Chapter 7

Classification of fault by Sweep Frequency Response Analysis

7.1 Introduction

SFRA have showed to be promising in both real cases and laboratory investigations. There still seems to be little knowledge on why and how the method works, and how the results can be interpreted. Before making this method a standard test for condition assessment, all interpretational aspects should be investigated. This can either be done by experiments or calculations (using transformer models), or presumably a combination and this is the main finding of this chapter as mentioned below in each section.

The aim of this chapter is to establish a guideline for the understanding the various type of fault analysis in transformer by SFRA. Fault in transformer effect the shape and features of the SFRA response and it is proved in this study by analysis of thousands of SFRA data colleted from field for both healthy and faulty data. Then, this knowledge is utilised to analyse the SFRA data and classify the fault for different make, design and rating.

7.2 Interpretation of SFRA for fault classification

SFRA plots provides information related to the physical geometry of the test specimen. Interpretation of the data is often subjective unless baseline data is available. Baseline data can be a previous test or data collected from a similar test specimen, such as a sister unit[42]. Due to the recent introduction of SFRA diagnostics, the majority of SFRA test is conducted without baseline data. Interpretation of the first time results can be limited and results are generally analyzed by comparing phases to recognize the obvious faults, such as severe deformation, open circuits and short circuits. Measured responses are analyzed for any of the following :

- Changes in the response of the winding.
- Variation in the responses of the three phases of the same transformer.
- Variation in the responses of transformers of the same design.

In all the above cases the appearance of new features or major frequency shifts are cause for concern. The phase responses are also being recorded but normally it is sufficient to consider only amplitude responses.

Where there are differences between responses, it is important to find the correct reasons. Whether it is the test procedure or some change within the transformer itself. The interpretation currently available is based on experience and very much subjective. This is because small variations may have large implications, and vice versa. Further, there are particular variations that are manufacturer specific which need to be extracted and examined in the light of experience. The state of the transformer, in terms of magnetization of core, affects low frequency results. While the application is fairly straightforward, interpretation requires experience to diagnose the type of fault and it is based on the overall transformer circuit parameter as shown in Figure 7.1.

The measured frequency range is divided into three sections: high frequency, middle frequency and low frequency section. Because of the diversity of structure of windings, the distribution of pole points of transfer function is different . So, in order to reflect the state of winding, division of the frequency range must be reasonable depending on the design of winding. An SFRA analysis is very effective diagnostic tool for predicting faults in transformer such as:

1. Core fault - Low frequency variation
2. Shorted turns fault - Low frequency variation
3. Open circuit high impedance winding fault - Low frequency variation

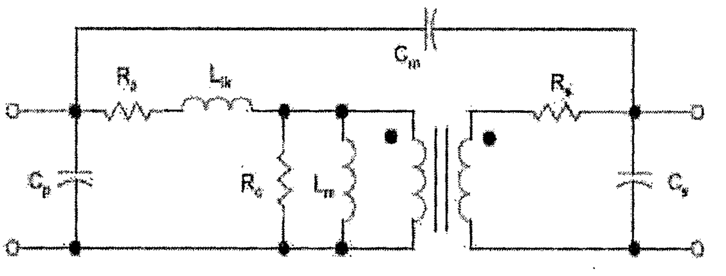

Figure 7.1: Equivalent circuit parameter of Transformer

4. Overall radial shift of the winding - Mid frequency variation
5. Axial shift of the winding - Mid to High frequency variation
6. Faults in tapchanger and tap winding - Mid to High frequency variation
7. Core earthing related faults in the transformer/ Tap changer leads and bushing leads related faults - High frequency variation

These faults will be discussed separately in the next section.

7.3 Low frequency response

For Frequency response of transformer in low frequency range of $10Hz$ to $1kHz$, the core effect is dominant, when the SFRA measurement carried out on a winding with all the terminals of other winding left open-circuited. Besides the magnetizing inductance, it also includes the self inductance as well as resistance of winding determined by the overall winding configuration as shown in Figure 7.2 . Any deformation in the core or winding like shorted turn or open circuit or high impedance fault will be detected by the change in SFRA plot in this region. Effectively there are two parts of inductance affecting the SFRA response; the core magnetizing inductance and the inductance of the windings up to $1kHz$, where the core resonance exits.

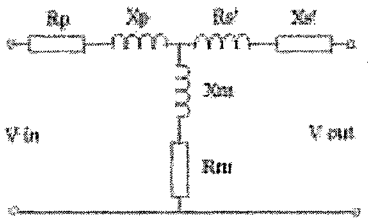

Figure 7.2: Equivalent circuit of Transformer at Low frequency

7.3.1 Core Fault:

Core related problems such as circulating currents, faulty grounding, clamping problems also have been detected by SFRA. In most of transformers, at frequency $10Hz$ to $1kHz$, the impedance is controlled by the core magnetization in case of open circuit SFRA plot. This is where core effects are seen and there is equivalence with an excitation current measurement. At low frequencies the flux is largely confined to the core. The low frequency inductance depends on the core reluctance, which can be changed either by changes in the incremental permeability of the core material caused by changes in the state of residual magnetization or by manufacturing differences in the core joints changing the reluctance locally or by localized overheating of core.

For the analysis of core related problem following points should be considered.

1. In core related fault like localized overheating of core due to circulating currents, there will be change in dB value or the change in shape of plot in frequency band of $10Hz$ to $1kHz$ based on the design of transformer as shown in Figure 7.3.

2. The short circuit plot of HV winding will be identical in two sister unit or between phase of one unit in the frequency band from $10Hz$ to $1kHz$ for core faults as shown in Figure 7.4.

3. The response of the center phase is slightly different between $200Hz$ and $500Hz$ area of frequency due to the different flux paths through the core compared to outer winding and it should not be misunderstood as core related issue. For core magnetization, it is possible to demagnetize the core and retest the transformer for SFRA. If

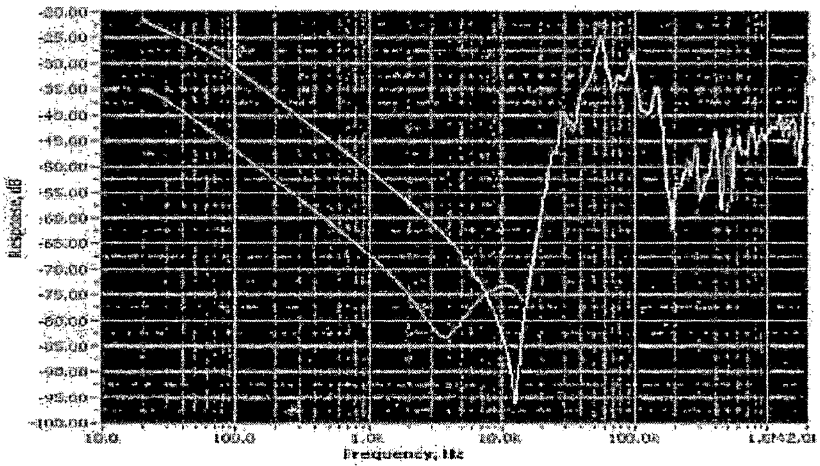

Figure 7.3: Open circuit plot for core fault (3-phase)

the low frequency variation does not go away - it is not a magnetization issue. Performing an Exciting current measurement before and after demagnetization would provide additional evidence for magnetization being the cause of variation.

7.3.1.1 Unintentional core ground

The integrity of the core ground should be checked. If the core ground is available externally on the transformer tank surface, it should be disconnected from ground circuit and IR value of core ground with respect to tank should be checked. Low or zero value of IR indicates unintentional core ground

Case study 1:

The SFRA test data (After installation at site) of new 100 MVA Auto Transformer, 220/132 kV is shown in Figure 7.5, Figure 7.6 and Figure 7.7. There was no base SFRA data available from factory test hence three phase comparison is performed in this case. It is evident that low frequency response of outer phases was not normal in frequency range of 10 Hz. to 1 kHz for open circuit SFRA plot shown in Figure7.5 and Figure7.6.

After detail investigation, it was found that connecting point of Core ground for earth connection was loose and visible from outside of the Tank. Transformer was commissioned

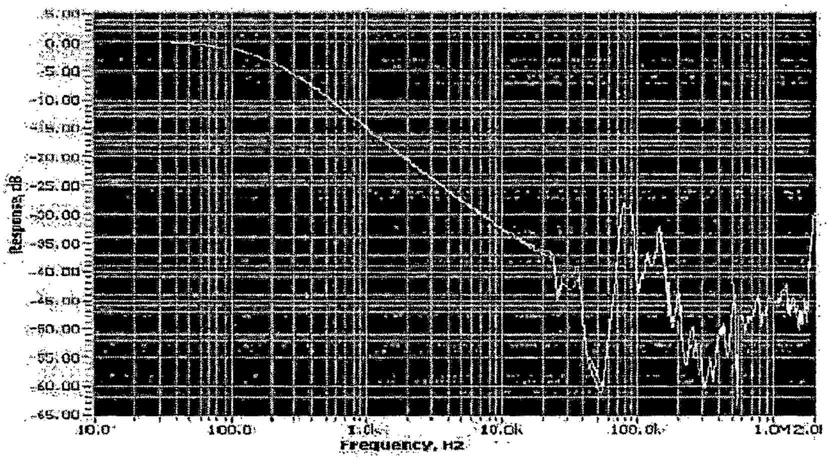

Figure 7.4: Short circuit plot for core fault (3-phase)

after making the earth point intact by repair and transformer is saved from unnecessary overheating of the core due to high eddy current circulation after energizing, if this problem was not rectified.

7.3.1.2 Shorted lamination providing additional eddy current loss

Case Study 2:

250 MVA, 220 KV / 110 KV / 33 KV auto-transformer was indicating increasing trend of dissolved gasses, since its commissioning. The DGA analysis indicated core fault (hot spot). After un-tanking, no abnormality in the windings or core was noticed on physical inspection. SFRA test conducted in this condition only and showed marked deviation of response between the phases from 500 HZ to 10kHZ frequency as shown in Figure 7.8. Here, the lower frequency is increased upto 10 kHz., since there was no oil and bushing on the transformer and overall capacitance of the winding is decreased. On removing the top yoke laminations obvious burn marks on lamination were observed. The top clamping board insulation pressed the laminations of the top yoke causing short circuited laminations at few places as shown in Figure 7.10. The core repair was carried out and all tests including SFRA test were done satisfactorily as indicated in Figure 7.9.

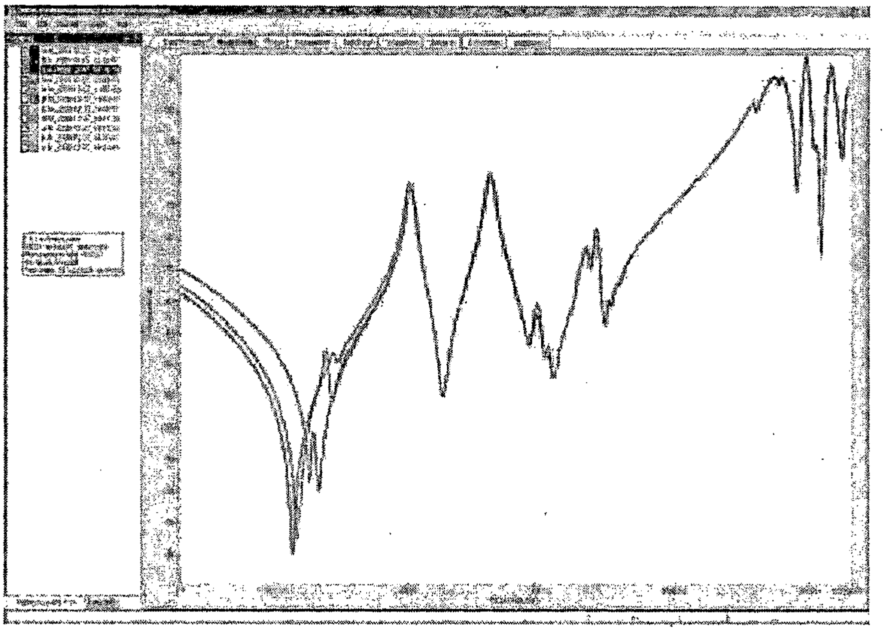

Figure 7.5: Open circuit plot for series winding (3-phase)

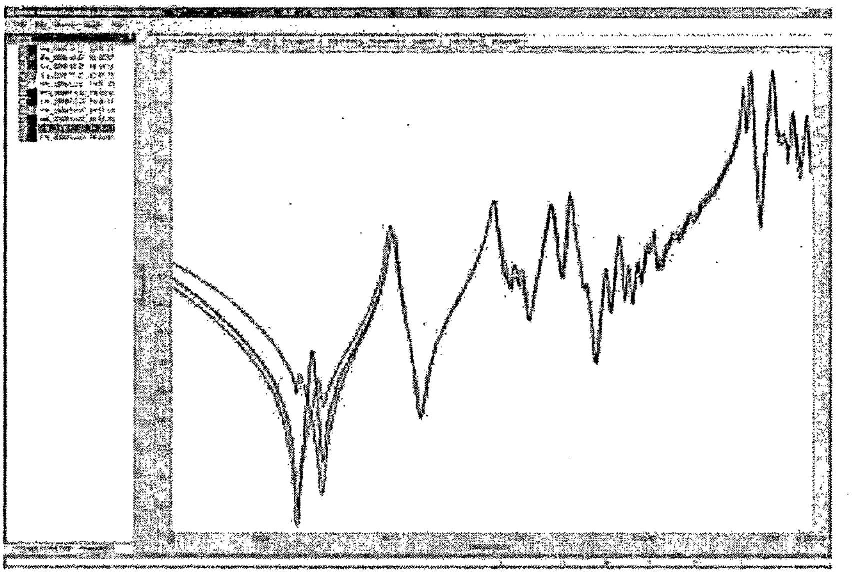

Figure 7.6: Open circuit plot for common winding (3-phase)

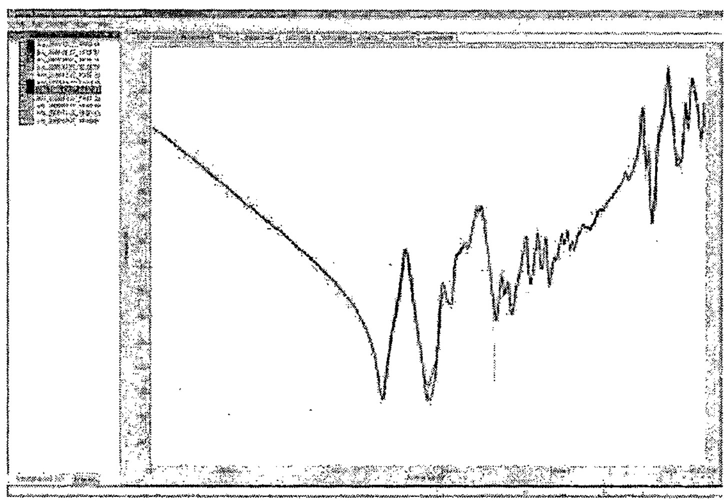

Figure 7.7: Short circuit plot for HV winding (3-phase)

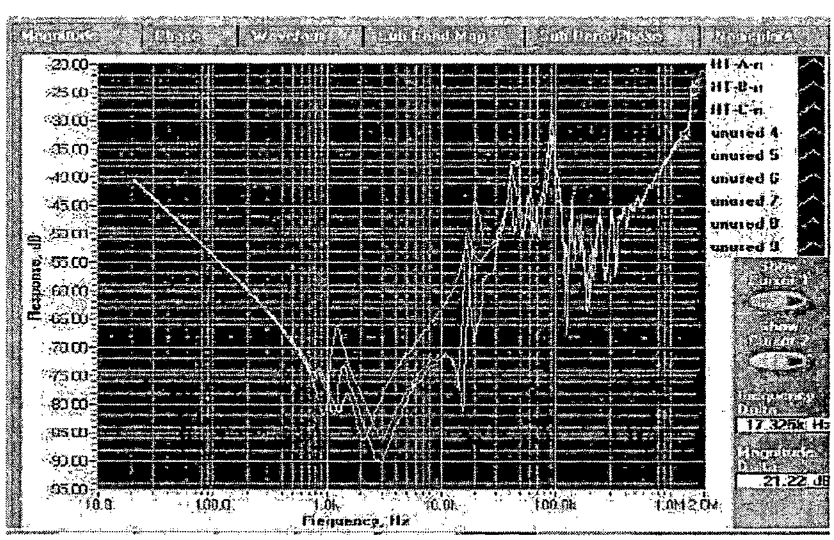

Figure 7.8: Open circuit plot after fault (3-phase)

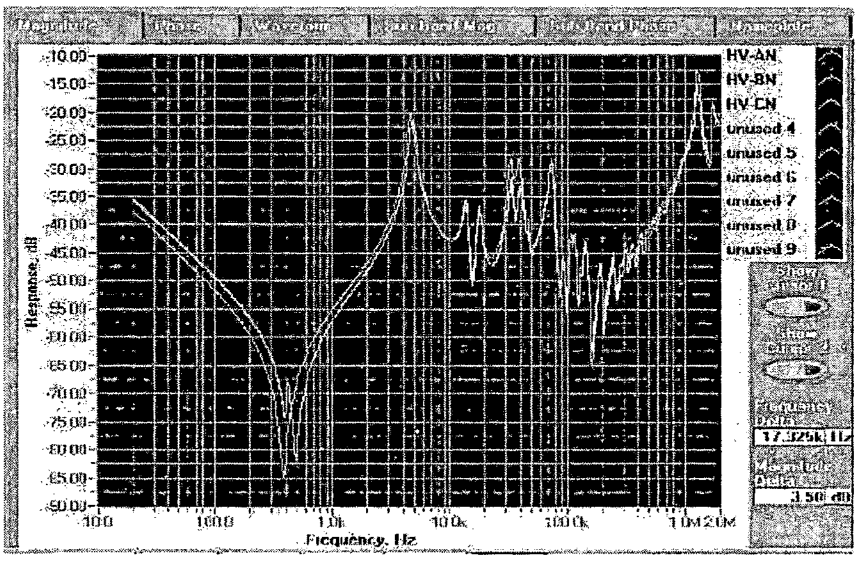

Figure 7.9: Open circuit plot after repair (3-phase)

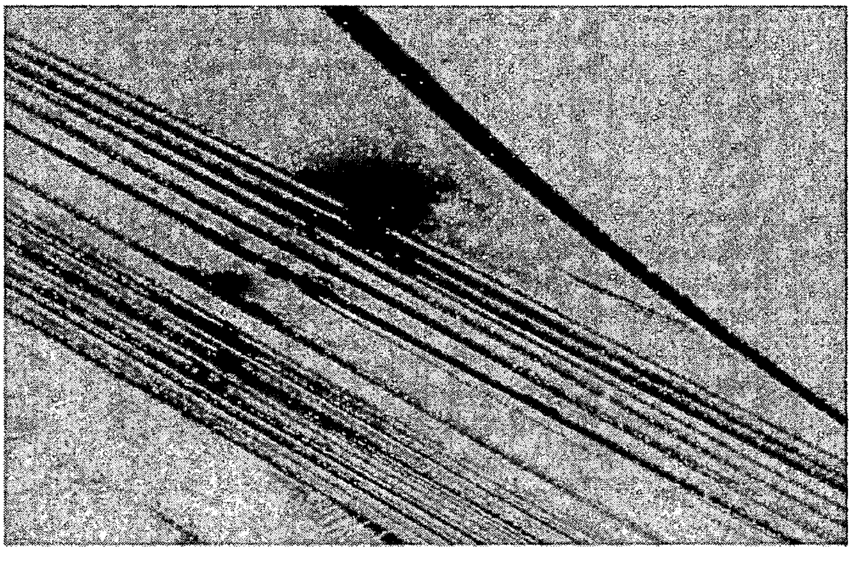

Figure 7.10: Photographs of the damaged laminations

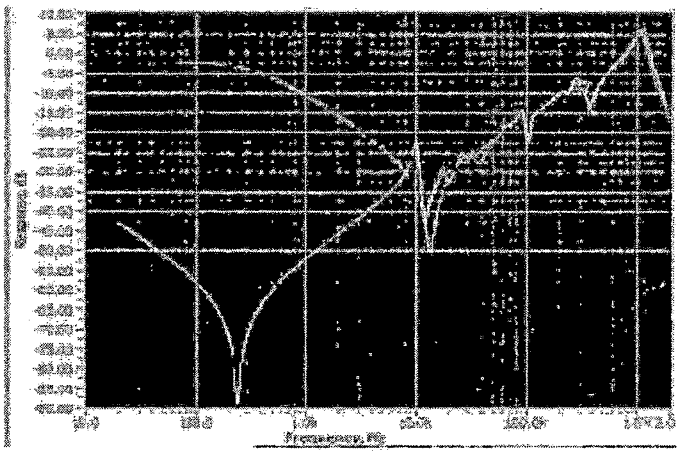

Figure 7.11: 3 phase Open circuit plot for shorted turn fault (blue color: H3-H0 phase)

7.3.2 Shorted turn Fault

For the analysis of shorted turn fault, following points should be considered:

1. In short circuit related fault, there will be change in dB value and change in shape of open circuit SFRA plot at frequency $10Hz$ to $1kHz$, as shown in Figure 7.11.

2. The short circuit plot of HV winding will be not be identical in two sister unit or between phase of one unit in the frequency band from $10Hz$ to $1kHz$ for such faults as shown in Figure 7.12.

3. In case of the short circuit fault of turn to turn or disk to disk type like as indicated in Figure 7.13, the core circuit is bypassed and hence variation is observed in open circuit plot up to 10 kHz and first core resonance will be absent as it is evident in Figure 7.11.

Case Study 3:

SFRA data of the two winding three phase transformer rated 17 MVA, 72 kV star-star with LTC had been reviewed for fault analysis as shown in Figure 7.11 and Figure 7.12.

From the three phase short circuit and open circuit plot , it was clear that there is short circuit turn to turn fault in the H3-H0 phase. In Figure 7.12 and Figure 7.11, the H3-H0 Phase winding deviates substantially from the other two phases in the lower

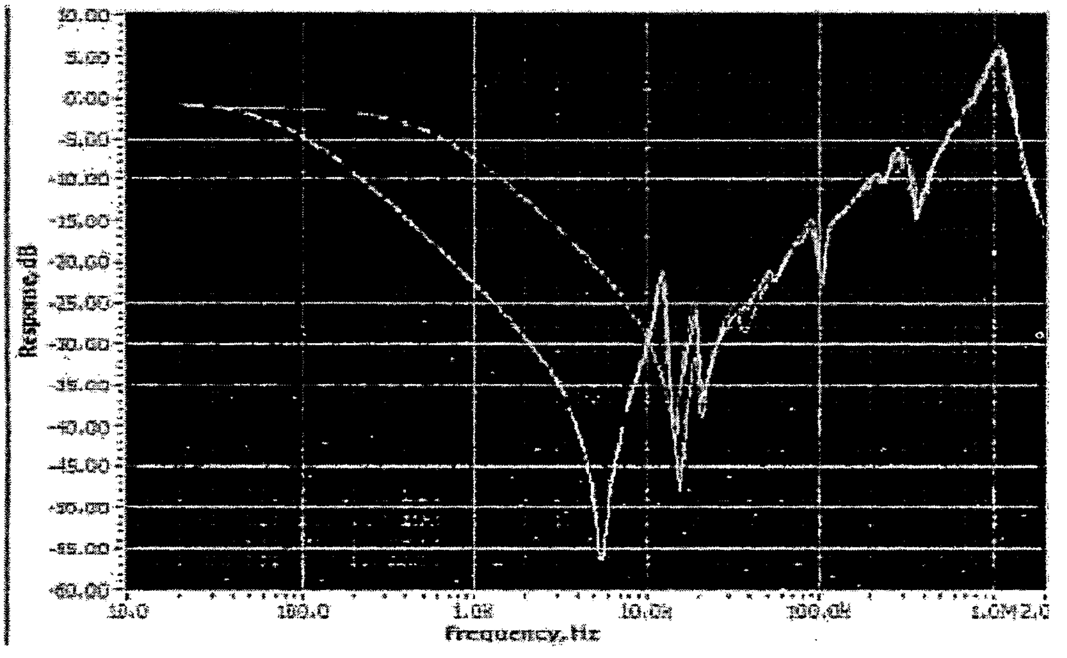

Figure 7.12: 3 phase Short circuit plot for shorted turn fault (blue color: H3-H0 phase

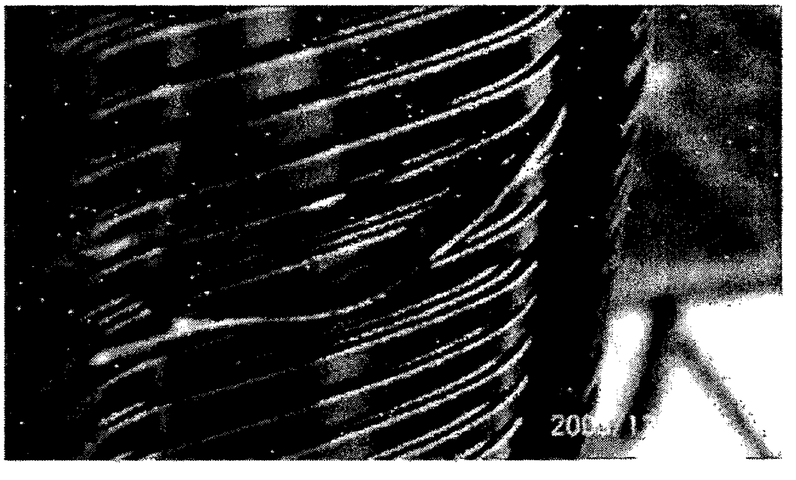

Figure 7.13: Shorted turn fault in transformer winding

frequencies, showing the characteristic of a short circuit. This characteristic includes the following:

1. The trace starts at much closer to 0 db than its sister phase traces, indicating a characteristic decrease in impedance.
2. The first resonant point was eliminated and replaced by a flat trace in the lower frequencies indicating a large decrease in the winding inductance that would be expected with a shorted turn.
3. In addition, the initiation of the H3-H0 phase(high Voltage winding short circuit traces) obtained with the Low Voltage winding short-circuited shown a deviation in the starting db of about 10 db as indicated in Figure 7.12. This is indicating a change in winding resistance caused by faulty or deteriorated connections in one of the windings in that phase.

7.3.3 Open turn or High impedance Fault

For the analysis of such type of fault following points should be considered:

1. In open circuit related fault, like developed high resistance or impedance in the winding circuit, there will be increase in dB value or the change in shape of plot at frequency 10 Hz. to 1 kHz.
2. The short circuit plot of HV winding will not be identical in two sister unit or between phase of one unit in the frequency band from 10 Hz. to 1 kHz for such faults as shown in Figure 7.14.

Case Study 4:

SFRA data of 25 MVA Power Transformer, 115 kV/ 24 kV/11 kV , HV/LV/Tertiary (Delta/Star/Star) was reviewed after a system fault.

The Short Circuit SFRA test confirmed the high resistance of the H3H1 winding. The major variation is seen in the short circuit response of other two windings as their shape also got changed . It can be due to the increase of resistance which occurred during open delta case. As Winding resistance indicated that H3H1 had (15.5mohm) two times higher

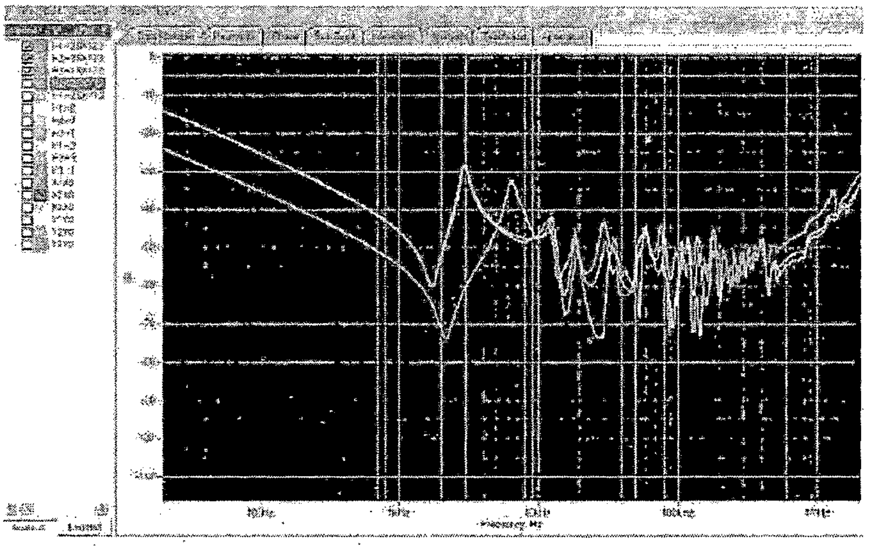

Figure 7.14: Short circuit plot for open circuit fault (3-phase)

resistance than other 2 phases (7.8mohm), it is obvious that H3H1 phase has open circuit fault .

Consider that R is the Resistance of phase winding. Then, during the measurement through SFRA or Winding resistance in delta winding configuration, the equivalent resistance between phase is 2R/3 for Delta winding . It increases to R for healthy winding and 2R for faulty winding in case of open Delta fault in the winding. So, it has effect on the Short circuit SFRA traces of HV winding for all three phase as evident from Figure 7.15,Figure 7.16 and Figure 7.17.

Case Study 5:

SFRA data of 100 MVA Power Transformer, 220 kV/ 24 kV , HV/LV (Delta/Star) was reviewed after a system fault. The Open Circuit SFRA test on LV winding as indicated in Figure 7.19 confirmed the high impedance fault in the V-Phase winding and it has affected the open circuit SFRA plot of HV winding also as indicated in Figure 7.18.

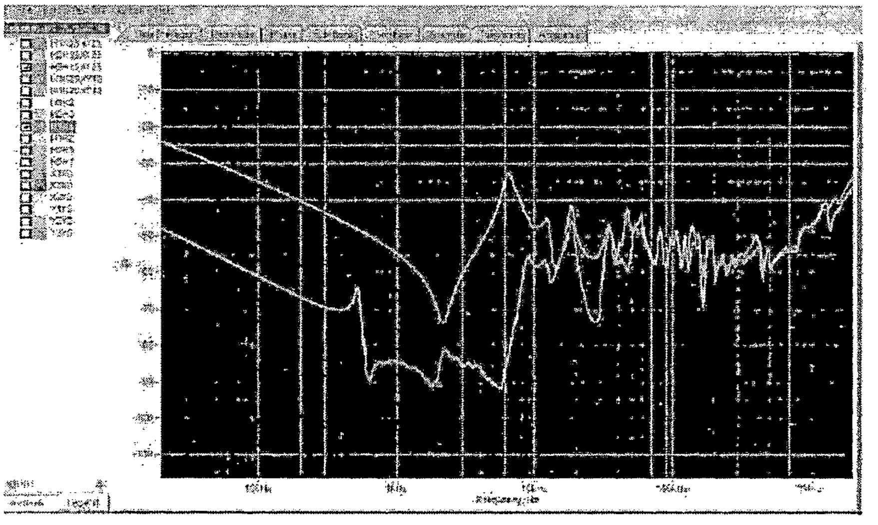

Figure 7.15: Comparison of Short circuit and open circuit plot for open circuit fault (A-phase)

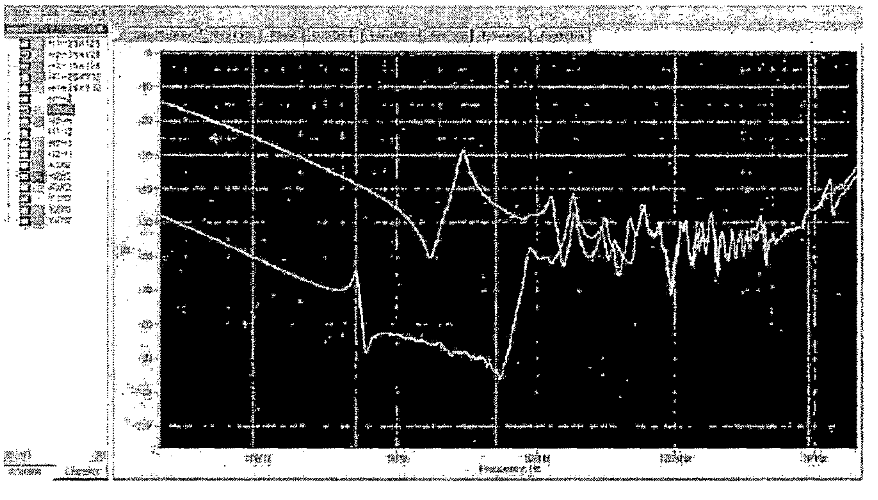

Figure 7.16: Comparison of Short circuit and open circuit plot for open circuit fault (B-phase)

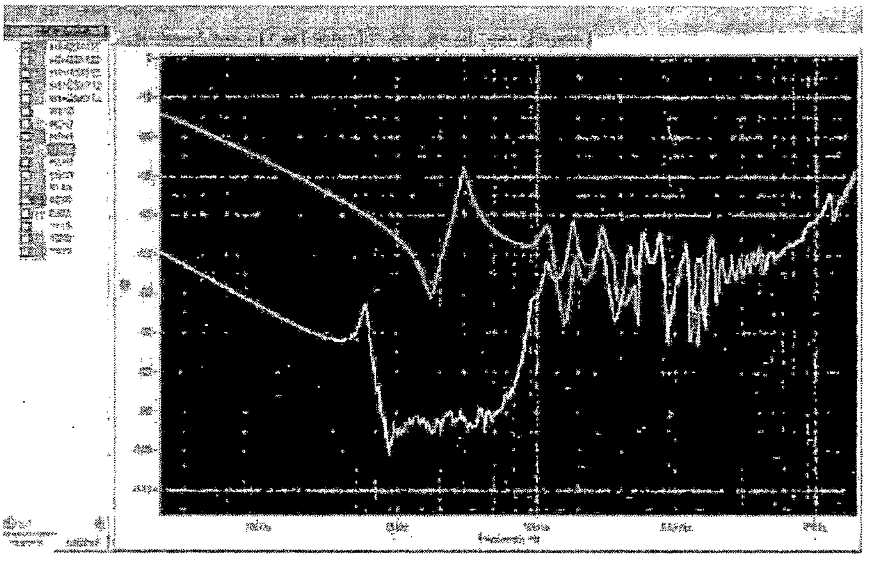

Figure 7.17: Comparison of Short circuit and open circuit plot for open circuit fault (C-phase)

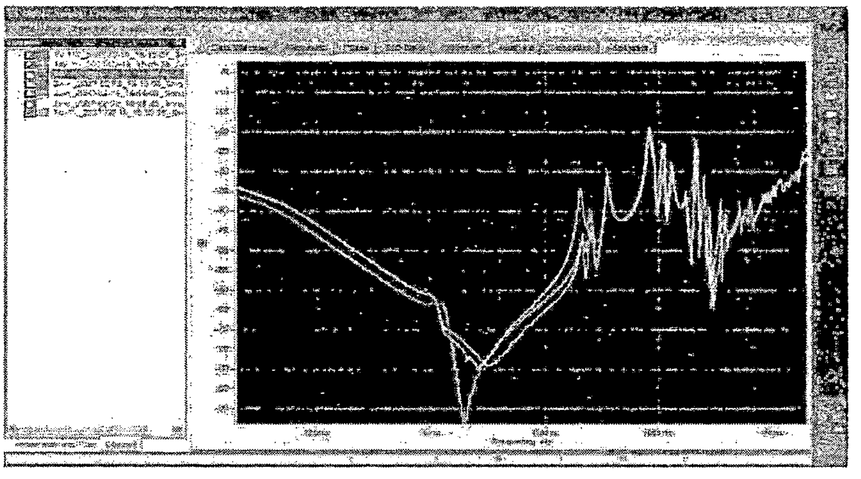

Figure 7.18: Comparison of 3-phase HV open circuit SFRA plot after fault

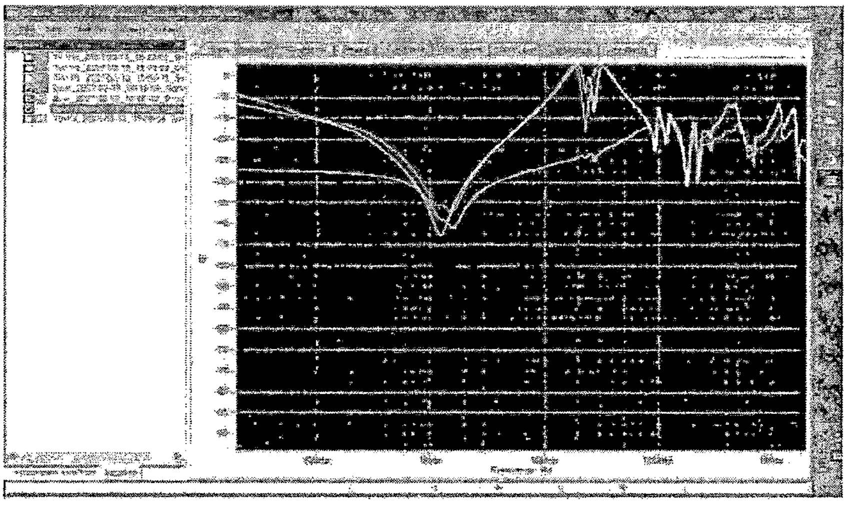

Figure 7.19: Comparison of 3-phase LV open circuit SFRA plot after fault

7.4 Mid-Frequency Response

The frequency response in the range from 1 kHz. to 1 MHz.. represent the main winding structure of transformer. In this region overall axial deformation of the HV, LV winding due to high short circuit system fault is detected well. The winding structure, especially for the winding under test, become dominant factor of the frequency responses and to represent a winding accurately in this frequency range series and shunt capacitance, self-inductance and mutual inductance are the relevant circuit parameters as indicated in Figure 7.20.

At the medium range of frequency i.e. after the core resonance around 1 kHz, there is a phase change of 180 deg and the impedance changes from being inductively to capacitively-controlled also for winding. At higher frequencies eddy currents is dominant and local leakage fluxes determine the winding inductances. The response is more dependent upon changes in the winding arrangement and the variation in SFRA plot in this range should be compared with the leakage reactance measurements. The inductive reactances of both windings increase with frequency and become high impedance in parallel with the capacitive reactances of the windings as shown in Figure 7.20

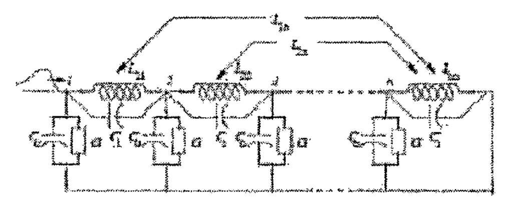

Figure 7.20: Equivalent circuit of Transformer at Mid Frequency

7.4.1 Hoop Buckling of LV winding

A possible failure mode for transformers subject to a short circuit fault is that of buckling, particularly radial buckling of the inner winding or windings. In transformer short circuit strength calculation, one factor is very much controversial i.e. the radial buckling. Because transformer windings are not ideal mechanical structures, they are difficult to analyze without making approximations. The nature of these approximations can be a source of further controversy. Their validity must be performed based on the specific test results, even if limited in number, or on the survivability of units which have been subjected to a short circuit either in test lab. or in the field and were designed according to the calculation method which has to be verified.

Under short circuit conditions, the forces and hence the resulting stresses acting on transformer windings increase considerably over their normal operating values. Among these are radial forces which act to push the outer windings out and the inner windings in for a core-form design. There is usually not adequate radial supports on the outer winding so that the outward force is counteracted only by tension in the conducting material of the winding. This tension results in a tensile stress which must be less than the proof stress of the conducting material to avoid any significant permanent deformation. On the inner winding, the inward forces may be counteracted by radial supports bridging the gap between the core and inner winding.

Buckling is essentially an instability problem. Given an applied force or stress on a structure having a certain ideal shape such as a straight column or circular ring, one examines whether a slight perturbation of this shape results in a shape change of progressively

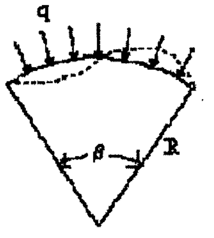

Figure 7.21: Radial buckling of a Section of winding

large amplitude under the next short circuit event. When this occurs, then the structure has buckled for that level of force or stress. Since real structures are not perfectly straight or circular, these perturbations are always present so that, in practice, buckling will occur when the force or stress is large enough. In Figure 7.21, radial buckling of a section of LV wining is shown.

Case Study 6:

30 MVA, 138/69 kV Transformer was subjected to over current when a generator was switched in behind it, out of phase. It was carrying 36 MVA at the time of the incident. Figure 7.22 shows the LV winding traces and it was clear that the phase x1-x0 has shifted resonance in mid frequency area of 2 kHz. to 200 kHz. indicating winding movement or distortion on this phase as detected and shown in Figure 7.23.

7.4.2 Prediction of Incipient Fault by SFRA in mid-frequency

Case Study 7:

315 MVA, 400/220/33 kV Autotransformer was subjected to OLTC fault and the OLTC fault was rectified on-site for this new transformer. SFRA was conducted after the on-site repair of OLTC to check the mechanical intactness of the transformer along with other diagnostic test. Based on the findings from the SFRA test data, it is recommended to have internal inspection of the tap changer parts and winding of the transformer after the repair of OLTC.

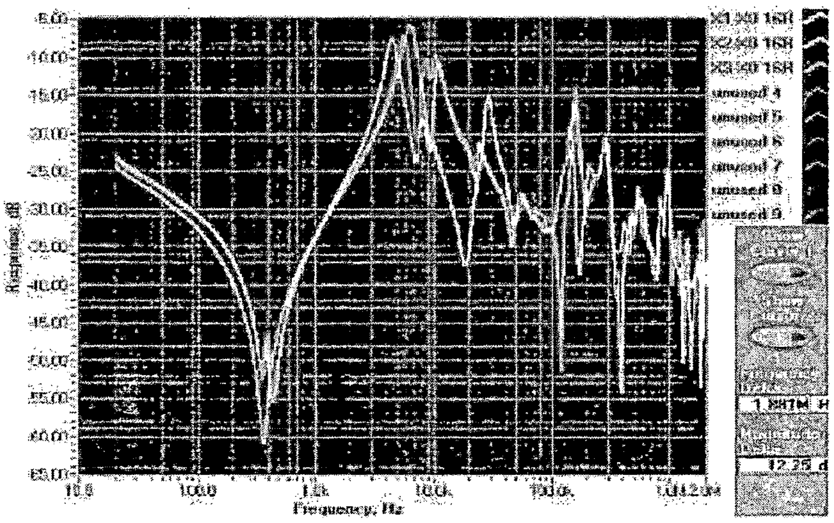

Figure 7.22: Three phase LV open circuit SFRA plot after fault

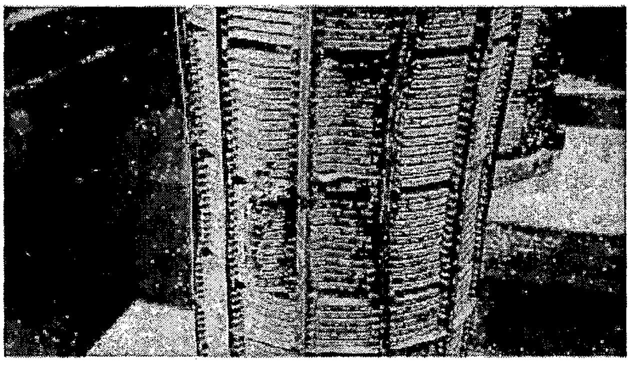

Figure 7.23: LV winding which buckled over about the one third of its axial height

Transformer should not be charged in this state as it is predicted mechanically weak in Y-phase, where the fault was initiated. The root cause of the deformation in Y-phase winding should be identified. There was a series of discussion with the manufacturer about internal inspection of the transformer and advised them not to energies the transformer in this condition after the repair of OLTC on-site. Still, the manufacturer did not agree about internal inspection.

Finally, the transformer was energized without any winding inspection and again similar tripping happen in the $Y - phase$ with a major fault, which was predicted as mechanically damaged winding by SFRA and sent for the repair. Repair is a very costly affair as now all the windings has to be replaced instead of one winding as predicted by SFRA. The argument for transformer charging was that other low voltage test parameter is okay as per the manufacturer's norms. This is typical case where the specialized test like SFRA gives more reliable information about the condition of the transformer if it is performed in a proper way and analysis is done accordingly, along with other test data as per the state of transformer.

Details of Transformer:

Two nos. of 3-phase Auto transformer (Sister unit) SFRA data was analyzed, having following nameplate details:

- 400 kV/220 kV/33 kV, 315 MVA Auto Transformer,
- ON LOAD Tap changer
- Winding configuration - HV/LV/Tertiary, Star/Star/Delta
- Year of Manufacturing:2007
- Serial No.: ICT 1 (Tripped at no load), ICT 2

7.4.2.1 Analysis of SFRA Data

The SFRA test involves measuring the frequency responses of each individual winding. Open circuit plots of ICT1 after fault are compared with its sister unit ICT2 and Base plot of ICT1 in the following sections.

(i) **Comparison of Sister Units (ICT 1 and ICT2) open circuit SFRA Plot on per phase basis after fault on ICT1:**

Open circuit responses measured for the HV and LV windings for both the sister units at tap no. 1 and 17 are shown in Figure7.24 to 7.35. The dominant features of these plots are the first minima at low frequency near 200 Hz-300 Hz in all windings. This is the general feature of any winding and is due to the fact that at the lowest frequencies windings behave as simple inductances. This result in increasing attenuation of a transmitted signal with frequency until a frequency is reached when winding series capacitances start to become significant and allow a recovery in transmitted voltage.

The low frequency minimum is determined by low frequency open circuit inductance of winding. The position of minimum will vary somewhat depending on the remnant magnetism of relevant core flux circuits , which is prominent in this case due to different magnetic state of the winding when the plots are compared in low frequency.

Observations:

1. For winding H1-X1-Tap1 (Figure7.24), H3-X3-Tap1 (Figure 7.26) , H1-X1-Tap 17(Figure 7.27) , H2-X2-Tap 17 (Figure7.28) , H3-X3-Tap17 (Figure7.29), both the per phase sister unit plots are identical , which indicates that there is no significant winding movement in these part of the transformer.
2. *For winding H2-X2-Tap 17 (Figure 7.25), the sister unit plots are not identical and showing major shift and anti-resonance in the response in the frequency region 10 kHz. to 200 kHz, which indicates that there is significant winding movement in Y-phase of the transformer. Also, clear shift in the resonance is observed in these plots which indicate the mechanical movement in the Y-Phase winding.*
3. *Y-Phase deviation is not present in the* H2-X2-Tap 17 (Figure7.28), so it is clear that major deformation is in Y-Phase Tapping winding.
4. For winding X2-N-Tap1 (Figure7.31), X3-N-Tap1 (Figure7.32) , X1-N-Tap 17 (Figure7.33) , X2-N-Tap 17 (Figure7.34),*the sister unit plots are not identical*

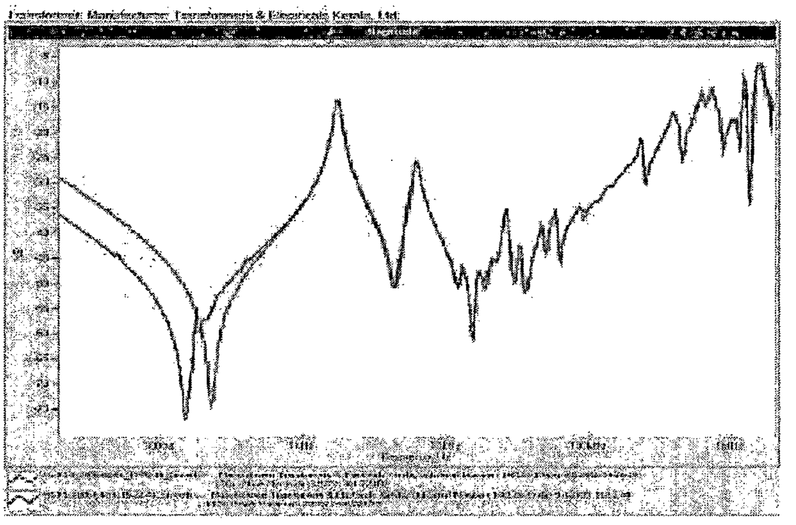

Figure 7.24: Open circuit SFRA plot of H1-X1 winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

and showing major shift and anti-resonance in the response in the frequency region 20kHz to 200kHz, which indicates that there is significant winding movement in all phases of LV winding of the transformer.

ii) Comparison of SFRA Plot after fault on ICT1 with base data of ICT1(per phase basis):

Open circuit responses compared for the HV, LV and Tertiary windings before and after the fault of ICT1 at tap no. 9b are shown in Figure 7.36 to 7.44.

Observations:

1. For winding H1-X1-Tap 9b (Figure7.36), H3-X3-Tap 9b (Figure7.38), X1- N Tap 9b (Figure7.39) , both plots are identical in region 10 kHz. to 200 kHz. which indicates that there is no significant winding movement in these part of the transformer. There is a significant shift in the region 1 MHz to 2 MHz. which may be due to change in the measurement direction of the bushing i.e. LV to HV winding or bad earth connection.
2. For winding H2-X2-Tap 9b (Figure7.37), X2-N-Tap 9b (Figure7.40), X3-N-

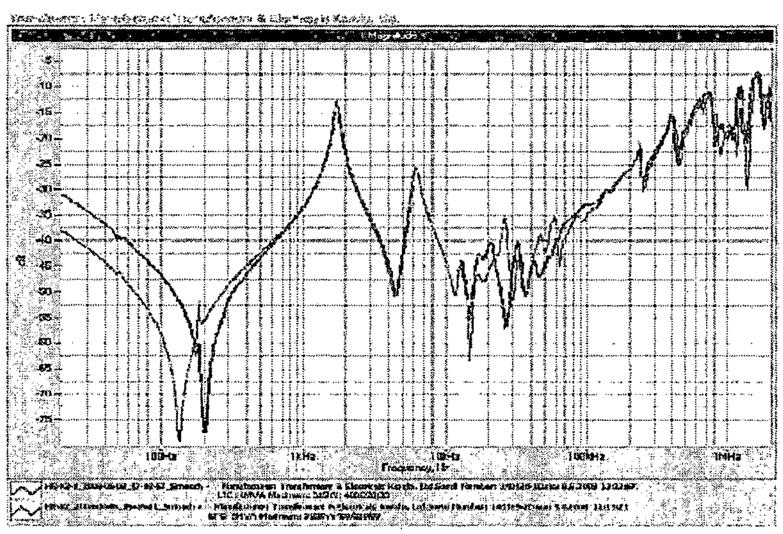

Figure 7.25: Open circuit SFRA plot of H2-X2 winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

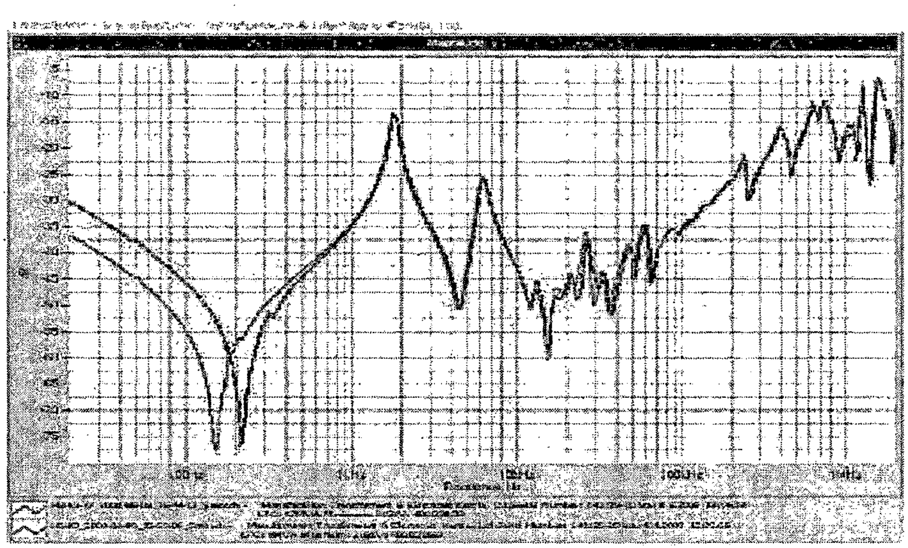

Figure 7.26: Open circuit SFRA plot of H3-X3 winding at Tap positions1 for ICT1 (Brown color)and ICT2(Blue color)

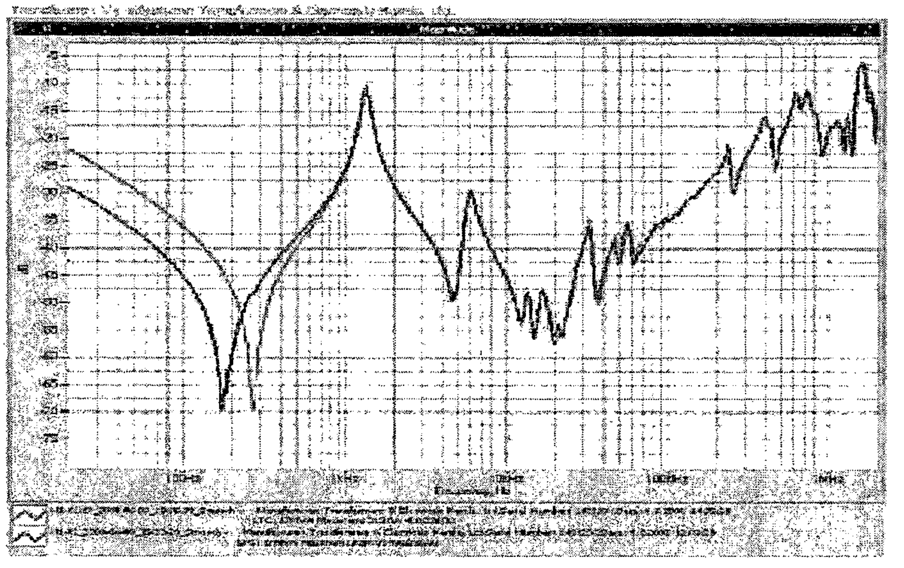

Figure 7.27: Open circuit SFRA plot of H1-X1 winding at Tap positions 17 for ICT 1(Brown color)and ICT 2 (Blue color)

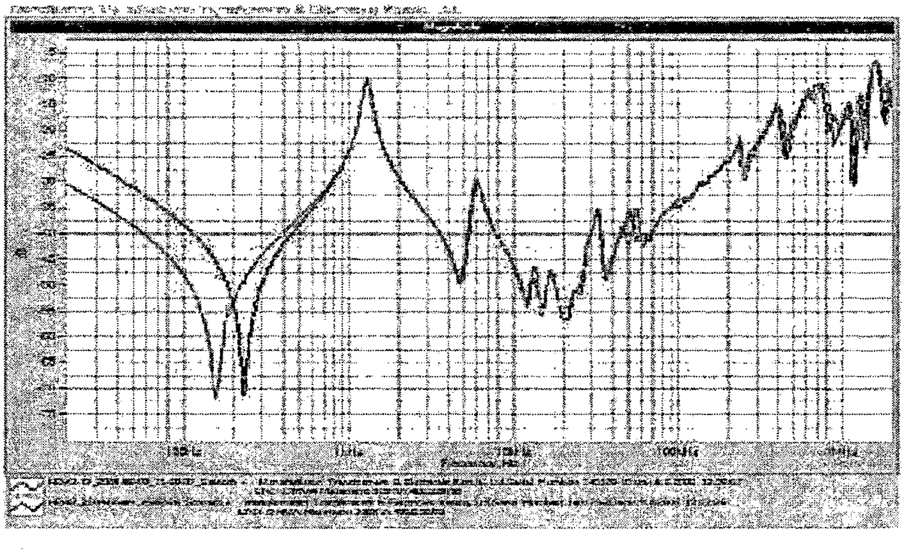

Figure 7.28: Open circuit SFRA plot of H2-X2 winding at Tap 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

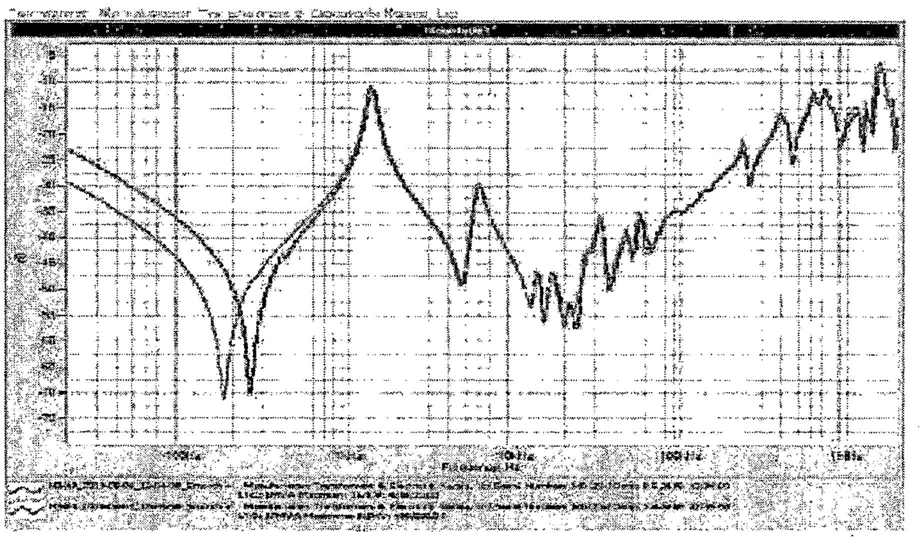

Figure 7.29: Open circuit SFRA plot of H3-X3 winding at Tap positions 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

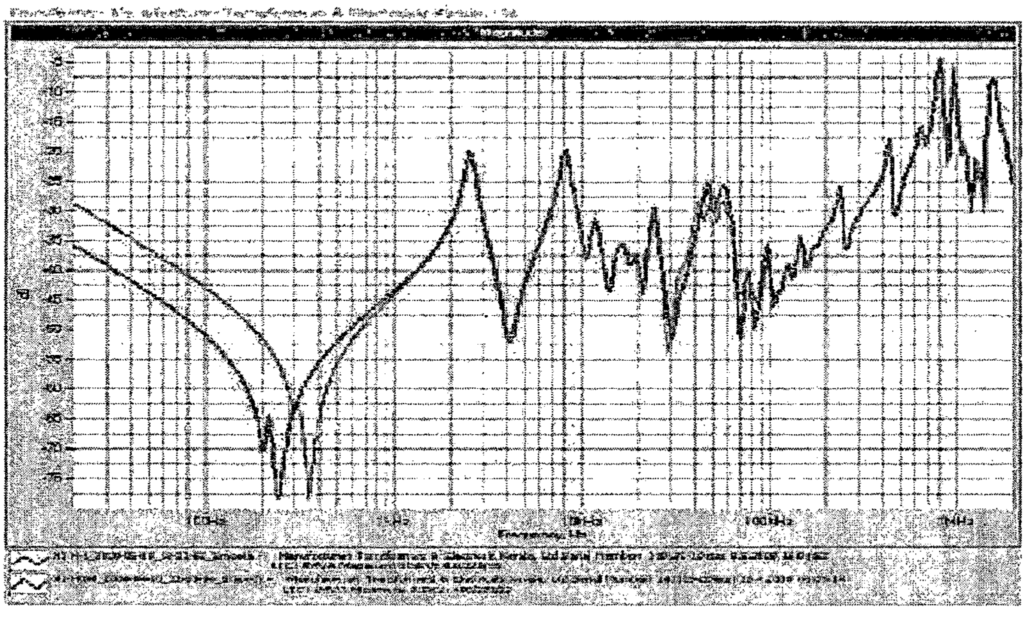

Figure 7.30: Open circuit SFRA plot of X1-N winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

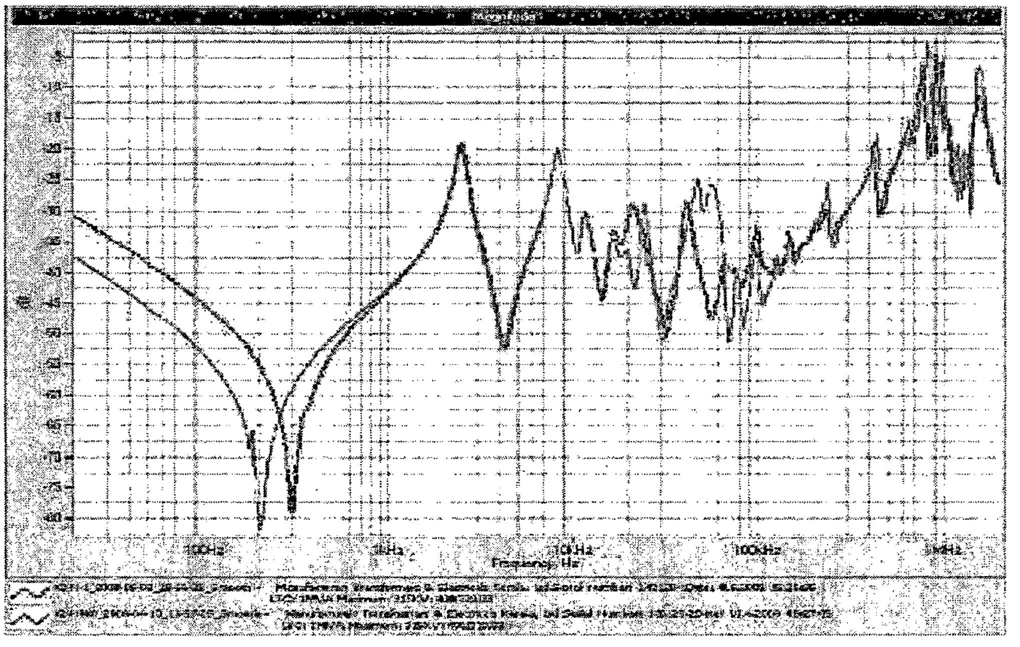

Figure 7.31: Open circuit SFRA plot of X2-N winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

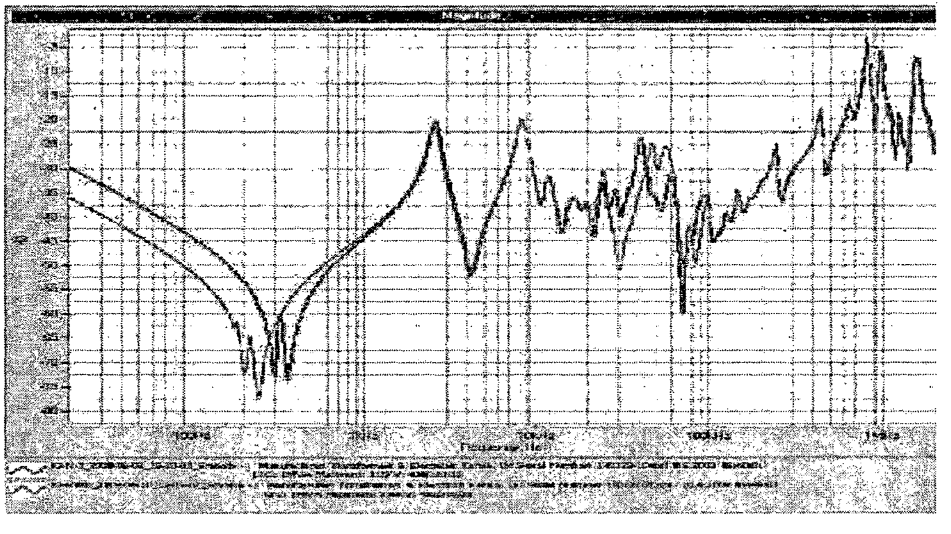

Figure 7.32: Open circuit SFRA plot of X3-N winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

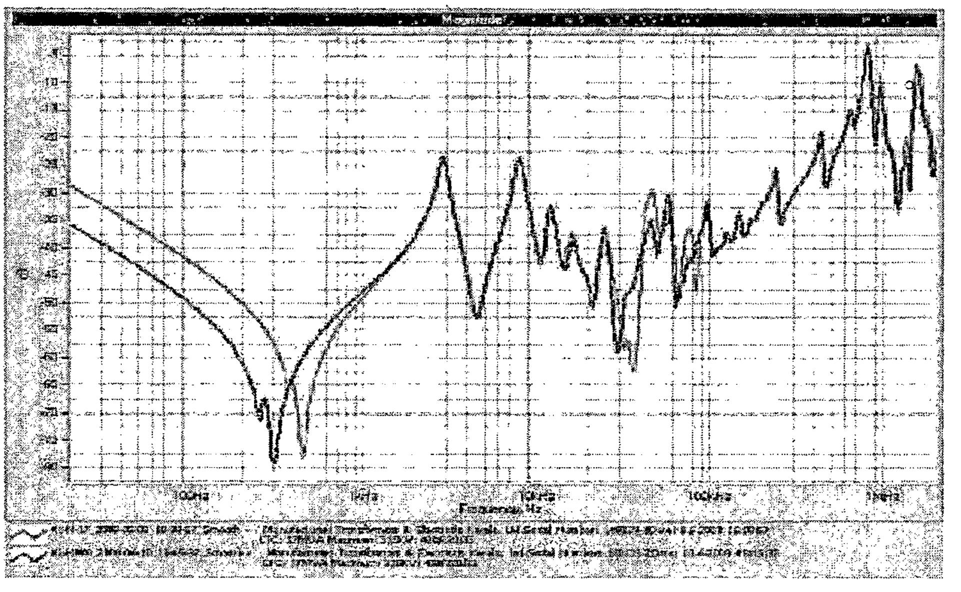

Figure 7.33: Open circuit SFRA plot of X1-N winding at Tap positions 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

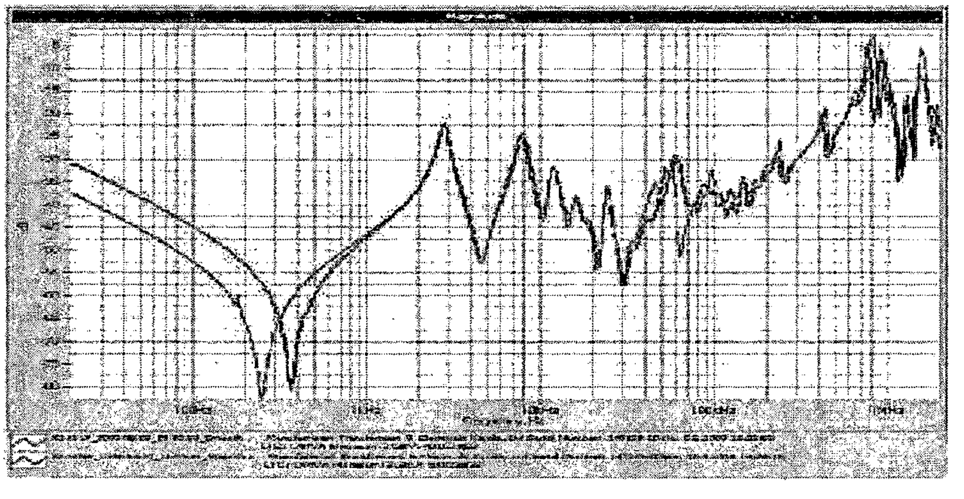

Figure 7.34: Open circuit SFRA plot of X2-N winding at Tap positions 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

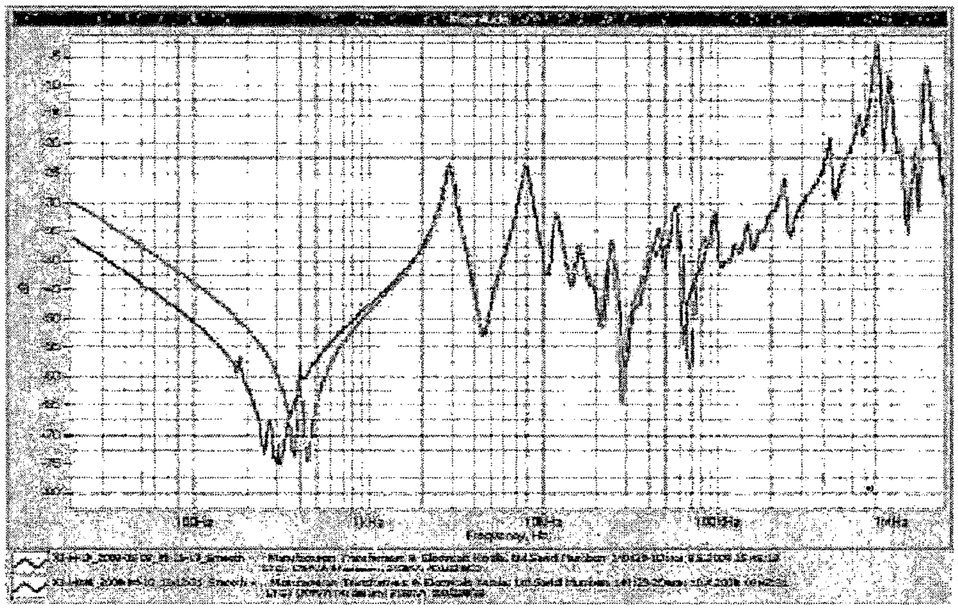

Figure 7.35: Open circuit SFRA plot of X3-N winding at Tap positions 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

Tap 9b (Figure7.41) plots are not identical and showing major shift and anti-resonance in the response in the frequency region 20 kHz. to 200 kHz., which indicates that there is significant winding movement in Y-phase and B-Phase of the transformer.

3. For winding Y1-Y2-Tap 9b (Figure7.42), Y2-Y3-Tap 9b (Figure7.43) , Y1-Y3-Tap 9b (Figure7.44),the plots are not identical and showing major shift and anti-resonance in the response in the frequency region 20 kHz. to 200 kHz, which indicates that there is significant winding movement in all phases of Tertiary winding of the transformer.

(iv) Comparison of Sister Units (ICT 1 and ICT2) Short circuit SFRA Plot on per phase basis after fault on ICT1:

Short circuit responses measured for the HV windings by shorting LV winding are shown at tap no. 1 and 17 are shown in Figure 7.45 to 7.50. The dominant features of these plots are that it starts from very low dB due to shorting of the LV windings

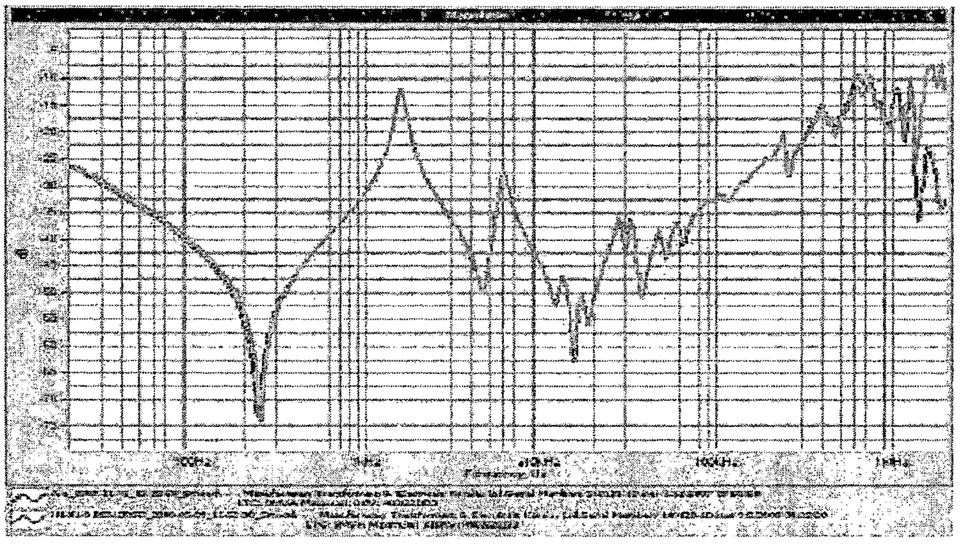

Figure 7.36: Open circuit SFRA plot of H1-X1 winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

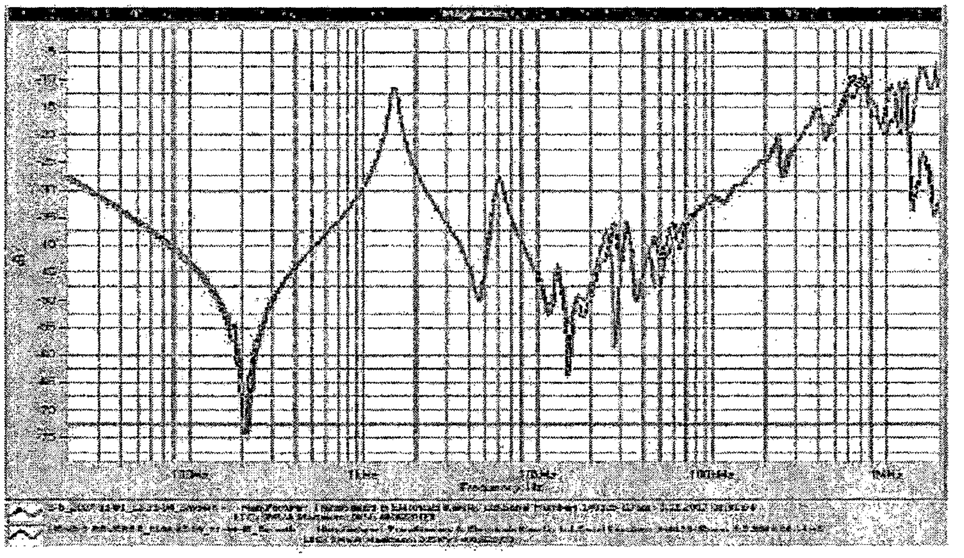

Figure 7.37: Open circuit SFRA plot of H2-X2 winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

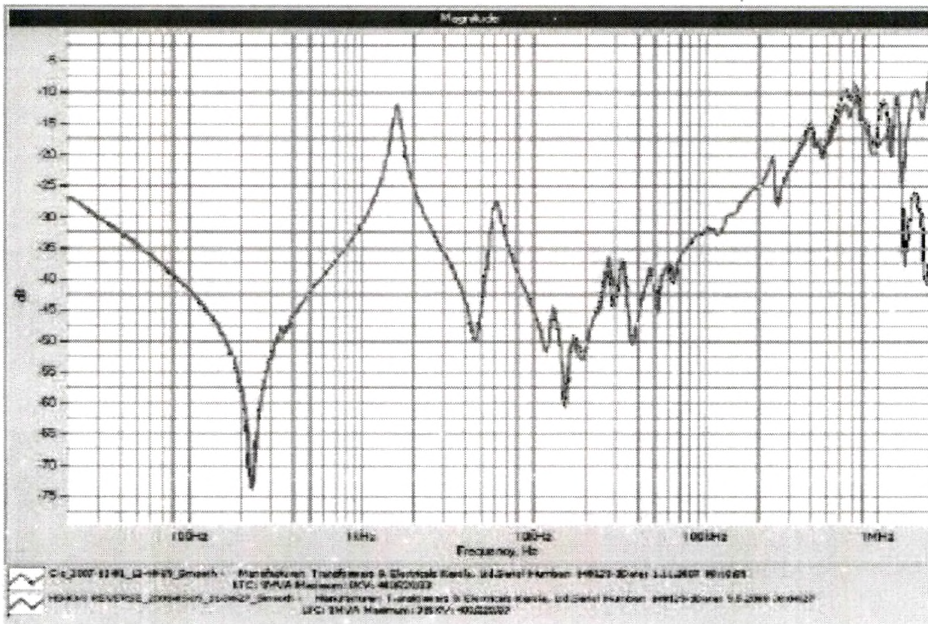

Figure 7.38: Open circuit SFRA plot of H3-X3 winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

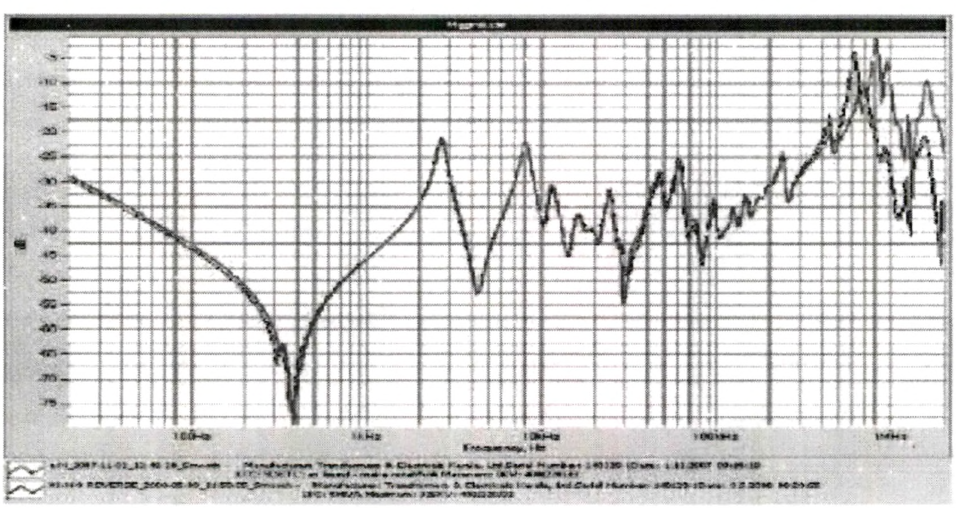

Figure 7.39: Open circuit SFRA plot of X1-N winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

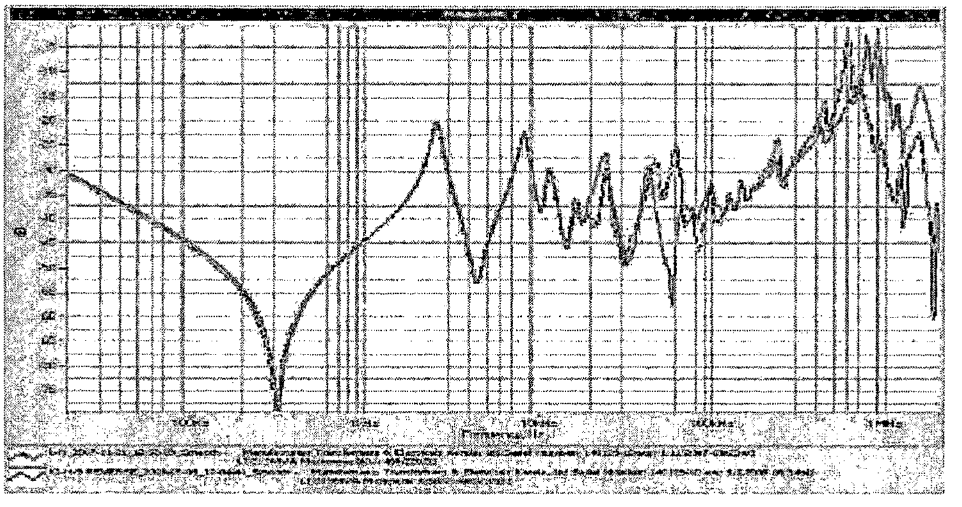

Figure 7.40: Open circuit SFRA plot of X2-N winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

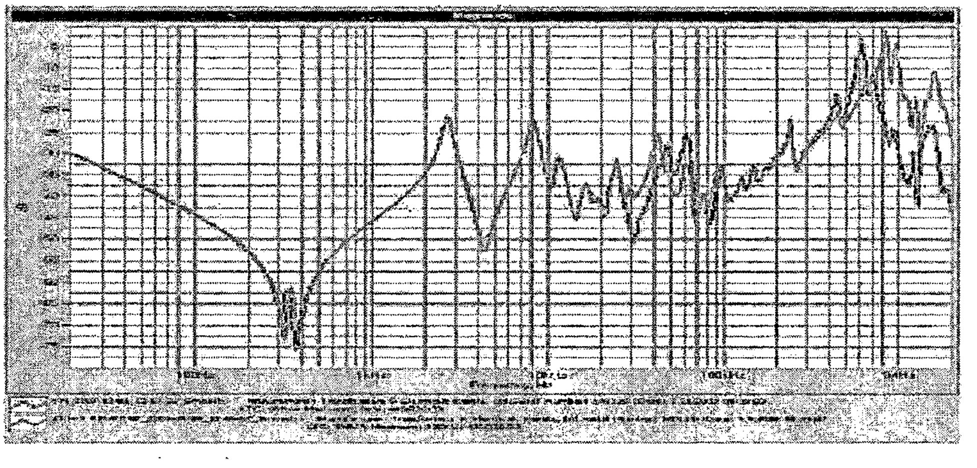

Figure 7.41: Open circuit SFRA plot of X3-N winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

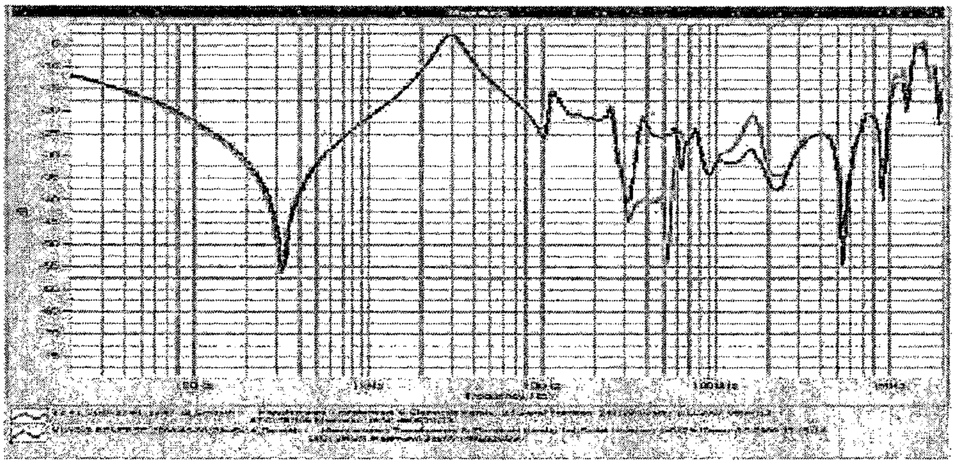

Figure 7.42: Open circuit SFRA plot of Y1-Y2 winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

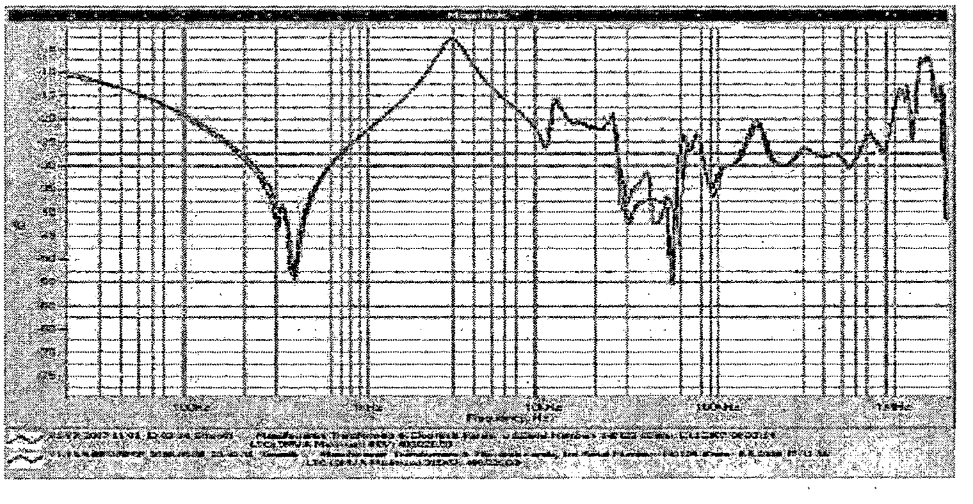

Figure 7.43: Open circuit SFRA plot of Y1-Y3 winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

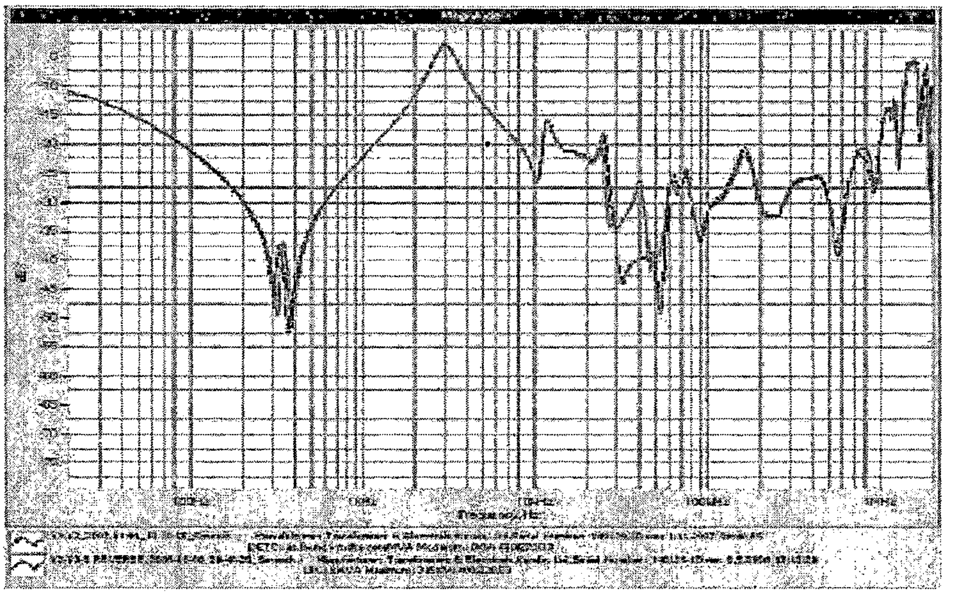

Figure 7.44: Open circuit SFRA plot of Y2-Y3 winding at Tap positions 9B for ICT 1 Before fault (Brown color) and After fault (Blue color)

(X1-X2-X3) which is near to the core.

Observations:

The difference between the all three phases and on per phase basis with the sister unit is below $0.2dB$ from $20Hz$ to $1kHz$ which is well within the limit for the new transformer. In this case, the low frequency minimum is not determined by low frequency open circuit inductance of winding which involve the core also. Hence, it purely represents the status of winding, i.e. indication of fault like Open circuit, Short circuit etc. So, Resistance and Self inductance of the all phases of ICT1 has not changed and indicate no electrical type of fault.

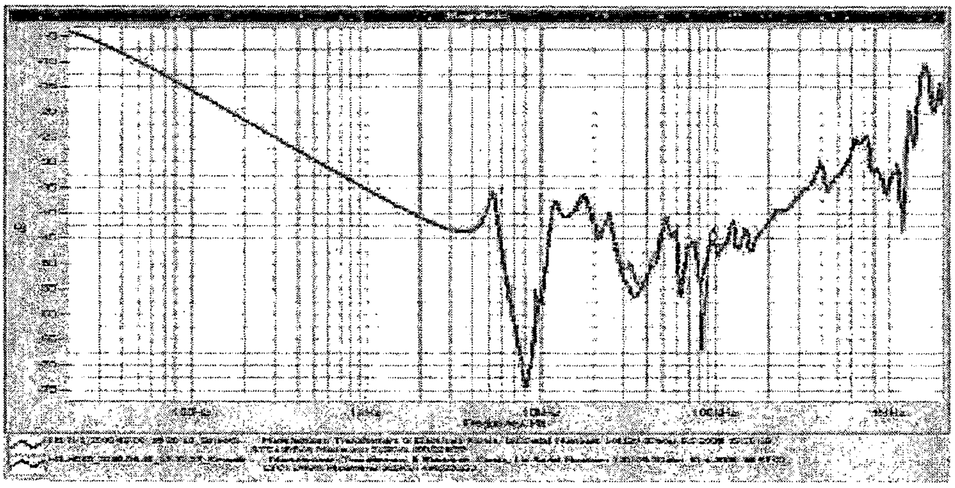

Figure 7.45: Short circuit SFRA plot of H1-N winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 Blue color)

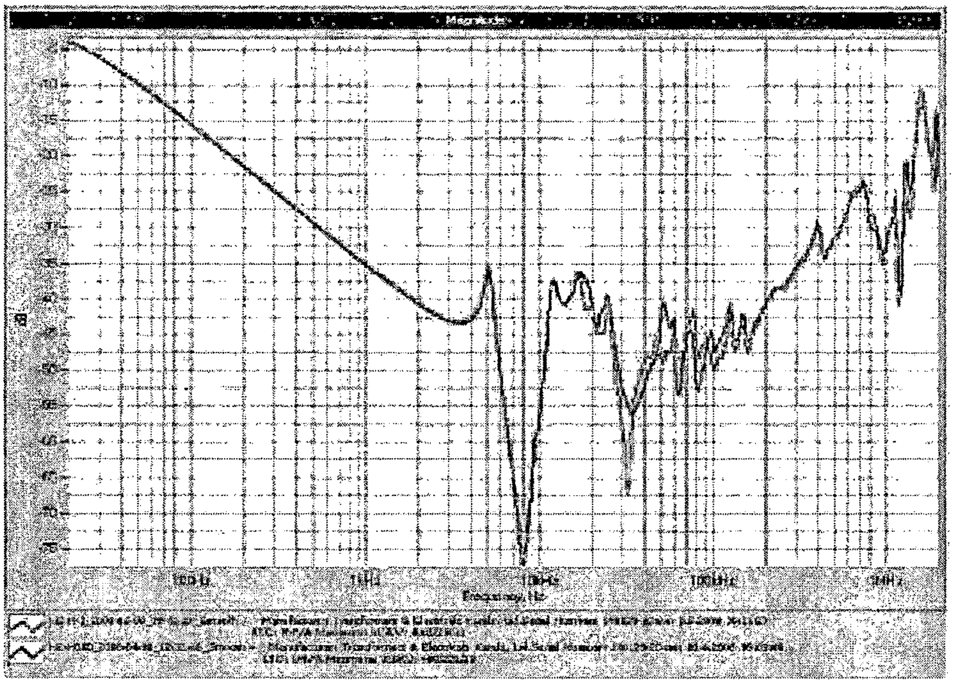

Figure 7.46: Short circuit SFRA plot of H2-N winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

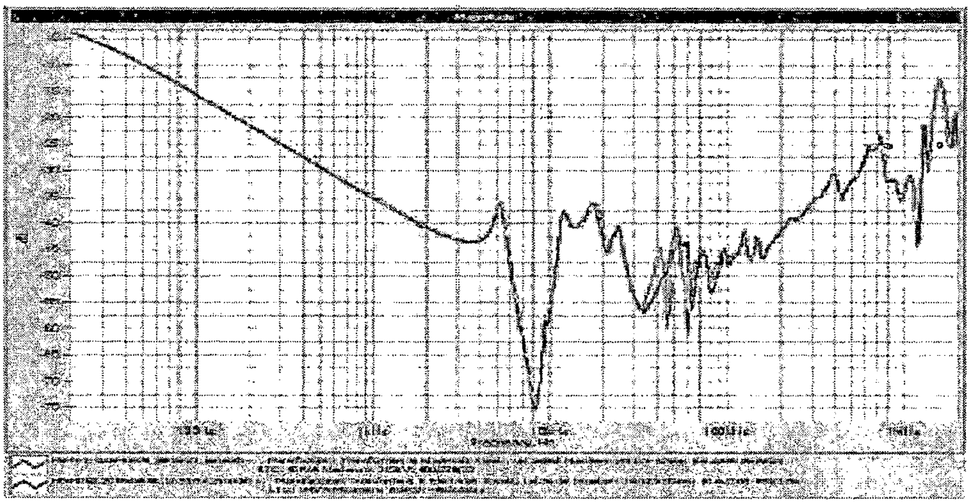

Figure 7.47: Short circuit SFRA plot of H3-N winding at Tap positions 1 for ICT 1 (Brown color)and ICT 2 (Blue color)

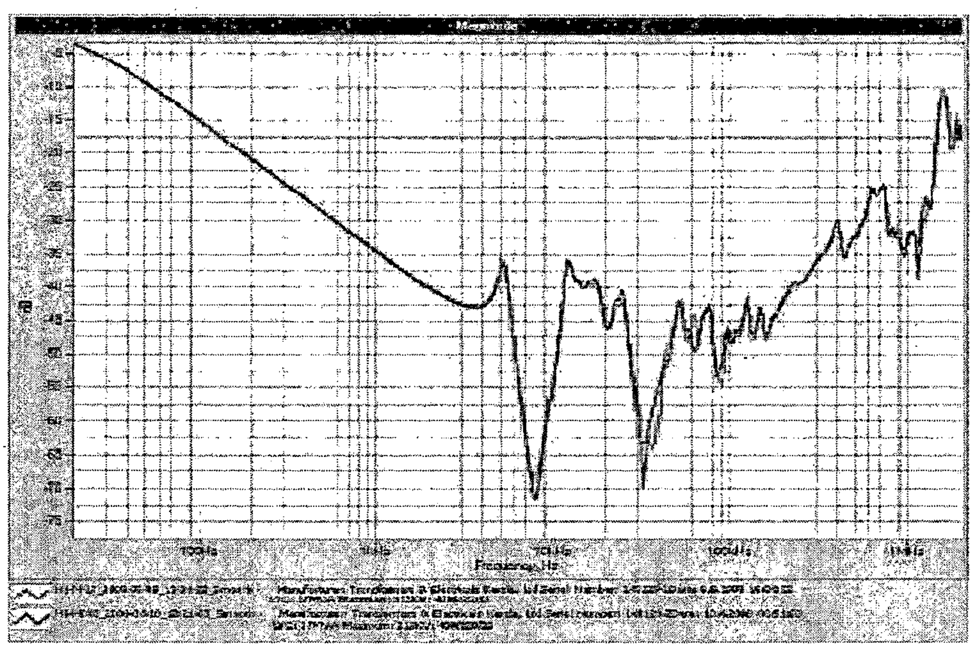

Figure 7.48: Short circuit SFRA plot of H1-N winding at Tap positions 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

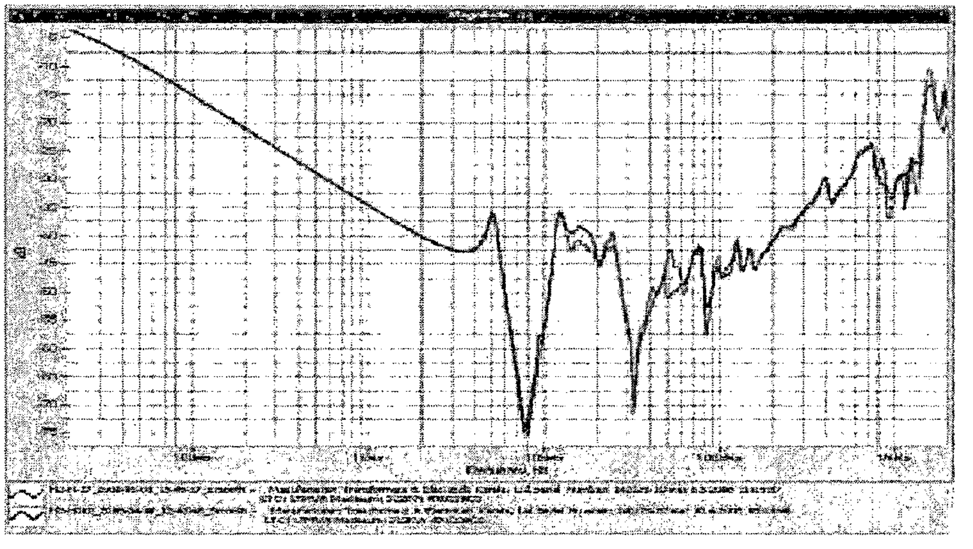

Figure 7.49: Short circuit SFRA plot of H2-N winding at Tap positions 17 for ICT 1 (Brown color)and ICT 2 (Blue color)

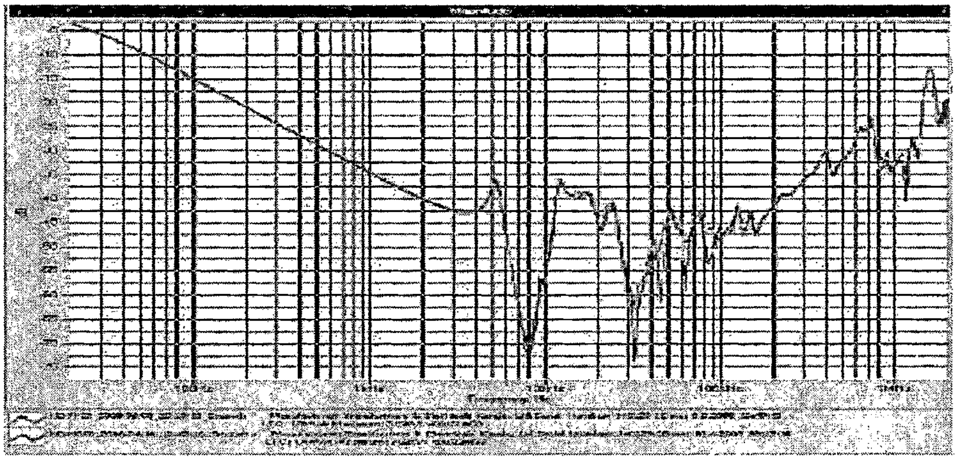

Figure 7.50: Short circuit SFRA plot of H3-N winding at Tap positions 17 for ICT 1(Brown color)and ICT 2 (Blue color)

Table 7.1: Capcitance measurement

SL NO	WINDING COMBINATION		BEFORE FAILURE 35^oC		AFTER FAILURE 37^oC	
			CAPACITANCE (pF)	$\tan\delta$	CAPACITANCE (pF)	$\tan\delta$
1	HV-IV/LV	UST	7306.02	0.253	7607.57	0.298
2	HV-IV/LV+G	GST	15291.19	0.357	15547.75	0.324
3	HV-IV/LV(Guard)	GAR R	7981.24	0.248	7923.99	0.354
4	HV-IV/LV	UST	7305.58	0.256	7617.90	0.299
5	HV-IV/LV+G	GST	2376.38	0.242	24377.98	0.262
6	HV-IV/LV(Guard)	GAR R	16453.81	0.237	16757.43	0.248

Table 7.2: No load current (HV) of ICT1

TAP POSITION	VOLTAGE APPLIED		BEFORE FAILURE CURRENT Measured	AFTER FAILURE CURRENT Measured
LOWEST(1)	R-N	10KV	21.30mA	19.41mA
	Y-N	10KV	14.57mA	6.687mA
	B-N	10KV	19.77mA	21.920
NORMAL(9b)	R-N	10KV	26.03mA	23.255mA
	Y-N	10KV	17.46mA	6.713mA
	B-N	10KV	23.65mA	28.040
LOWEST(1)	R-N	10KV	31.72mA	29.541mA
	Y-N	10KV	21.45mA	19.228mA
	B-N	10KV	28.74mA	34.965mA

Table 7.3: No load current (IV)

TAP POSITION	VOLTAGE APPLIED		BEFORE FAILURE	AFTER FAILURE
	BETWEEN	VOLTS	CURRENT Measured	CURRENT Measured
NORMAL	2R-N	10KV	70.09mA	68.304mA
	2Y-N	10KV	55.26mA	48.357mA
	2B-N	10KV	71.14mA	70.970mA

7.4.2.2 Capacitance and excitation current test data

Observations:

1. There is change in the inter winding capacitance (C-HL) value by 5 percent when compared with the base value of capacitance measured during commissioning of transformer.

2. Also, there is change in power factor of the C-HL which indicates contamination in the insulation.

Comments:

1. Change in the excitation current of HV winding, Y-phase at Tap no.1 and 9b after fault is showing similarity with the variation in SFRA plot. There is no significant change at Tap no. 17 in the excitation current, which indicate that tapping winding is having problem and series winding of Y-phase is healthy .

2. Major deformation in Y-phase Common and tapping winding is observed, based on SFRA result and it has affected the B-phase Common and tapping winding also of ICT1.

3. Series winding of Y-phase is not affected so much and it is comparable with R-phase and B-phase series winding.

4. Tertiary winding is also indicating deformation in all phases.

5. Resistance and Self inductance of the all phases of ICT1 has not changed and indicate no electrical type of fault.

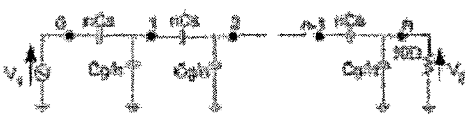

Figure 7.51: N-stage capacitive ladder network

6. Capacitance and no load excitation current measurement is also indicating that Y-phase common and tapping winding is deformed.

Recommendation:

Based on all these findings from the test data it is recommended to have internal inspection of the tap changer parts and winding of the transformer. Transformer should not be charged in this state and the root cause of the deformation should be identified.

7.5 High-Frequency Response

In high frequencies region between $1MHz$ to $2MHz$, a transformer winding behaves as a purely capacitive element, and power transformers having both higher voltage and larger power rating usually have smaller negative response magnitudes as the capacitance is high.

At very high frequencies, the transformer winding can be represented as a capacitive ladder network as shown in Figure 7.51.

Case Study 8:

Auto-transformer of 400 kV /220 kV/33kV, is indicating very low megger value between core and tank after movement of transformer from factory to site. Upon comparison of factory and site SFRA plot significant shift was found in frequency range of $1MHz$ to $2MHz$ for all the series and common winding of transformer.

The three phase comparison of reference and fresh signatures separately are very good as indicated in Figures 7.52 to 7.57, while comparision of reference and fresh signatures of same winding do not match among themselves and this is common to all windings as

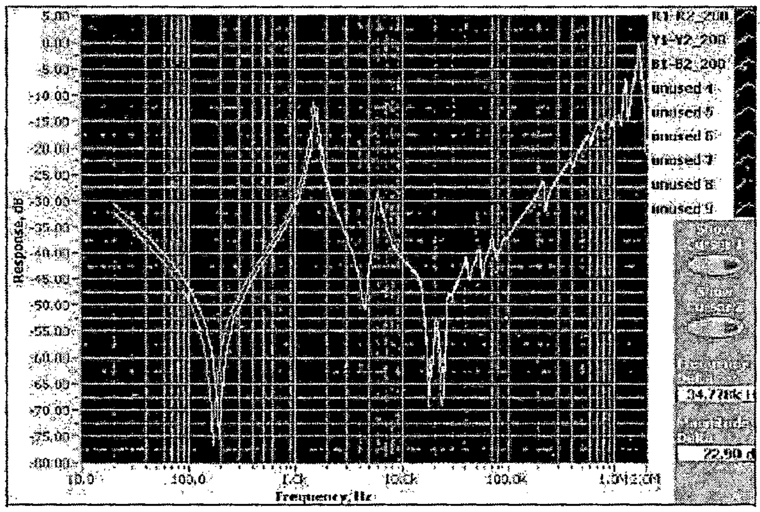

Figure 7.52: Three phase comparison of fresh signatures of series windings at tap position 9b

indicated in Figure7.58 to 7.63 . The shift in the resonance is due to the change in the capacitance between the core and tank due to the core eearth fault.

Test Procedure:

The transformer tested was completely isolated from the power supply. In order to maintain consistency and repeatability of measurements, all terminals that are not under test were isolated and floating.

7.6 Overall Frequency Variation of SFRA

Case Study 9:

After a system fault , SFRA plot of three phase Auto Transformer with Tertiary winding of rating 315 MVA and rated voltage of 400/220/33 KV was analyzed as mentioned below. IIt was a overall deformation of U-phase common winding (1U-2U) of auto transformer which was evident from the SFRA plot shown in Figure 7.64. Also same pattern of deviation is observed in SFRA short circuit plot indicating an high impedance fault with overall deformation of U-phase as mentioned in Figure 7.65and 7.66.

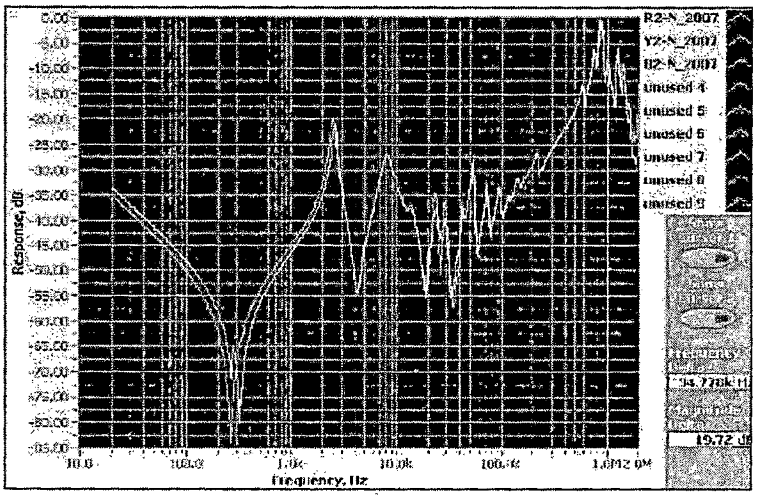

Figure 7.53: Three phase comparison of fresh signatures of common windings at tap position 9b

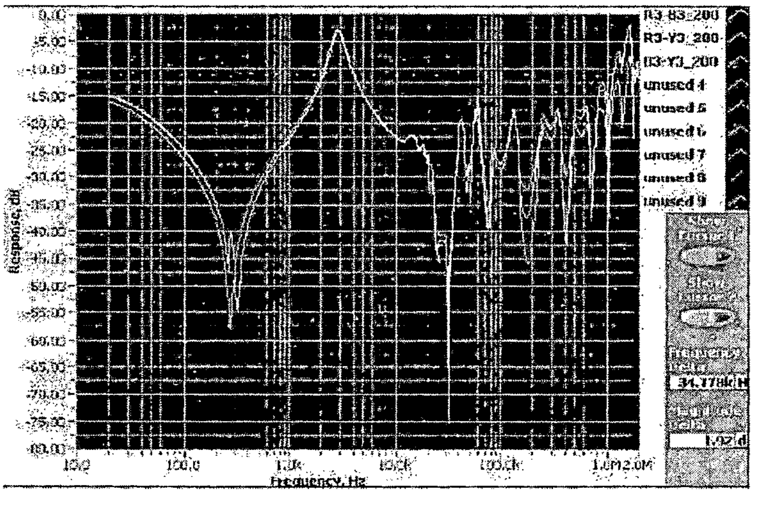

Figure 7.54: Three phase comparison of fresh signatures of LV windings at tap position 9b

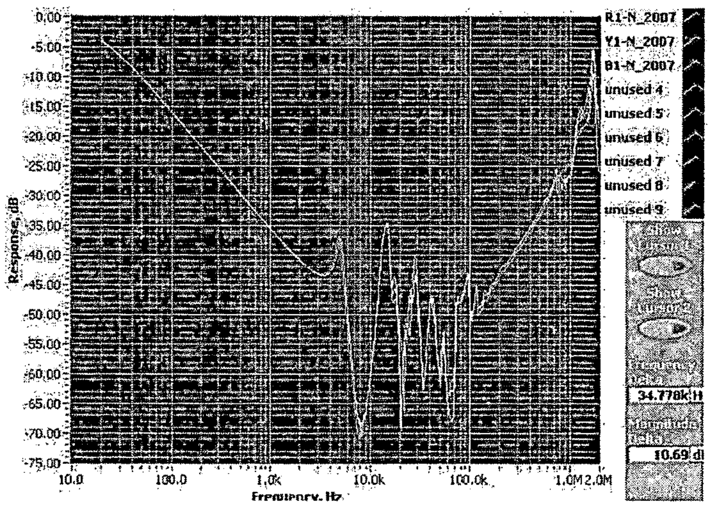

Figure 7.55: Phase to phase comparison of fresh signatures of HV (series common) windings at tap position 9b with IV shorted.

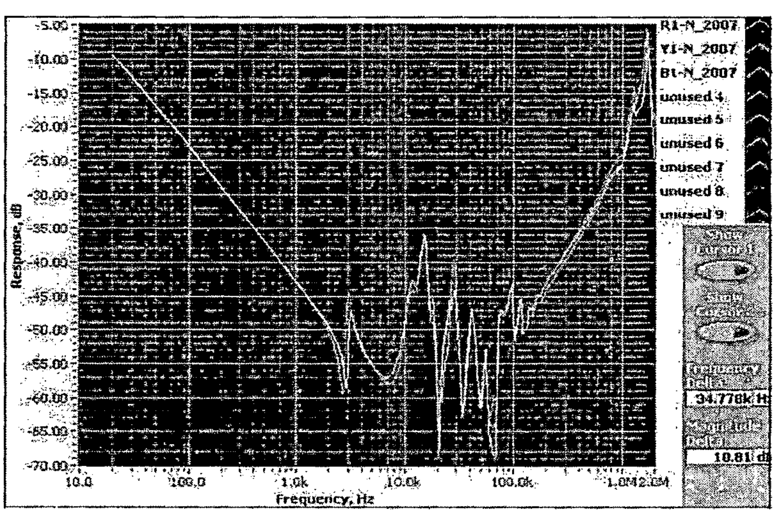

Figure 7.56: Phase to phase comparison of fresh signatures of HV (series common) windings at tap position 9b with LV shorted.

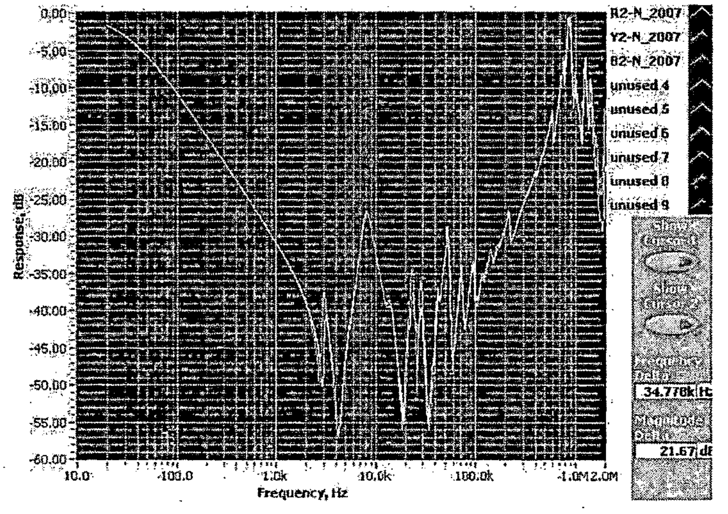

Figure 7.57: Phase to phase comparison of fresh signatures common windings at tap position 9b with LV shorted.

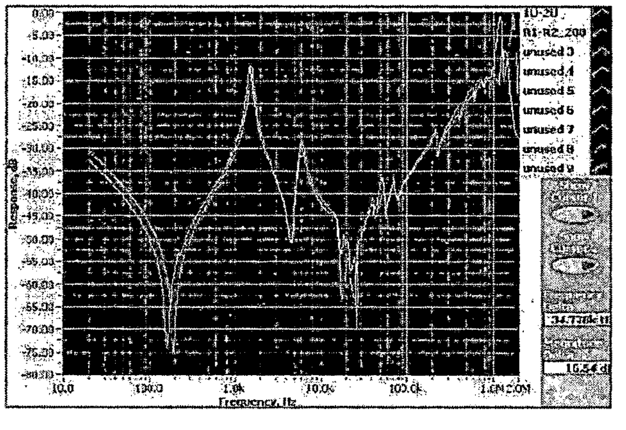

Figure 7.58: Comparison of reference and fresh signatures of U-phase series winding at tap 9b

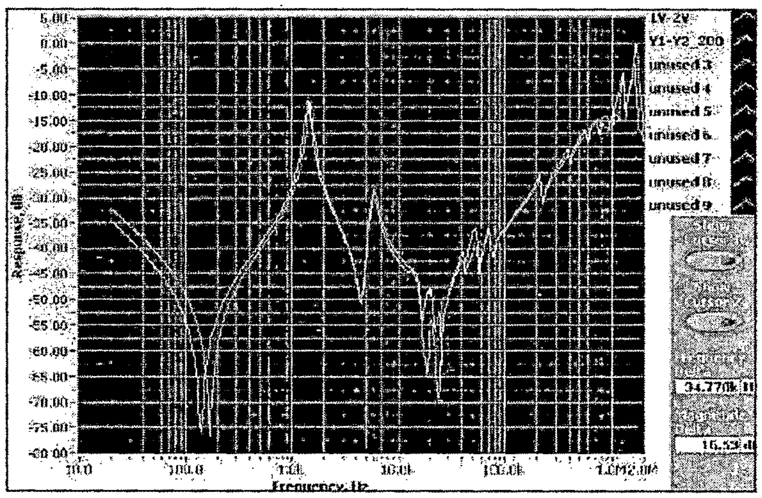

Figure 7.59: Comparison of reference and fresh signatures of V-phase series winding at tap 9b

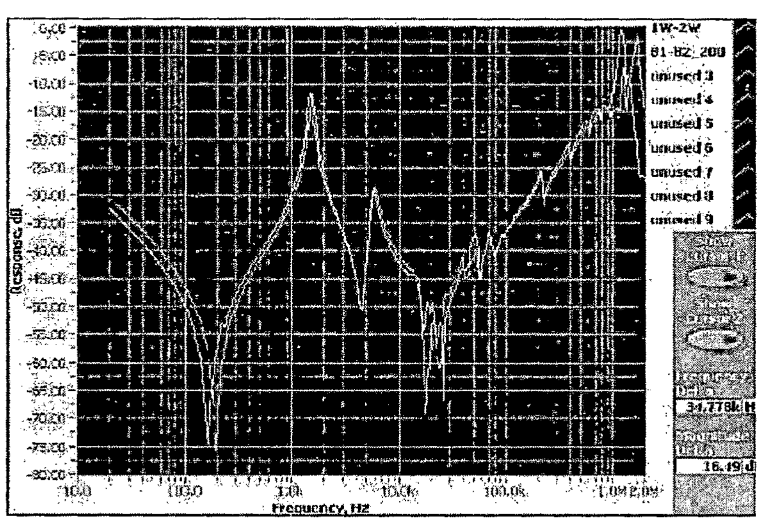

Figure 7.60: Comparison of reference and fresh signatures of W-phase series winding at tap 9b

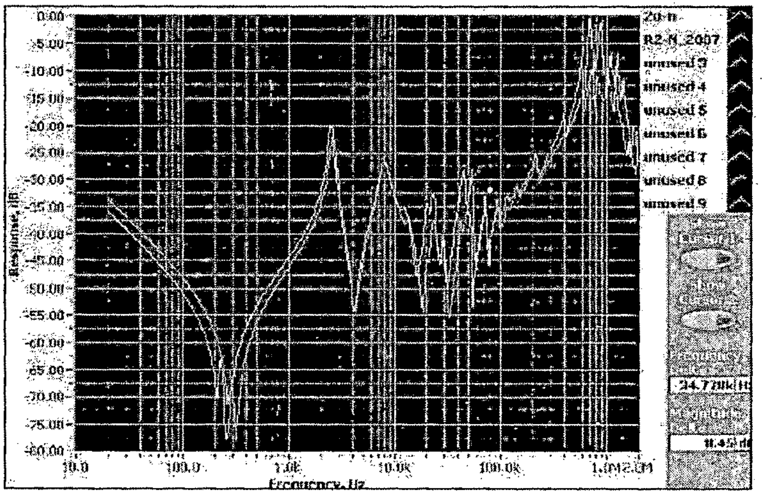

Figure 7.61: Comparison of reference and fresh signatures of U-phase common winding at tap 9b

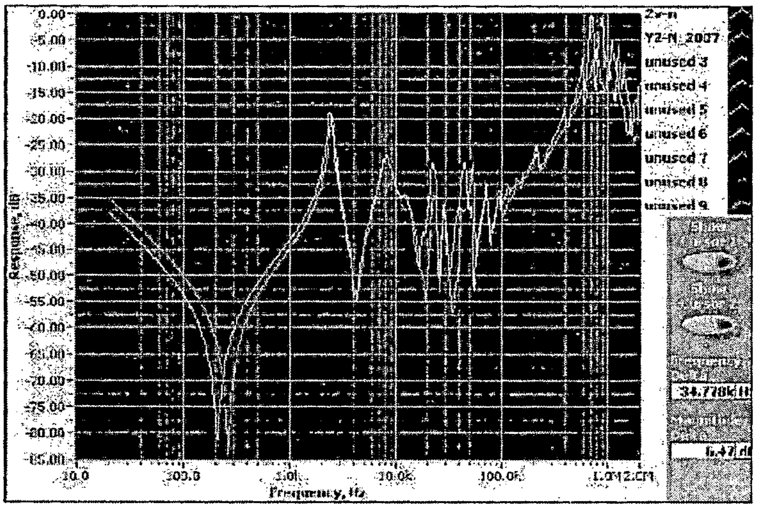

Figure 7.62: Comparison of reference and fresh signatures of V-phase common winding at tap 9b

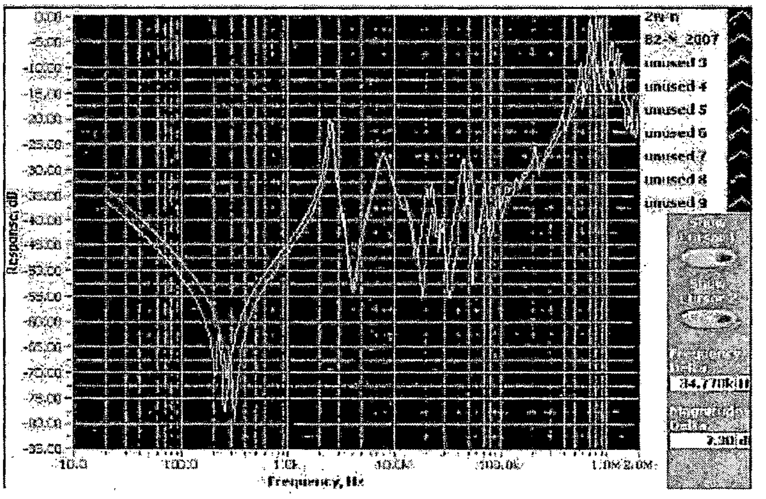

Figure 7.63: Comparison of reference and fresh signatures of W-phase common winding at tap 9b

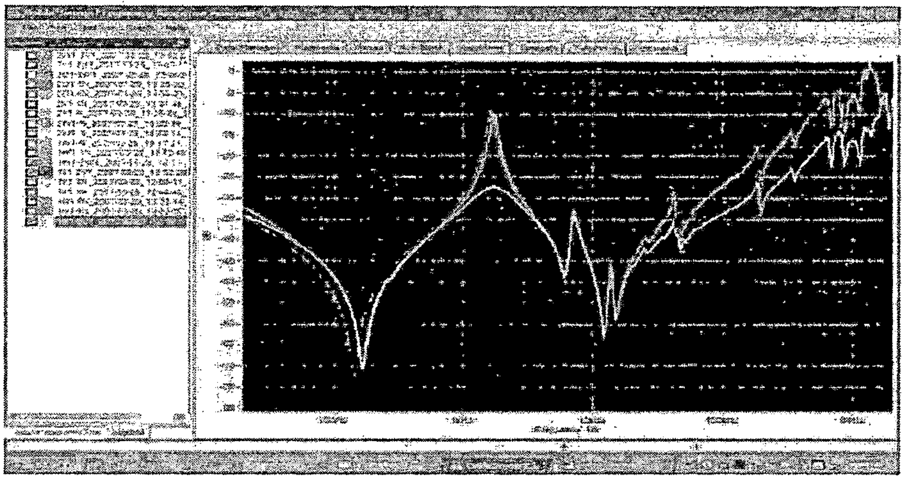

Figure 7.64: Comparison of three phase open circuit plot of common winding (U phase-white color)

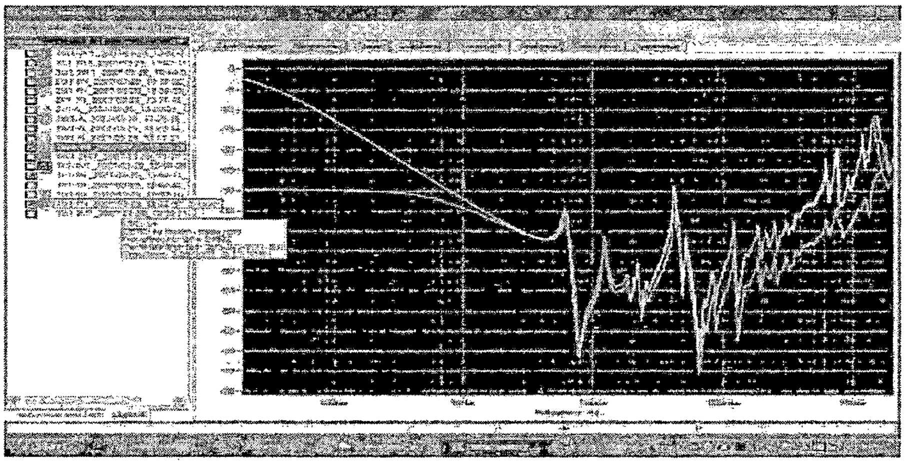

Figure 7.65: Comparison of Short circuit plot for three phase HV winding by shorting LV winiding (U phase- pink color)

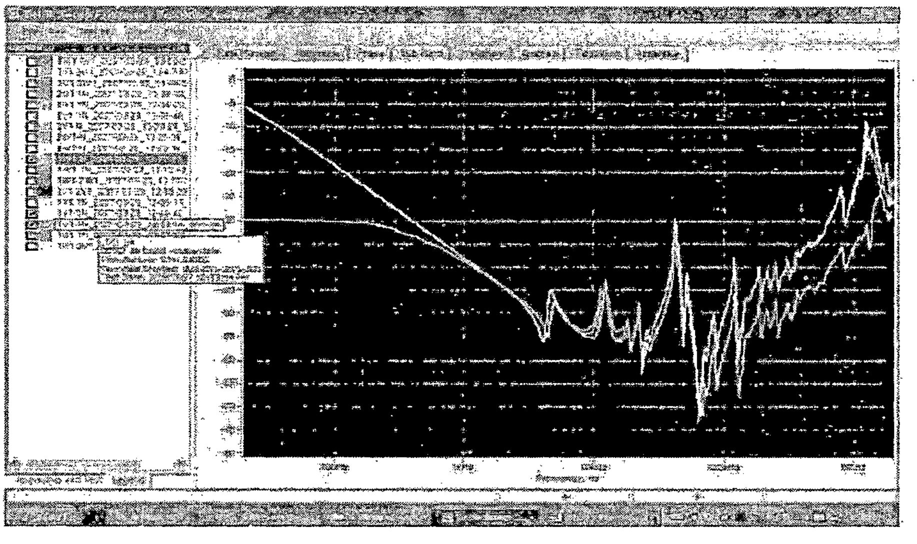

Figure 7.66: Comparison of short circuit plot for three phase HV winding by shorting tertiary winding (U phase -blue color)

7.7 Conclusion

The Sweep frequency Response Analysis (SFRA) diagnosis is made based on the comparison between two SFRA responses and any significant difference in low frequency region, shift of existing resonance, creation of new resonance, change in shape of plot would potentially indicate mechanical or electrical problem with the winding and core of Transformer as mentioned in this chapter. However, the ability to interpret such 'differences' when comparing the SFRA responses is of a great challenge and then expertise to further analysis of the plot for classification of fault is very limited today for the users who are not very familiar with SFRA and need experts for the conclusions and findings. Hence, there is a need for the expert system based tools to assist in the analysis of SFRA results and it will be discussed in the next chapter.