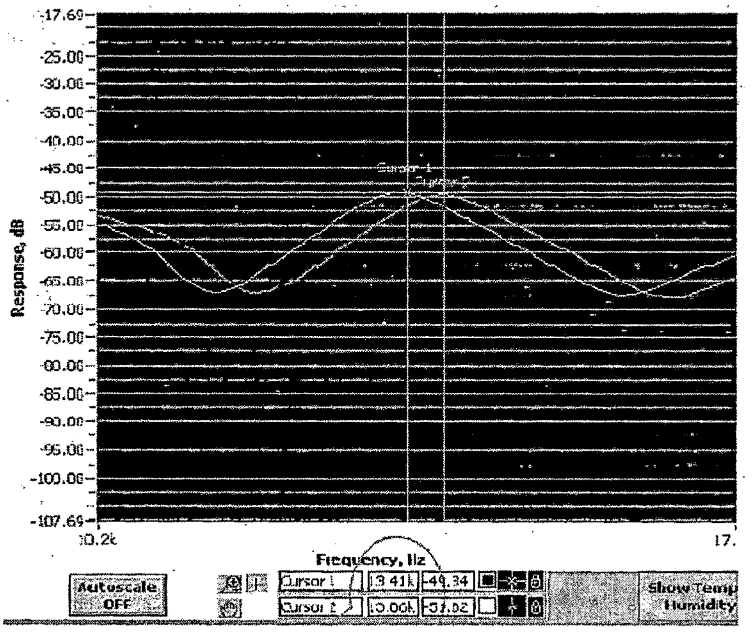

Figure 6.7: Expanded view of Comparison of per phase Open circuit SFRA plot before and after drying out

As the geometrical parameters are unchanged and no shift is observed in the low freq region of SFRA plots, it is assumed that there is no effect of LFH process on the inductance of the circuit. Therefore,

$$L_1 = L_2 \tag{6.4}$$

Applying equation (8.4) in equation (8.3)

$$\frac{F_{r_1}}{F_{r_2}} = \frac{\left(\frac{1}{2\pi\sqrt{C_1}}\right)}{\left(\frac{1}{2\pi\sqrt{C_2}}\right)}$$

i.e.

$$\frac{C_2}{C_1} = \frac{F_{r_1}^2}{F_{r_2}^2} \tag{6.5}$$

Putting values of F_{r_1} and F_{r_2} (From Figure 6.7) in equation (8.5)

$$\frac{C_2}{C_1} = \frac{13.41^2}{13.86^2} = 0.9361 \qquad \textit{(derived)} \tag{6.6}$$

This means, ratio of the effective capacitances after LFH and before LFH is 0.9361. In order to verify this, capacitance values obtained during C and $\tan\delta$ test were compared. $C_2' = 6369.1$ pF and $C_1' = 6849.41$ pF.

Where,

C_1' = capacitance between HV-LV+GND before LFH

C_2' = capacitance between HV-LV+GND after LFH

$$\frac{C_2'}{C_1'} = \frac{6369.1}{6849.41} = 0.9298 \qquad (measured) \tag{6.7}$$

As seen from equation (8.6) and equation (6.7)

The ratio of capacitances derived (0.9361) from SFRA signature is almost equal to the ratio of capacitances obtained (0.9298) by capacitance measurement.

Analysis:

1. Since the geometrical parameters are unchanged, change in capacitance is possible only with change in relative permittivity as $C = \epsilon_o \epsilon_r A/d$ (the only variable term is relative permittivity).

2. After application of LFH drying out, it removed excessive moisture which caused relative permittivity to reduce.

3. Therefore, capacitance value has gone down which infact shifted the SFRA signature towards right as $F_r = (1/2\pi\sqrt{LC})$.

4. The effect of change in moisture content on SFRA plot is due to change in effective capacitance (relative permittivity).

6.4 Variation in SFRA plot due to Residual Magnetism of the Core

Residual magnetization within the core must be identified and should not be mis-interpreted. Residual magnetization is caused by a section of core steal holding on the magnetic polarity due to an applied DC bias. DC winding resistance testing, DC insulation test, switching operations, and geomagnetic phenomena are source of residual magnetism. Residual magnetization can be identified by the shifting of the low frequency core resonance (zero) to the right from demagnetized results. Residual magnetization can be removed by demagnetizing the core, and should be conducted if there is concern about the condition of the core.

SFRA test conducted on a transformer before and after the short circuit test. The details of the transformer is mentioned below.

Details of	Power Transformer (1 Nos.)
Transformer	Mfg. year.: - 2006
	Rating: - 145/66/33kV, 50MVA (Star/star)
	Total Nos. of Taps: 17 (3 Normal)
	3-Ph Transformer

SFRA data was analyzed for the above mentioned new transformer manufactured in 2006, which was subjected to the short circuit test as part of type test. There was variation in the open circuit plots before and after short circuit test in each phase as shown in the Figure 6.8, Figure 6.9 and Figure 6.10. Short circuit SFRA plots are identical before and after the Short circuit test as shown in Figure 6.13, Figure 6.14 and Figure 6.15. Transformer has passed the short circuit test and all the routine test before and after the Short circuit test was within acceptable limit as per standard.

In case of Open circuit SFRA plot, above $2kHz$ all open circuit SFRA measurements before and after the Short circuit test are identical i.e. no sign of any winding movement as indicated in Figure 6.8,Figure 6.9 and iFigure 6.10. For HV responses measured with the LV's shorted there is no difference at lower frequencies either before and after Short circuit test, hence HV winding is intact Figure 6.13, Figure 6.14 and Figure 6.15after the Short circuit type test at high power lab.

Observation and Possible Causes of Low Frequency Response Variation in case of open circuit SFRA plots:

Below about $2kHz$ the open circuit HV and LV SFRA measurements show differences before and after the Short circuit test which can be due to core degradation or residual magnetism. To trace the reason, the test data related to core issue like no load magnetization current and magnetic balance test before and after Short circuit test were evaluated and shown in Table 6.2.

When energizing on V phase the balance of induced voltages on the outer phases is

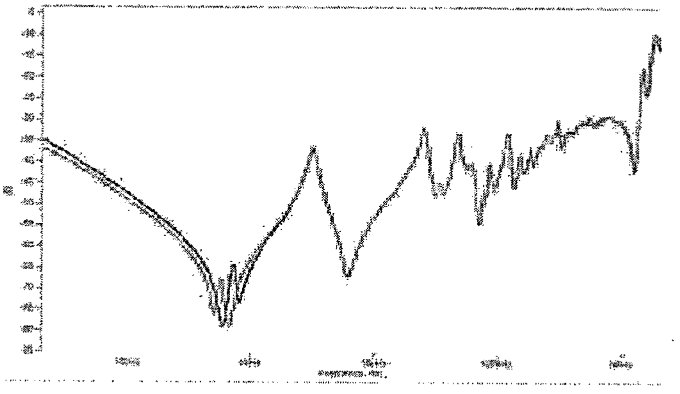

Figure 6.8: Open circuit HV U phase- winding plot before and after short circuit test

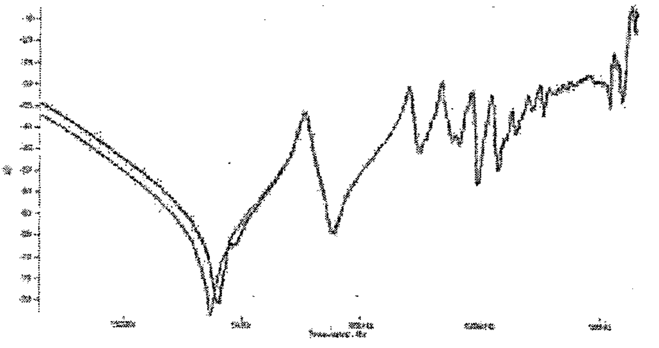

Figure 6.9: Open circuit HV V phase- winding plot before and after short circuit test

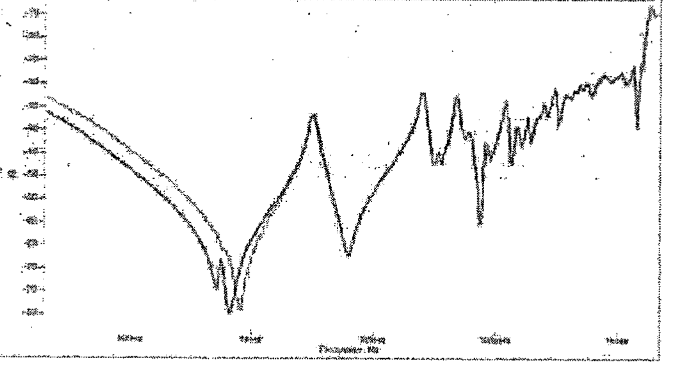

Figure 6.10: Open circuit HV W phase- winding plot before and after short circuit test

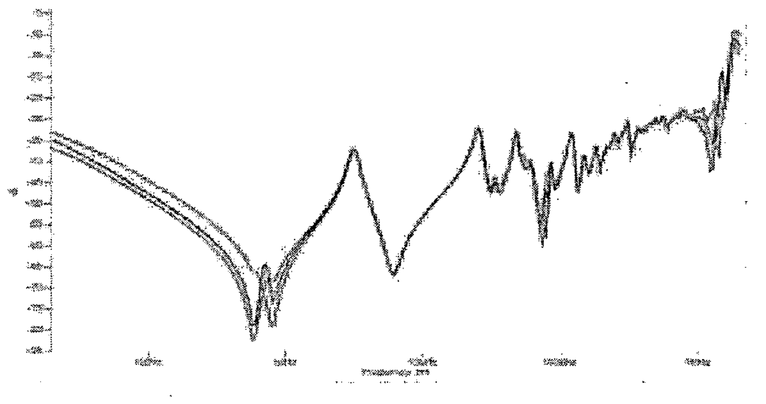

Figure 6.11: Open circuit HV winding plot before short circuit test

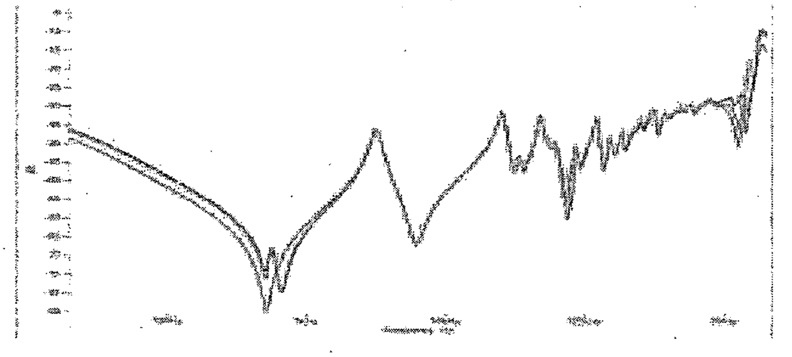

Figure 6.12: Open circuit HV winding plot after short circuit test

slightly better after the Short circuit test. The observation is same with respect to the SFRA plot near the core resonance of $700Hz$ when we compare the three phase plot in Figure 6.11 and Figure 6.12 and Short circuit test it appears that the trace has 'renormalised' what was a slightly unbalanced pattern of remanent magnetism before the test. Obviously SFRA measurements at low frequencies and magnetic balance measurements will both be affected by remanent magnetism. The magnetic balance test shows a slight change in the voltage measured across the U and W limb when energising on V, before and after the Short circuit test shown in Table above.

Hence, in this case, the variation in SFRA plot below $2kHz$ is only to be expected due to change in the residual magnetism of the core during short circuit test.

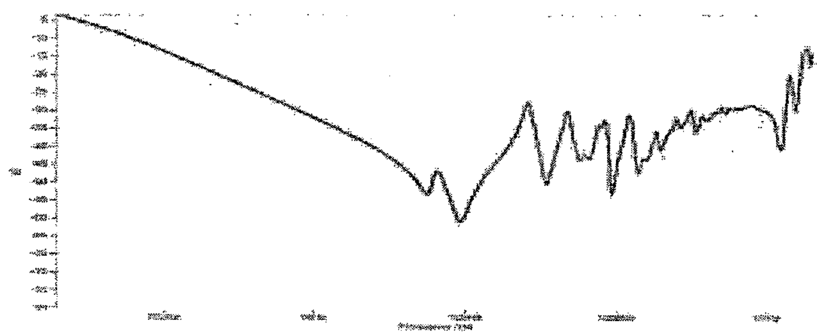

Figure 6.13: Short circuit HV U phase- winding plot before and after short circuit test

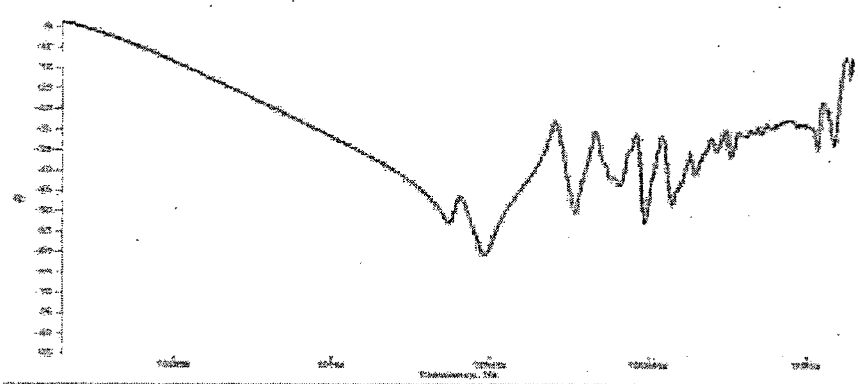

Figure 6.14: Short circuit HV V phase- winding plot before and after short circuit test

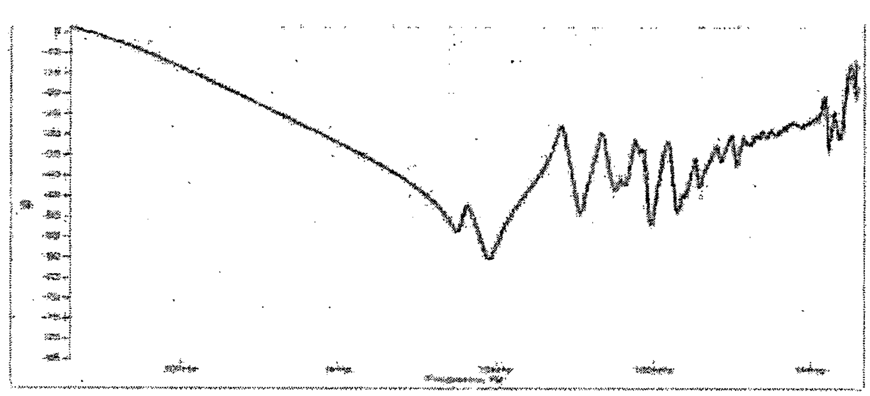

Figure 6.15: Short circuit HV W phase- winding plot before and after short circuit test

Table 6.2: Magnetic Balance Before and After short circuit test:

Applied Terminals	Condition of Transformer	Measured terminal voltage (V)		
		1U-1N	1V-1N	1W-1N
1U-1N	Before SC test	230.6	210.7	20.72
1U-1N	After SC test	230.8	213.7	17.52
1V-1N	Before SC test	**123.2**	**231.1**	**108.0**
1V-1N	After SC test	**117.7**	**231.0**	**113.8**
1W-1N	Before SC test	20.89	210.9	231.6
1W-1N	After SC test	21.71	210.3	231.1

6.5 Variation in Contact Resistance and Earth Resistance

50 MVAR reactor of following details was repaired on site by manufacturer after fault and commissioned on 15.02.2007. The reactor is connected to 400 kV line circuit. The line tripped on 27.07.2007 due to operation of reactor back up protection. The line was charged after withdrawing reactor out of service and the reactor was tested on 28.07.07 for SFRA plot after fault.

Reactor Details:

400 kV, 50 MVAR, 3 phase reactor

Winding configuration: Star

Year of manufacturing: 1989

Test data analysis: Two sets of SFRA plot data was there for analysis, base plot taken on 14.02.07 and post fault data on 28.07.07

Observation:

There is a variation in the SFRA plot of individual phases when compared with the previous base plot at high frequency and observations are as follows:

The SFRA plot taken on 28.07.07 has high lead resistance characteristics for all the three phases from frequency range $1.6MHzto2MHz$ and compared with the plot taken on

14.02.07 as shown in Figure 6.16,Figure 6.17 and Figure 6.18. This variation can happen in SFRA test due to change in contact resistance of measurement set up or variation in earth resistance of the test setup, since it is observed in all the phases. Otherwise, the pattern of resonance in each phase is matching with the base plot which indicate no mechanical deformation of the winding due to change in its overall capacitance or inductance.

Conclusion:

In summary, the SFRA plot test result of reactor is not indicating any sign of mechanical damage. Variation in the frequency region from $1.6MHz to 2MHz$ is attributed to the difference in test condition and test set up. But this statement is not generalized for whole frequency range and variation of such magnitude at low frequency below $1kHz$ need to be investigated always, which is not the case here.

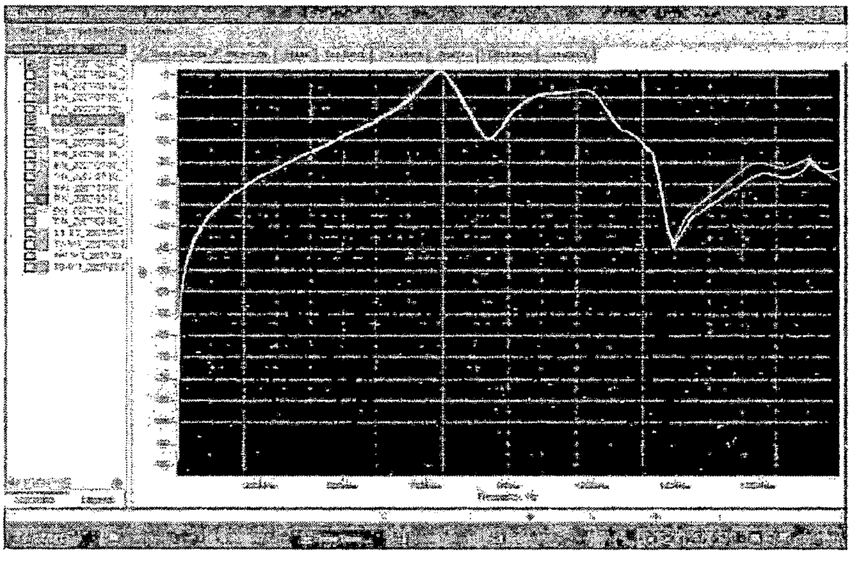

Figure 6.16: Comparision of Base and Post fault R-phase SFRA plot for reactor

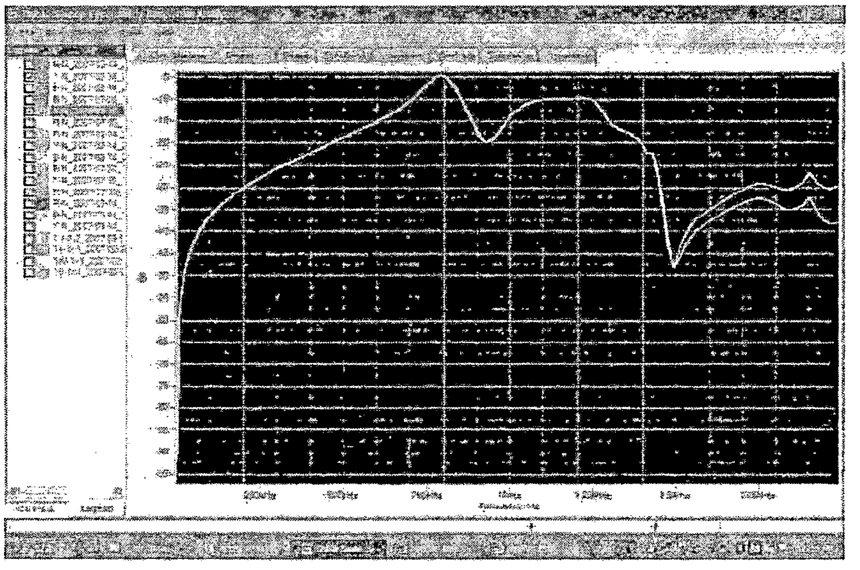

Figure 6.17: Comparision of Base and Post fault Y-phase SFRA plot for reactor

6.6 Effect on SFRA plot due to Electrical Interfrence in Substation

Noise can be defined as unwanted disturbances that may be superimposed upon a useful (desired) signal. Noise tends to obscure the information content of the useful signal and for this reason its detection and mitigation is imperative. As in any other electrical diagnostic method, the SFRA results can also be affected by noise. An understanding of the sources of noise, their effects and suppression methods is very important.

In a substation environment the noise can be found basically in two forms, i.e., as a wideband or as narrowband noise. A typical narrowband noise is the power frequency noise ($50 or 60 Hz$ noise). At frequencies higher than$300Hz$ is it very unusual to find narrowband noise. In substations with high harmonic pollution some narrowband noise at frequencies multiple of the power frequency could also be present.

Other possible source of narrowband noise could be some communication signals in the substation, or noise generated by corona discharges, but these sources are in higher frequencies and are very hardly found in the SFRA plots. With respect to wideband noise, there will be always a noise floor that will affect the SFRA plots. The presence of

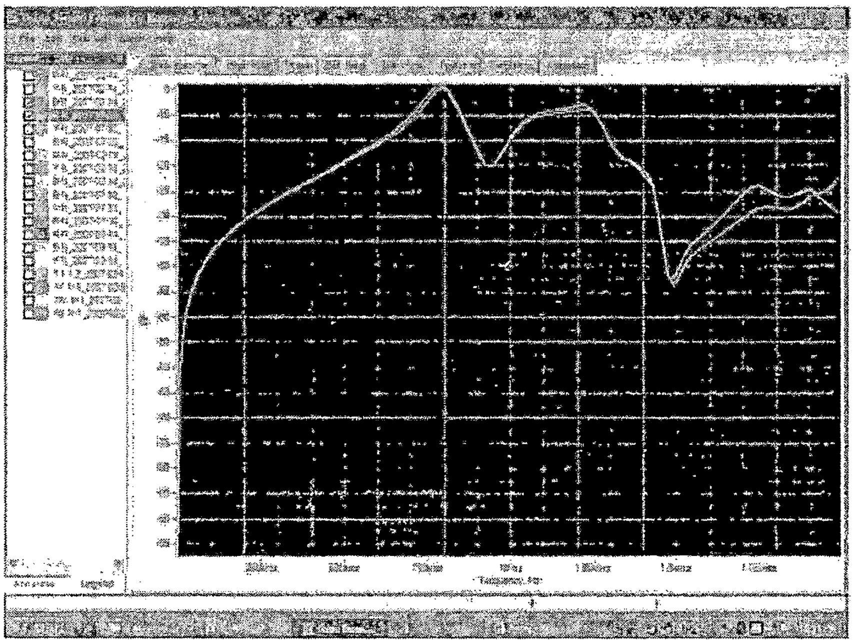

Figure 6.18: Comparison of Base and Post fault B-phase SFRA plot for reactor

this noise is very close related to the dynamic range of the SFRA measuring instrument as indicated in Figure 6.19.

One no. of Three phase Auto transformer was tested for base SFRA data having following details . 220/132/11 kV, 150 MVA, 3 phase Auto transformer Winding configuration: Star/Star Year of manufacturing: 1994

Test data analysis: Base SFRA plot was analyzed and it is observed that there is interference signal picked up in open circuit plot as shown in figure6.20, at 50Hz. due to high level of interference in substation. The same is absent in Short circuit plot as the output signal in much better in SC test as shown in figure6.21. Open circuit and Short circuit plots are the good SFRA base plot for this transformer for future comparison.

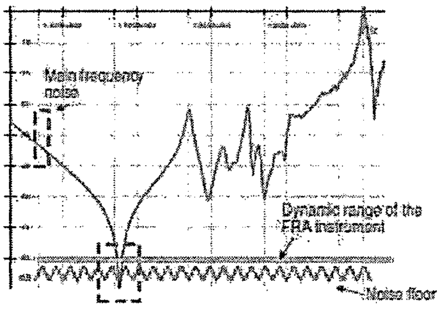

Figure 6.19: Characterisation of noise sources in a typical FRA plot

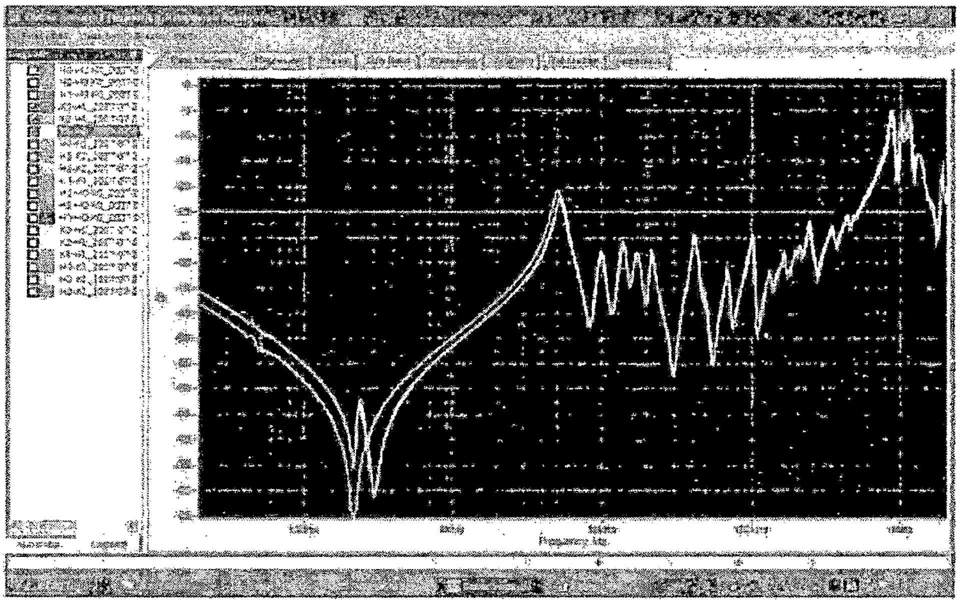

Figure 6.20: Comparison of three phase Open circuit Base SFRA plot

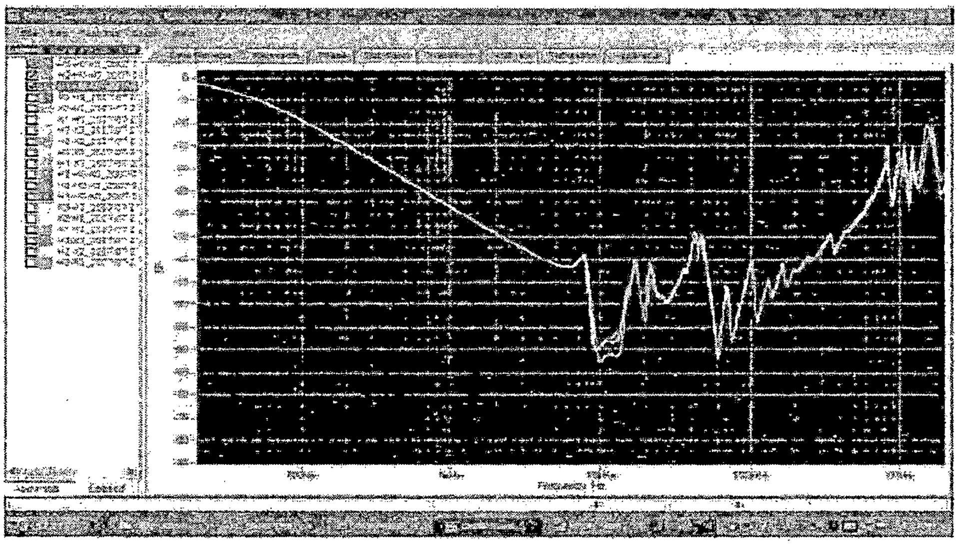

Figure 6.21: Comparison of three phase Short circuit Base SFRA plot