Chapter 5

Modelling of Transformer winding for Interpretation of SFRA

5.1 Introduction

The Sweep frequency Response Analysis (SFRA) is an emerging method for investigation of transformer mechanical integrity after through fault in the system and its relocation. There are cases found, where SFRA has been a key tool in the decision making either to scrap, rewind or reenergize a transformer after an incident [30][13]. Based on the practical experience with SFRA analysis, the frequency range from $10Hz$ to $2MHz$ is sufficient for the analysis [27] and can be divided into three frequency band. These frequency band are governed separately by the inductive effect of core, self and mutual inductance of the winding, series and shunt capacitance of the overall winding structures and the lead/tap connections.

SFRA data of over 1000 power transformers has been collected both for the new and aged transformer including the failed transformer in the field. These results have been carefully analyzed while focusing on various similarities and differences. Since transformers design and application vary, the SFRA plots inherit diverse properties and characteristics and basic circuit of transformer winding applicable to SFRA has to be analyzed for this purpose.

Interpretation of SFRA responses is crucial in order to assess the integrity of transformer windings. In order to achieve the correct interpretation of SFRA response, the effect of various circuit parameters of transformer winding on SFRA plot is studied in detail and discussed in this chapter. Hence, this chapter addresses one of the major factors that influenced the SFRA responses, the winding structure itself in low, medium and high frequency range.

5.2 Basic Circuit of Transformer

SFRA normally measures the frequency response of a transformer from $10Hz$ to $2MHz$. Circuit modeling thus needs to accurately represent the behavior of a transformer across this wide range of frequency. But, no such universal circuit model exists that can represent a transformer accurately over this entire range. Hence, modeling techniques for SFRA have been developed in several frequency regions, depending on the modeling accuracy required and the dominant components in each frequency region [30]. The different type of circuit model in each frequency band, which is considered for the SFRA analysis in this research work are described below.

5.2.1 Low frequency model

The equivalent circuit of transformer winding at low frequency from 10 Hz. to 1000 Hz. is shonwn in Figure 5.1. The dominant features of low frequency plots are the first minima at low frequency normally below 1000 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 core capacitance start to become significant and allow a recovery in transmitted voltage. The low frequency minimum is determined by self inductance of winding, inductance and capacitance of core. 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.

In low frequencies, a transformer winding behaves as an inductive element, and the SFRA response follows a increasing negative magnitude trend across the frequency range with a linear slope and this may not be exact linear also due to core non-linearity with frequencies. As the inductance is increased, the magnitude is increased. Power transformers with higher voltage and larger power rating usually have larger negative response magnitudes. Effectively there are two parts of inductance affecting the SFRA response;

the core magnetizing inductance and the self inductance of the windings. Each affects the response in different frequency ranges. The leakage inductance affects the SFRA response in lower frequencies of no more than $100Hz$ while the core magnetizing inductance influences the SFRA response at high frequencies up to $1kHz$.

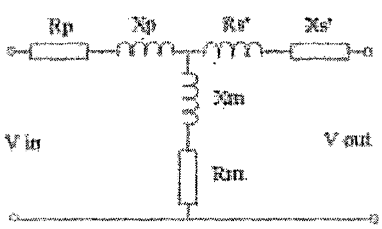

Figure 5.1: Equivalent circuit of Transformer winding at Low frequency

The magnetizing inductance of the core, L_m which decides the magnitude of X_m in Figure 5.1 is influenced by the winding number of turns, N and the reluctance, R which is given by

$$L_m = \frac{N^2}{R} \tag{5.1}$$

The magnetic path of the middle phase is different compared to the magnetic path of the outer phases due to the symmetrical core construction of transformer in case of middle phase and it is also affecting SFRA. This magnetic reluctance, R is analogous to the resistance in the electrical circuit and thereby is influenced by the length of the magnetic path, l and the area of the cross section of the core, A.

The inductance is divided in two groups self and mutual inductance of the winding as shown in Figure 5.2.

Because of such a coarse representation of the windings, localized winding movement will not be reflected in this low frequency region unless the winding moves significantly. The SFRA measurement in the low frequency region are primarily used to detect problems related to the transformer core and major winding faults like shorted turn, open circuit and high impedance fault in the early developing stage.

5.2.2 Mid Frequency model

The equivalent circuit of transformer winding at mid frequency from 1kHz. to 1000 kHz. is shonwn in Figure 5.3. In mid frequency range, as the frequency increases, the effect

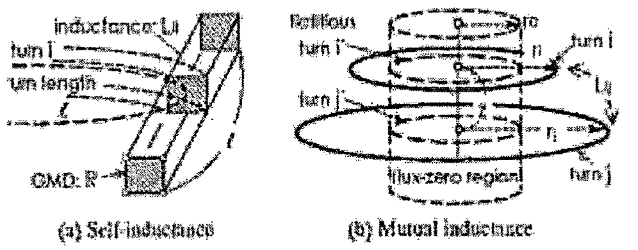

Figure 5.2: Winding self and mutual inductance

of core will become less significant as the flux penetration depth in the core is frequency -dependent and it is worst effected by DC voltage creating the core saturation problem after the DC test like resistance measurement. Hence, in mid frequency range around $10kHz$, core will behave as an earth plate. The winding structure, especially the winding under test, becomes dominant factor of the frequency responses.

Therefore, it is necessary to use the multiple LC element equivalent network to model the winding accurately in mid frequency range[50].However, in transformer winding, the basic components are combined together and the transformer winding structure becomes more complex than a simple LC element.

To represent a winding accurately in the medium frequency range, a detailed RLC ladder network of the winding is required. Each winding is divided into cells. The cell is represented as lumped -element unit, which consists of a series capacitance (C_s) and a self inductance (L). The capacitive coupling between the cells and the tank wall (C_g) for the outer winding cell and for the inner winding cell the shunt capacitance are included between the cell and the core. This transformer model is considered to be detailed enough to provide reasonably accurate SFRA results in the frequency range governed by the main winding structure , which is normally from about $10kHz$ to $500kHz$.

A uniformly structured winding can be represented by an n-stage ladder network, as shown in Figure 5.3. The winding total leakage inductance L, the winding total series capacitance C_s and the total shunt capacitance C_g are evenly distributed between the n stages.

The effect of dielectric losses or resistances connected either in series with the inductance or connected in parallel with the capacitance on the SFRA response, is to attenuate

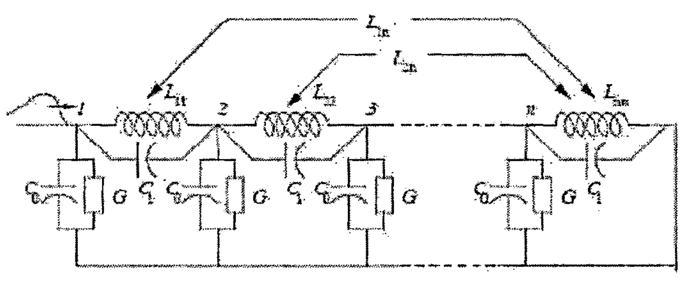

Figure 5.3: n-stages lumped ladder network

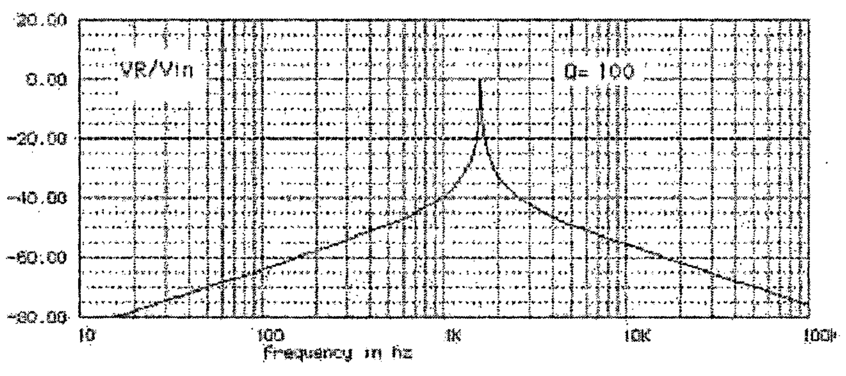

Figure 5.4: Series resonance of the RLC circuit having low R value

the sharpness of the resonances and the anti-resonances. The effect on the sharpness of resonance of series *RLC* circuit due to change in the resistance is shown in Figure 5.4 and Figure 5.5.

The combination of winding inductance and winding series capacitance results in parallel *LC* circuit and will produce parallel anti-resonance, consequently, blocking the signal at that particular frequency. Also, the simplest representation of *LC* in series is a $T - connection$ where the shunt capacitance is connected in the middle of the two halves of the winding inductance. The SFRA response of winding inductance and shunt capacitance in the *LC* network shows a series resonance, amplifying the signal at that particular frequency. In summary, the basic features of SFRA response can be shown in Figure 5.6.

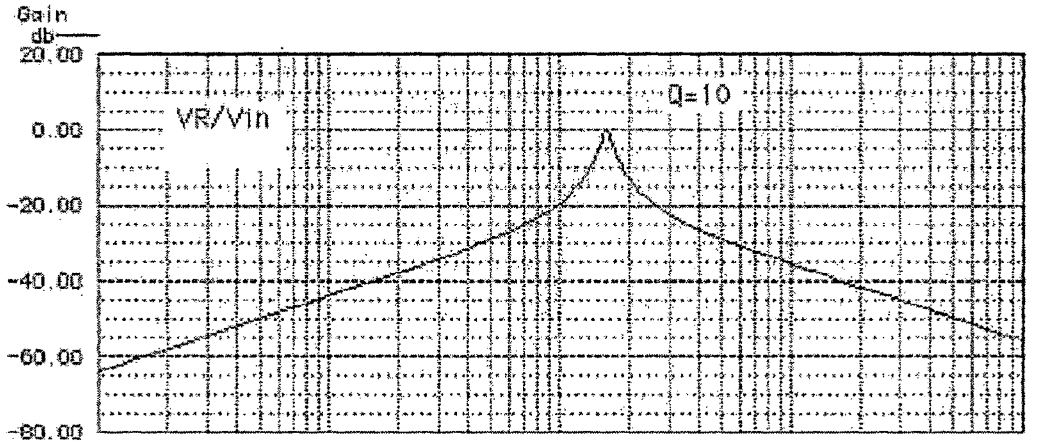

Figure 5.5: Series resonance of the RLC circuit having high R value

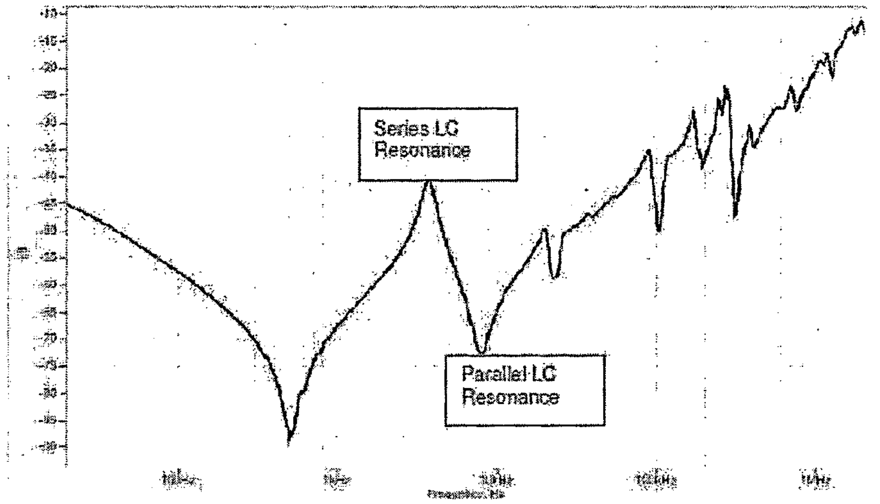

Figure 5.6: Series and Parallel resonance of the winding

However, in transformer winding, these basic components are combined together and the transformer winding structure becomes complex.

The general solution for voltage and current at any point x on the network shown in Figure 5.3 can be represented by Equation (5.2).

$$\begin{aligned} u(x, j\omega) &= A\cosh(\gamma x) + B\sinh(\gamma x) \\ i(x, j\omega) &= \frac{1}{Z}\left[A\sinh(\gamma x) + B\cosh(\gamma x)\right] \end{aligned} \tag{5.2}$$

where

$$\gamma^2 = \frac{\frac{LC_g}{n^2}\omega^2}{1 - LC_s\omega^2} \quad and \quad Z = \sqrt{\frac{L}{C_g\left(1 - LC_s\omega^2\right)}}$$

A and B are constants, x is the number of stages along the winding, starting from the injecting end, Z is the characteristic impedance and γ is the propagation constant of the winding.

SFRA response oscillate between capacitive and inductive and when multiple local resonances are produced at the frequencies as

$$f_k = \frac{k\pi}{2\pi\sqrt{LC_g + (k\pi)^2 LC_s}}, (\gamma n = k\pi) \qquad k = 1, 2, \ldots, n-1 \tag{5.3}$$

In terms of the structure of single windings, these can be categorized into windings with either high- or low- series capacitance in proportion to the shunt capacitance. Correspondingly, the SFRA responses of transformer windings of high series capacitance exhibited the increasing trend of magnitude in the frequency range between $10kHz$ and $500kHz$ while the windings of low series capacitance displayed the steady magnitude trend with the resonances and anti-resonances (camel humps) features in the frequency range between $10kHz$ and $2MHz$ [53].

Figure 5.7 illustrates the effect of having high or low series capacitance, C_s in the 8-stage lumped network obtained from simulation. With low C_s, the response begins with flat magnitude trend and resonances at intervals of frequencies determined by Equation (5.3) and then followed by a decreasing inductive trend. In Figure 5.7 , it is illustrated that as C_s is increased, some of the resonances diminish and the anti-resonance appears at lower frequency .

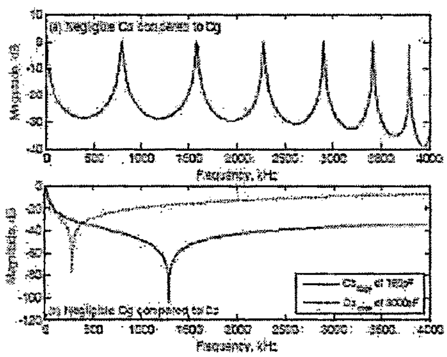

Figure 5.7: FRA response from 8-stage of lumped ladder network (L=800H) with extreme cases of (a) Cs=0, Cg=480pF and (b) Cg=0, CsLOW=190pF, CsHIGH=3000 pF

The extreme cases of the 8-stage lumped network with negligible C_s or C_g are shown in Figure 5.7. Figure 5.7(a) depicts the features of winding with low C_s such as the continuous disc while Figure 5.7(b) depicts the features of winding with high C_s or negligible C_g in comparison to C_s such as the interleaved winding.

Using the knowledge gained from the experimental studies during this research and theoretical back-up, this factor is shown to dominate the SFRA responses of power transformers in certain frequency ranges. In terms of the structure of single windings, these can be categorized into windings with either high- or low- series capacitance in proportion to the shunt capacitance. Correspondingly, the SFRA responses of transformer windings of high series capacitance exhibited the increasing trend of magnitude in the frequency range between $20kHz$ and $500kHz$ while the windings of low series capacitance displayed the steady magnitude trend with the resonances and anti-resonances (camel humps) features in the frequency range between $20kHz$ and $2MHz$.

5.2.3 High frequency model

In high frequencies, a transformer winding behaves as a capacitive element[54], and power transformers having both higher voltage and larger power rating usually have smaller negative response magnitudes in high frequency range as the capacitance is high. At very high frequencies, the network can be represented as a capacitive ladder network as shown in Figure 5.8.

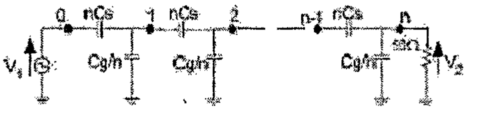

Figure 5.8: n-stage capacitive ladder network at high frequencies

The general solution of this equivalent circuit can be represented by Equation (5.4).

$$u(x, j\omega) = A\cosh(\gamma x) + B\sinh(\gamma x) \quad i(x, j\omega) = \frac{1}{Z}\left[A\sinh(\gamma x) + B\cosh(\gamma x)\right] \tag{5.4}$$

where

$$\gamma^2 = \frac{C_g}{n^2 C_s} \quad and \quad Z = \frac{1}{j\omega}\sqrt{\frac{1}{C_g C_s}}$$

To be accurate in higher frequencies, a transformer winding would need to be represented in more detail. A distributed parameter model using Multiple Transmission line theory is then needed. This modeling techniques treats each turn of the winding as one transmission line. The parameters of the winding are calculated as distributed capacitance per unit length and the high frequency signal travels through the winding as transverse electromagnetic waves.

This method of detailed winding modeling ensures sufficient accuracy for the higher frequency range, where effects such as the arrangement of tapping lead connections are regarded as significant. However, representing all of the phase windings down to the details of individual turns will result in a massive matrix size. This modeling technique is only suitable to model a part of winding or the lead connections, whilst the rest of the transformer is modeled simply as a ladder network.

The theoretical studies suggest that in general, the proportion of the series capacitance, C_s and the ground capacitance, C_g is significant in determining the SFRA response for a specific winding structure like shown in Figure 5.9 is the example of one winding where C_s is higher than C_g. It does not only determine which winding type has higher magnitude but also determine the shapes and the position of the resonances and anti-resonances and whether these appear at lower frequencies or higher.

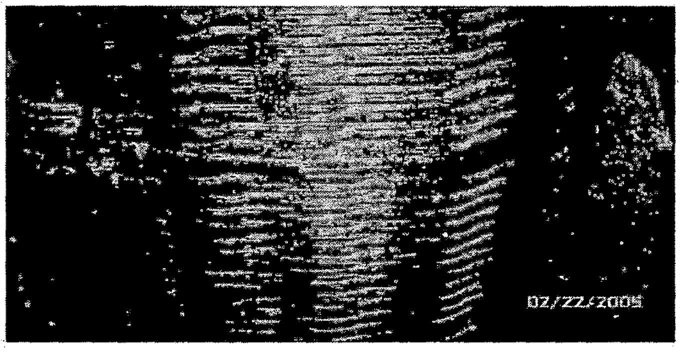

Figure 5.9: Photograph of high Cs winding

5.3 Method of Interpretation

Trace comparison is the primary method for the analysis of SFRA results. Comparisons can be made against the baselines or previous data, sister unit results, and phases[34]. Assuming the method used is repeatable, the initial expectation is that any data comparison should result in near prefect overlays. The comparison criteria for the analysis are as follows:

1. General observation for overall winding transformer measurements and defining various properties for high-voltage windings, low-voltage windings, inter-windings, series windings, and common windings.

2. Comparisons of previous test results, sister units, and phases.

3. Winding configuration such as Delta and Wye connection.

4. Influence of testing error like bad surface contact and poor measurement ground.

The collected database indicates that various levels of expected comparisons exist [[43],[46]] and are categorized in the following section.

5.3.1 Phase to Phase Comparison

Many times for old transformers when reference signature is not available the first step is to compare the signatures of phases of the transformer. It means comparing the signatures of phase U with phase V and phase W.It is assumed that for majority of cases there

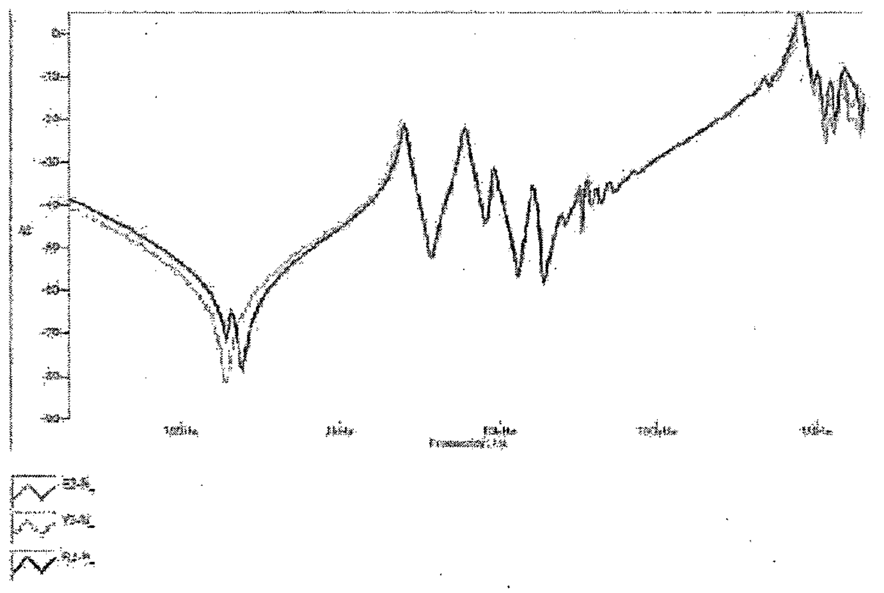

Figure 5.10: Three Phase SFRA comparison for open circuit plot of normal transformer

would be good matching between phase U and phase W as they are symmetrical being on extreme limbs.

Where as phase V (Center phase) would not be matching with the other two phases particularly in the region $10Hz$ to $2kHz$ as the magnetic path for the center phase is different. In phase to phase comparison, the signatures obtained after short circuiting other winding of the transformer on the same limb, compares well as the effect of core is eliminated. Typical examples are given in Figure 5.10 and Figure 5.11 below.

Open circuit responses measured after fault for the HV windings at highest tap are shown in Figure 5.10. The dominant features of these plots are the first minima at low frequency near $200Hz$. The position of minimum will vary somewhat depending on the remnant magnetism of relevant core flux circuits. As there is no deviation in SFRA plot after the fault among the three phases in Figure 5.10, it gives indication of no sign of any winding movement.

Winding having higher impedance will attenuate the signal more at beginning of the plot. This is evident from the in general observation of the plot where starting dB level of LV winding at $10Hz$ frequency is (around $-40dB$) always lower than the dB level of HV winding at 10 Hz. (around $-60dB$).

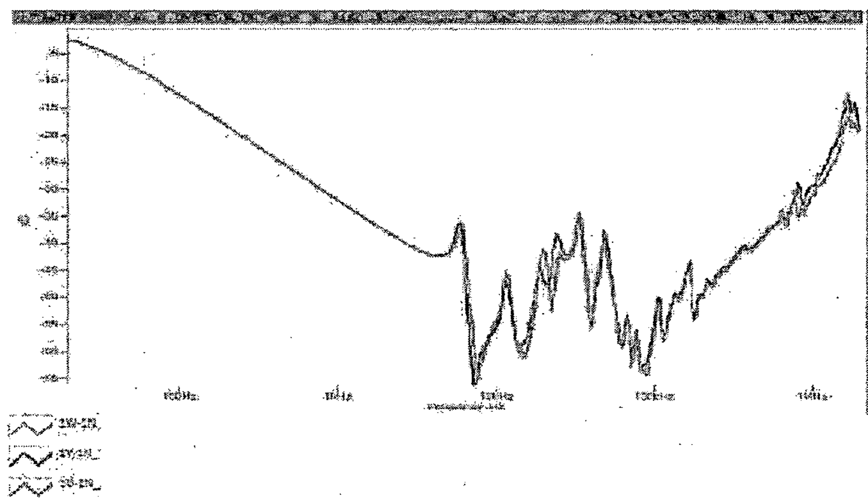

Figure 5.11: Three Phase SFRA comparison of Short circuit plot for normal transformer

Short circuit SFRA responses measured for the HV windings at highest tap is shown in Figure 5.11. The dominant features of these plots are that it starts from very low dB due to shorting of the LV $(2U - 2V - 2W)$. 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 fault etc.

Short circuit virtually eliminates the effect of magnetic core due to opposite flux of short circuit current and lowest impedance path of the shorted winding compared to core as explained in Figure 5.12 and Figure 5.13. The response in band $10Hz$ to $2kHz$ matches well for all 3 windings U, V, W which is clear in Figure 5.11.

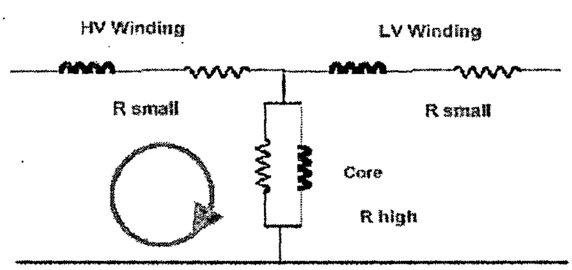

Figure 5.12: Simple Model of a Transformer

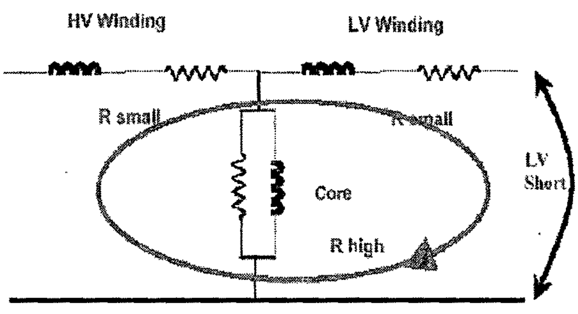

Figure 5.13: Short Circuit Transformer Model

Comparison of Open and Short circuit responses measured for the same winding at any specific tap position reveals that low frequency open circuit inductance of winding involve the core which is clear from the first minima at open circuit plot. This first minima is absent in short circuit plot due to shorting of LV winding and after 10 kHz. the both the response are identical as indicated in Figure 5.14. At higher frequencies a more complicated form of response is seen which is unique to the detailed arrangement of winding involved. This represents the fingerprint or signature of winding design involved. At these frequencies, winding inductance is dominated by leakage fluxes local to the winding conductors, and remnant magnetism of the core has no influence.

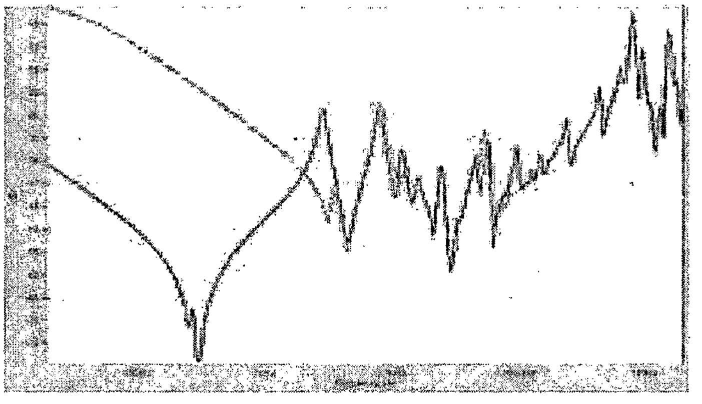

Figure 5.14: Open circuit and Short circuit SFRA plot comparison of same winding for normal transformer

However it is not necessary that the good matching that is shown in Figure 5.10 and

Figure 5.11 would be found always. Phase comparisons are the most difficult and are open to subjective analysis. It overlays with reasonable similarity and can deviate in high frequency region.

The center phase, especially in core type transformers, exhibits the most deviation when comparing all three phases. Different flux paths seen by each phase contribute to the observed differences.The affects of the core saturation and magnetic state of the core are expected at the lower frequencies.

The actual windings of a three phase transformer are almost identical, but the connection scheme between phases is very different. As an example, the phases of a wye winding are all at different distances from the neutral and also LTC connections fall into the same category. Thus, since the windings are not equilaterally spaced, the varying lead length entering and leaving the windings, influence the individual transfer function of each winding. This would generally be found in two winding three phase transformers.

5.3.2 Sister Unit Comparision

5.3.2.1 Comparison of SFRA plot of two sister unit

Two nos. of single phase Auto transformer were tested in Live 400 kV Substation and they were sister units having following specification.

400 kV/220 kV/33 kV, 167 MVA Auto Transformer
Winding configuration - HV/IV/Tertiary
Year of manufacturing - 1997
Serial No.: T1 and T2

Transformer of Sr. No. T1 is showing slight increase of C2H4 and SFRA was taken on this unit for further investigation. SFRA plot of HV, IV and Tertiary windings were taken for both the sister unit by different Model of SFRA unit and one in 2004 (Sr. No. T2) and other in 2006 (Sr. No. T1). The two units are having identical SFRA plot as shown in Figure 5.15 and Figure 5.16 which indicate the repeatability of the SFRA plot for healthy sister unit.

In absence of base data , the main basis of analysis for the suspected unit T1 is the comparison with the sister unit plot of T2. Analysis of the plot is done by comparing with Open circuit, Short circuit plots at Tap positions. The results are very similar for the two

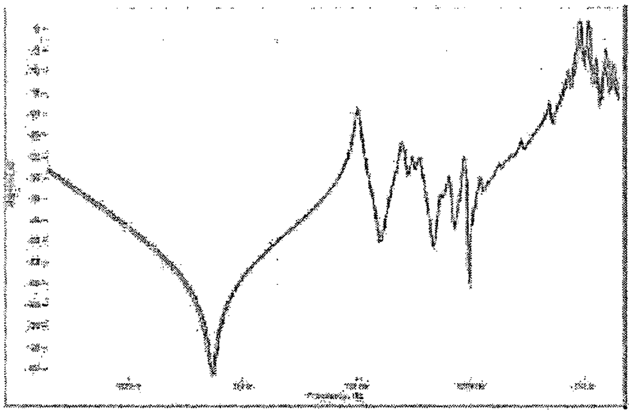

Figure 5.15: Open circuit SFRA plot of Common winding (2U-N) for two sister unit (Sr. No. T1 and T2)

sister units and do not indicate significant variation between them. Here the design and manufacturing quality of the transformer is verified and also the test operator has good knowledge and has made good measurements on these units. The SFRA data on each unit provides a good baseline for future reference.

Effective comparison of SFRA plot between sister transformers thus becomes important for good and more conclusive diagnosis.In absence of reference signatures, for multi-winding transformers or complex transformer circuits phase to phase comparison becomes very difficult rather it is not possible.In such situation and in absence of reference signatures, signatures of sister transformers help.

This comparison works with assumptions that there will not be significant manufacturing variations with regard to materials or skills or due to tolerances provided in manufacturing. Also, there would be no movement within winding due to shocks or vibrations during transit while transporting the transformer. These assumptions will always be questioning the diagnosis, whenever certain deviations found in comparison of signatures of sister transformers.

5.3.2.2 Comparison of SFRA plot of multiple sister unit

The SFRA plot of 3-phase power transformer of various rating installed in Indian network has been compared and there are similarities found in the pattern of plot for the transformer of same rating and various make as shown in Figure 5.17 and Figure 5.18.

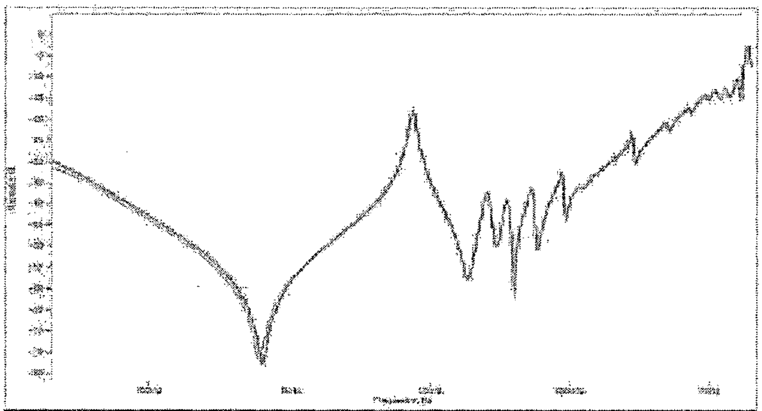

Figure 5.16: Open circuit SFRA plot of Series winding (1U-2U) for two sister unit (Sr. No. T1 and T2)

It is expected to happen, as the various parameters which effect the SFRA response in different frequency range are identical in this case and explained in detail below.

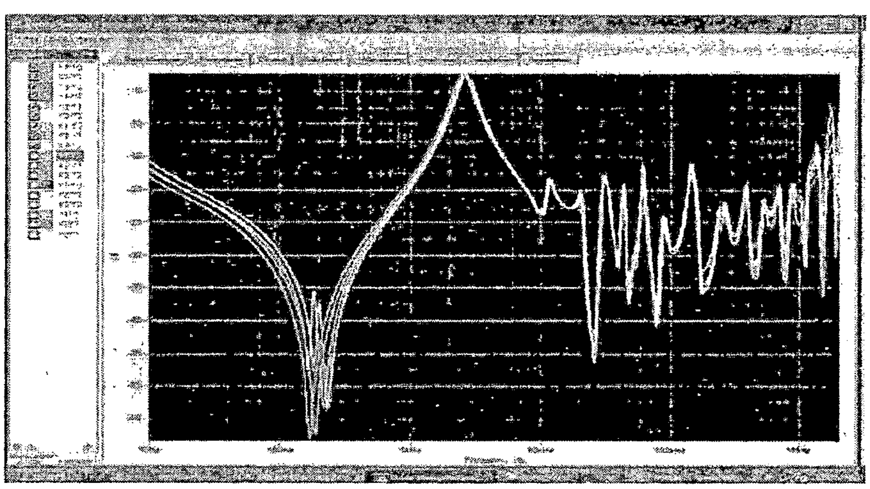

Figure 5.17: Open circuit plot of tertiary winding , 3- phases, for three transformer

Case 1- 315 MVA, 400/220/33kV, 3-phase : Three nos. of transformer of identical design parameter and different make

Due to similarity in the design parameters and same achieved during manufacturing process it is possible to achieve this type of correlation in SFRA plots of Transformers of various makes.Manufacturing tolerances can be the factor to deviate the overall responses

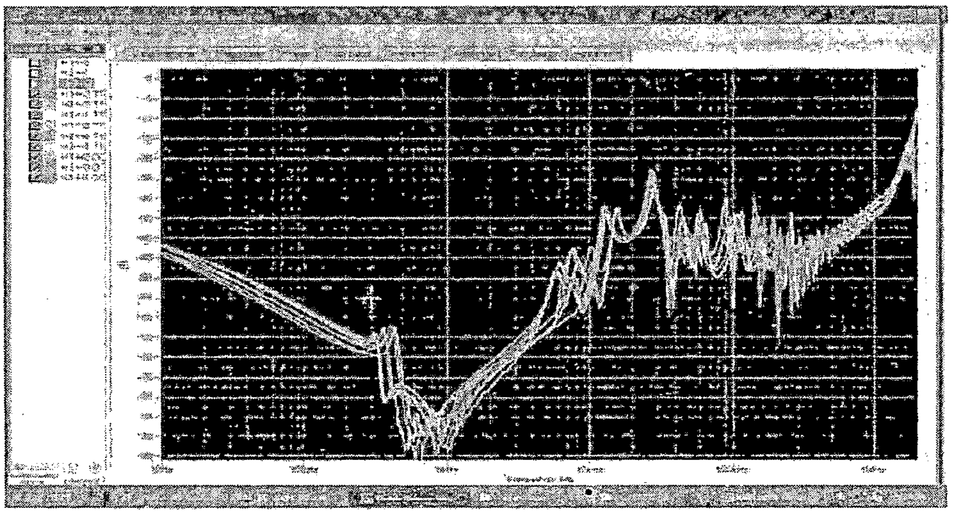

Figure 5.18: Open circuit plot of HV winding , 3- phases, for the three transformer

measured on two different transformers of the same design parameters but do not modify the overall shape.

Figure 5.17 and Figure 5.18 proves that there is a good matching of signatures for all transformers beyond $10kHz$. However it is not a good match in frequency range of $10Hz$ to $10kHz$. Variation in this range is observed , mainly due to variation in inductance (magnetizing inductance) of the windings . It would be due to variations in core assemblies of transformers caused by skill difference in core assembly, manufacturing tolerances and variation in permeability of materials.

5.3.2.3 Auto- Correlation Method for Data Comparison

Comparison of responses with sister transformers is though a better method than phase to phase comparison as it is not as straight forward as comparison of response with initial reference signature.

If transformers are same by design and by manufacture, ideally frequency response data should match one to one and correlation coefficient **"CC"** should be = 1. But in practice it is not so and the data varies.

It is required to compute the relative factor Rxy of the two sister unit plots , in the different frequency ranges (1kHz-100kHz, 100kHz-600kHz and 600kHz-2MHz) according equations in **A1, A2, A3** and **A4.**

Table 5.1: Relation between relative factors and degree of transformer winding deformation (only for reference)

Winding Deformation degree	Relative factor R
Severe deformation	$R_{LF} < 0.6$
Obvious deformation	$1 > R_{LF} > 0.6, R_{MF} < 0.6$
Slight deformation	$2 > R_{LF} > 1$ or$1 > R_{MF} > 0.6$
Normal winding	$R_{LF} > 2, R_{MF} > 1$ and $R_{HF} > 0.6$

A1 Calculate the standard variance of the two SFRA data sequences:

$$D_x = \frac{1}{N}\sum_{k=0}^{N-1}\left[X(K) - \frac{1}{N}\sum_{k=0}^{N-1}X(K)\right]^2$$
$$D_y = \frac{1}{N}\sum_{k=0}^{N-1}\left[Y(K) - \frac{1}{N}\sum_{k=0}^{N-1}Y(K)\right]^2$$

A2 Calculate the covariance of these two sequences

$$C_{xy} = \frac{1}{N}\sum_{k=0}^{N-1}\left[X(K) - \frac{1}{N}\sum_{k=0}^{N-1}X(K)\right]^2 \times \left[Y(K) - \frac{1}{N}\sum_{k=0}^{N-1}Y(K)\right]^2$$

A3 Calculate the normalization covariance factor of these two sequences.

$$LR_{xy} = C_{xy}\sqrt{D_x D_y}$$

A4 Calculate the relative factor Rxy as per the following formula:

$$R_{xy} = \begin{cases} 10 & 1 - LR_{xy} < 10^{-10} \\ -1g(1 - LR_{xy}) & others \end{cases}$$

A5 Judge the degree of deformation of transformer winding as mentioned in Table 5.1.

5.4 Conclusion

A frequency response plot provides a fingerprint for a transformer. Fingerprints from similar transformers have common features due to common winding parameters. Subsequent tests on a unit provide responses that may differ from the original due to both test set up and internal state of the transformer itself and this internal and external factor effecting SFRA plot will be discussed in the next chapter.