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"Evaluation of Transfer Function of Power Transformer Using SFRA Technique"

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Abstract

Transformer is one of the most basic units in modern power system. The use of ferrite core gives an improvement in this direction since it has very high permeability because of which it can withstand higher voltages at reduced physical sizes. Attention has also been given to the fact that at which frequency the transformer works best, i.e. amplifies the input the most. This can be useful while using ferrite core in testing transformers. The transformer windings compose an electrical network in the space. This network must necessarily have a transfer function. By evaluating this transfer function, we can have a good understanding of the transformer windings and equivalent network which have several meshes depending upon order of transfer function. .When a fault occurs, the windings get displaced and in-turn the distribution of impedance parameters gets disturbed. Transfer function through analyzed by Sweep Frequency Response Analysis (SFRA) of power transformer characteristics.

Keywords: *Sweep Frequency Response Analysis (SFRA), Swept Frequency Method, Transformers, Voltage*

INTRODUCTION

Sweep Frequency Response Analysis (SFRA) is a tool that can give an indication of core or winding movement in transformers. This is a plot performed by measurement of voltage and compared by standard measurement and plot which is looking at how well a transformer winding transmits a low voltage signal that varies in frequency. Just how well a transformer does this is related to its impedance, the capacitive and inductive elements of which are intimately related to the physical construction of the transformer. Changes in frequency response as measured by SFRA techniques may indicate a physical change inside the transformer, the cause of which then needs to be identified and investigated by using MATLAB Software.

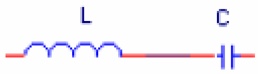
SFRA TECHNIQUE: The Frequency Response measurements were first investigated in depth by Dick and Erven at Ontario Hydro in Canada in the 1970's. The most useful SFRA measurement is the response of individual winding sections of the transformer at different frequencies. This allows problems to be associated with individual winding sections, rather than on a phase or winding generally. The SFRA does this in a simple way by injecting a signal of known frequency into one end of the winding and measuring the response at the other. By sweeping through the frequency range of interest, from just above DC to several MHz, it is possible to make accurate, repeatable and reliable measurements. SFRA measurements are independent of the lead arrangement and of the measuring device up through the frequencies of interest.

To make an SFRA measurement, a transformer must be prepared as it would for power factor and capacitance measurements. Each winding section, HV and LV, is analyzed separately. Transfer function measurements, from HV to LV, may also be made, but these are less effective at detecting movement. Short circuit SFRA measurements, made for example by performing an SFRA on a HV winding with the LV winding shorted, provides further information about winding integrity and relates to transformer Leakage Reactance.The SFRA provides a wealth of information in the form of a frequency response plot, which needs to be interpreted.

Deferent combination of transfer functions in power transformer.

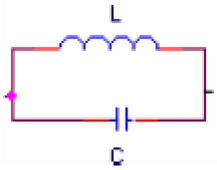
Realization of LC Network

1. Series Combination



$$Z_1(s) = Ls + \frac{1}{Cs} = \frac{LCs^2 + 1}{Cs}$$

2. Parallel Combination



$$Z_1(s) = \frac{1}{\frac{1}{Ls} + Cs} = \frac{Ls}{LCs^2 + 1}$$

The same forms are obtained on a susceptance basis, and it is noted that these functions possess only imaginary poles and zeros at s=0 and $s = \pm j\sqrt{1/LC}$. It would appear that all driving point reactance and susceptance functions have poles and zeros restricted to the imaginary axis. From these considerations, two conclusions can be reached concerning the driving point functions of pure reactance networks. These conclusions can be stated as follows:

1. Poles and zeros of $Z_1(s)$ must be simple or first order, and they must occur on the jω- axis in conjugate pairs.

2. The jω-axis poles and zeros must mutually separate each other.

3. The residues of each of the poles must be positive real values.

Realization of RC Network

1. Series Combination

For a network restricted to resistance and capacitance elements, the magnetically stored energy represented by T_0 is zero; therefore,

$$Z_1(s) = \frac{E_1(s)}{I_1(s)} = \frac{1}{|I_1(s)|^2}\left(\frac{F_0(s) + V_0}{s}\right)$$

The driving point admittance will be

$$Y_1(s) = \frac{I_1(s)}{E_1(s)} = |I_1(s)|^2\left(\frac{s}{F_0(s) + V_0}\right)$$

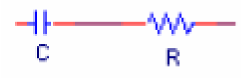
Poles and zeros of Z1(s) or Y1(s) in 3.23 and 3.24 occur at s=0 and $s = -V_0/F_0$.

Therefore, because F_0 and V_0 must be positive functions of s, the poles or zeros at $s = -V_0/F_0$ must be real and negative.

Consequently, the poles and zeros of a driving point impedance or admittance of an RC network must lie on the negative real axis or at the origin of the s-plane. It will also be seen that these poles and zeros must mutually separate each other similar to those of reactance functions. Finally, at real frequencies, the driving point functions of RC network will have both real and imaginary components. In other words Z_1 (jω) will be a combination of resistance and reactance, and Y_1 (jω) will be a combination of conductance and susceptance.

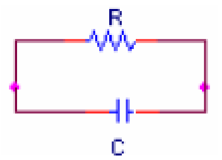
The poles and zeros of an RC driving point functions must lie at the origin or on the negative real axis. It can be illustrated by considering the impedance of a series and parallel combination of resistance R and capacitance C.

(a) Series Combination



$$Z_1(s) = R + \frac{1}{Cs} = \frac{RCs+1}{Cs} \quad ....1.10$$

4. Parallel Combination



$$Z_1(s) = \frac{1}{\frac{1}{R}+Cs} = \frac{R}{RCs+1}$$

In series combination, there is a pole at s=0 and a zero at s=-1/RC; whereas, the parallel combination has a pole at s=-1/RC. Similar results are obtained on an admittance basis. A network composed of a series or parallel RC combinations will have a driving point function with poles and zeros restricted to the origin and the negative real axis.

Realization of RL Network:

Consider the function

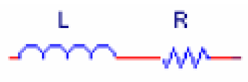
$$Z_1(s) = K\frac{s^n + a_{n-1}s^{n1} + ...}{s^m + b_{m-1}s^{m-1}.................}$$

If the driving-point impedance of an RL network is written as $Z_1(s)$ = P(s) / Q(s), the highest-order terms of P(s) and Q(s) may be of equal degree or P(s) can be of higher degree than Q(s) by unity. This fact can be stated as n=m or n=m+1. Likewise, the lowest-order terms of P(s) and Q(s) may of equal degree or P(s) can be of higher degree than Q(s) by unity.

The possibility of Q(s) being higher-order than P(s) is forbidden, since division of P(s) by Q(s) would yield a term of the form K/s which could be identified as the impedance of a capacitor. The polynomials P(s) and Q(s) can be factored into terms of the form (s + σn), where the σn terms are positive real numbers.

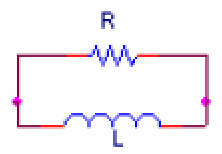
An RL driving-point impedance or admittance function may assume four different forms depending on the behavior of the function at s = σ = 0 and s = σ =∞. The series and parallel combination of resistance R and inductance L are as follows:

(a) Series Combination:



$$Z_1(s) = Ls + R$$

(b) Parallel Combination:



$$Z_1(s) = \frac{RLs}{R + Ls} = \frac{Rs}{s + \frac{R}{L}}$$

APPLICATION OF THE TRANSFER FUNCTION FOR DIAGNOSTIC PURPOSES TO DETECT WINDING DISPLACEMENT

Electrical Faults

A short-circuitwas simulatedbyconnectingtwoadjacentturnsint hetapwinding.Theresults of FRAmeasurementusingtheimpulseresponse method.

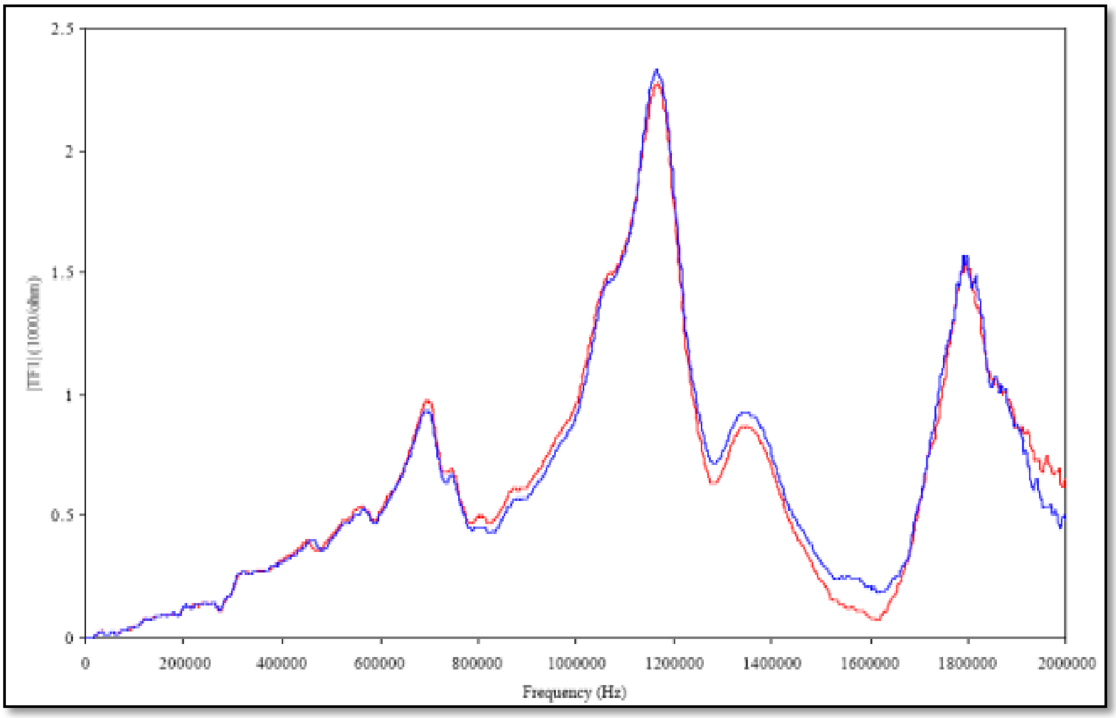


Fig. 1 FRA Results (Impulse Response Method) with Simulated Short-Circuit Fault

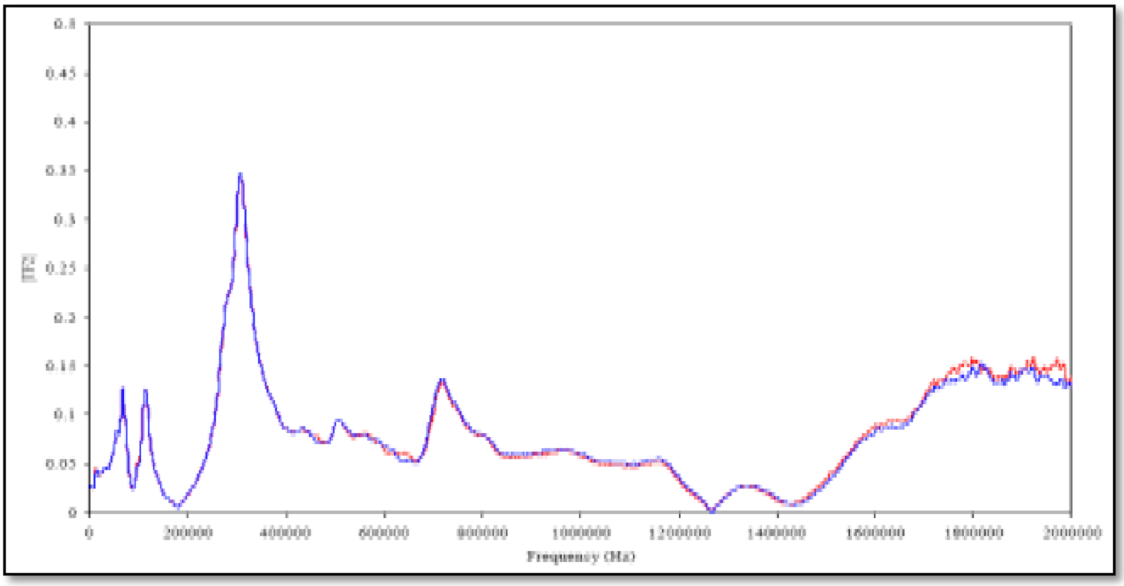


Fig.2 FRA Results (Impulse Response Method) with Simulated Short-Circuit Fault

The results of FRA measurements using the swept frequency method are shown in figure 2 There are significant differences between the FRA results with and without the short-circuit from about 100Hz to about 20 kHz. The resonant frequencies are shifted and there is a large reduction in the modulus of the impedance.

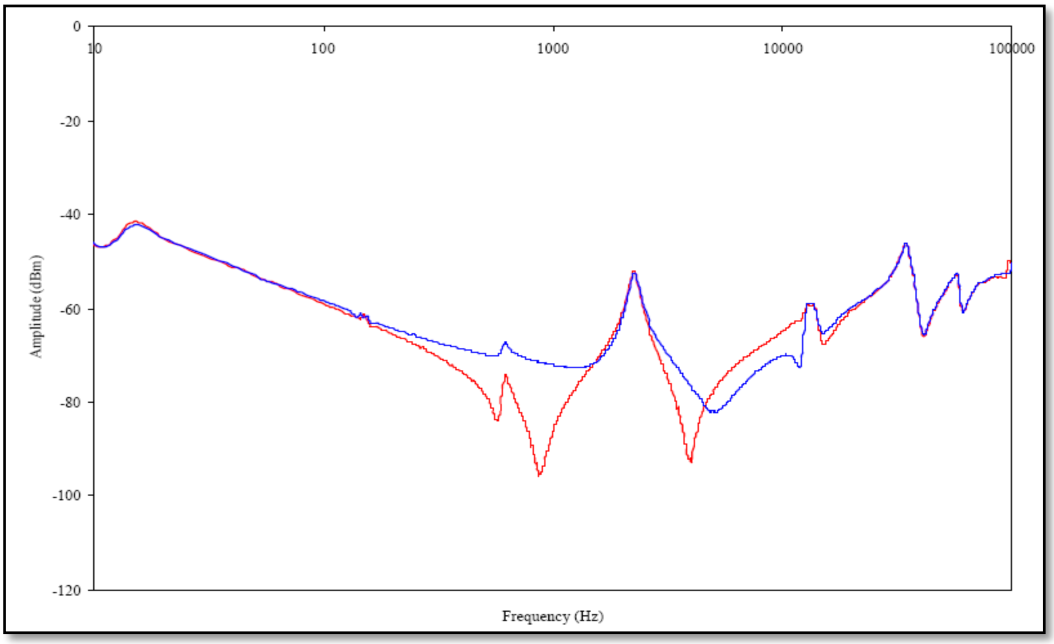


Fig.3 FRA Results (Swept Frequency Method) with Simulated Short-Circuit Fault

Mechanical Fault

Detecting mechanical damage to transformer windings is one of the main interests of FRA. Mechanical deformation was simulated by adding additional inter-turn separators to the HV tap winding, which was the only accessible winding.

Several different thicknesses of additional inter-turn separators were used. The results of the FRA measurements made using the impulse response method.

Some changes to TF2 seem to be apparent around 1MHz. It is believed that these changes are caused by natural variation rather than by the simulated mechanical fault. Some changes remained even when the winding was returned to its original position.

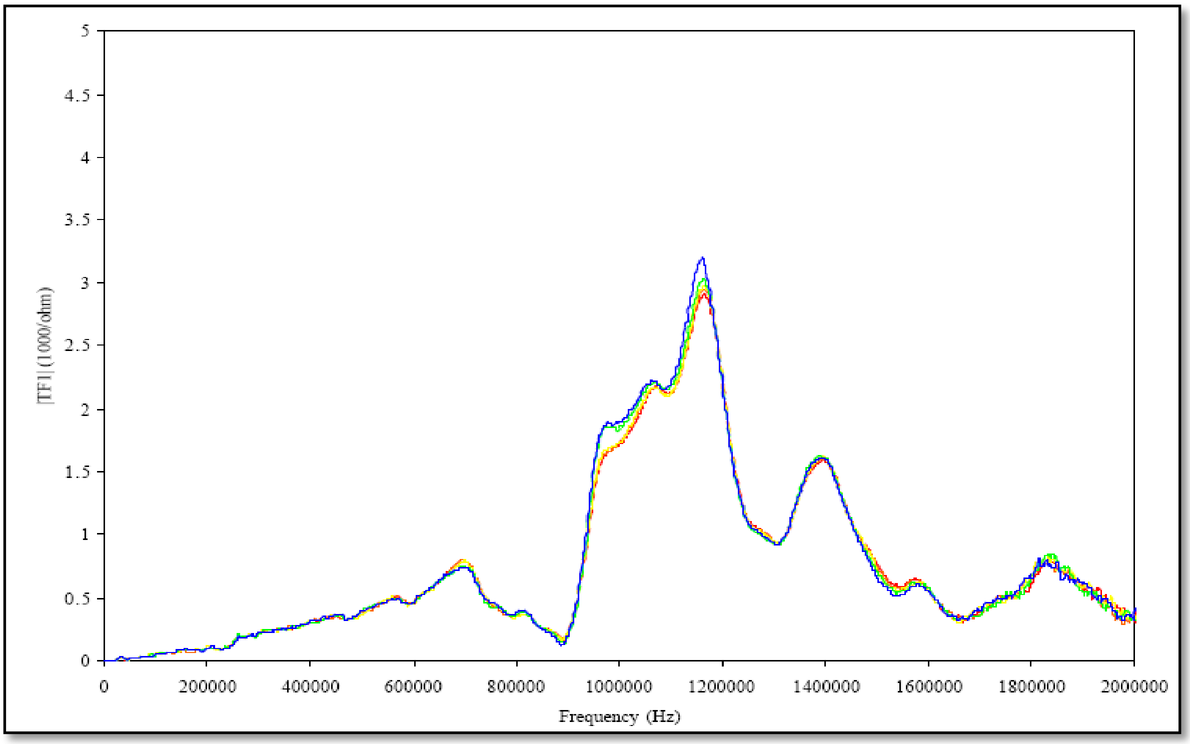


Fig.4FRAResults (ImpulseResponseMethod)withSimulatedWindingDisplacement.

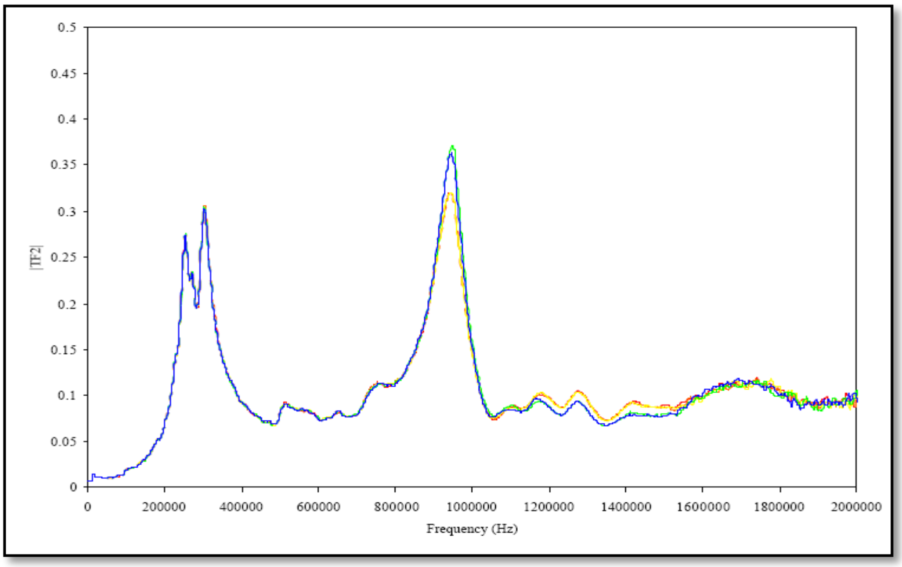


Fig.5 FRAResults (ImpulseResponseMethod)withSimulatedWindingDisplacement

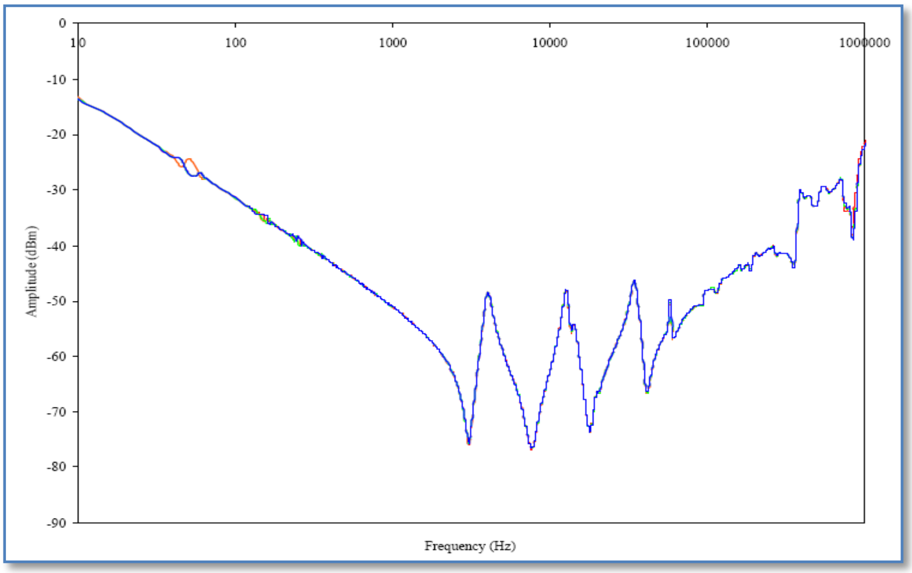


Fig.6 FRAResults (SweptFrequencyMethod)withSimulatedWindingDisplacement.

The results of the FRA measurements made using the swept frequency method .

CONDITION FOR SFRA

- On all new transformers for fingerprinting purposes.
- As part of routine electrical tests.
- After relocation.
- After long duration short circuits.
- After repairs to tap-changer.
- After any vacuum treatment, purification and regeneration.
- After any type of fault.
- After any type of maintenance.

Table no. 1 location and nature of fault

Region	FrequencySub-Bands	Component	Failure Sensitivity
1	<.2kHz.	Maincore,Bulk winding Inductances	Coredeformation, opencircuits,shortedturns and residual magnetism
2	2kHzto20kHz	Bulkcomponents,Shunt impedances	Bulkwindingmovement betweenwindings andclamping structure
3	20kHzto400kHz	Mainwindings	Deformationwithinthemaintapwindings
4	400kHzto1 MHz	Mainwindings tap windings andinternal leads	Movementofthemainandtap windings,groundimpedances variations

TEST SETUP

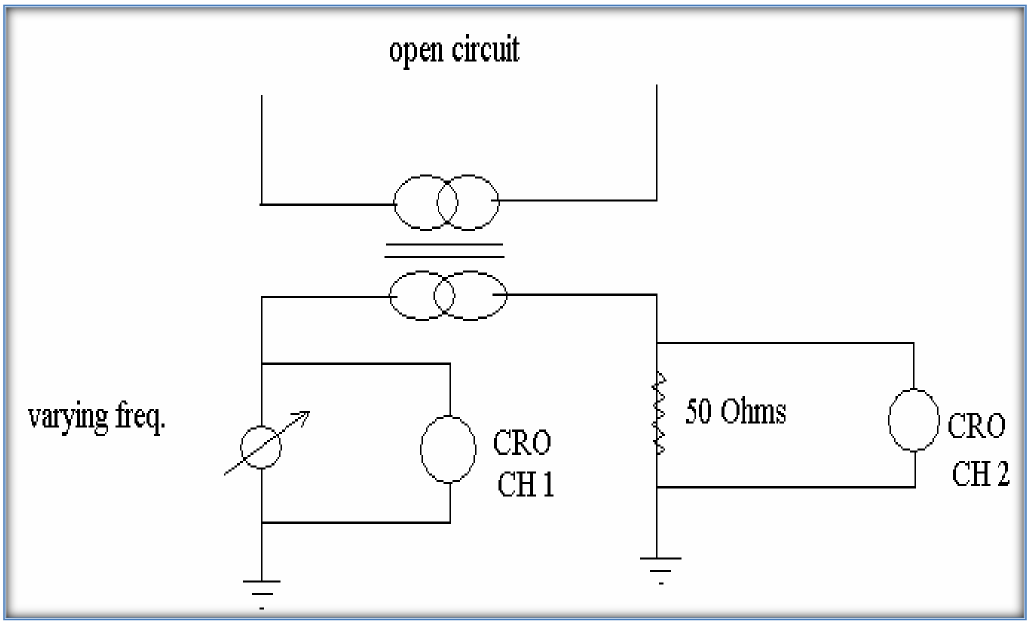


Fig.7 circuit diagram

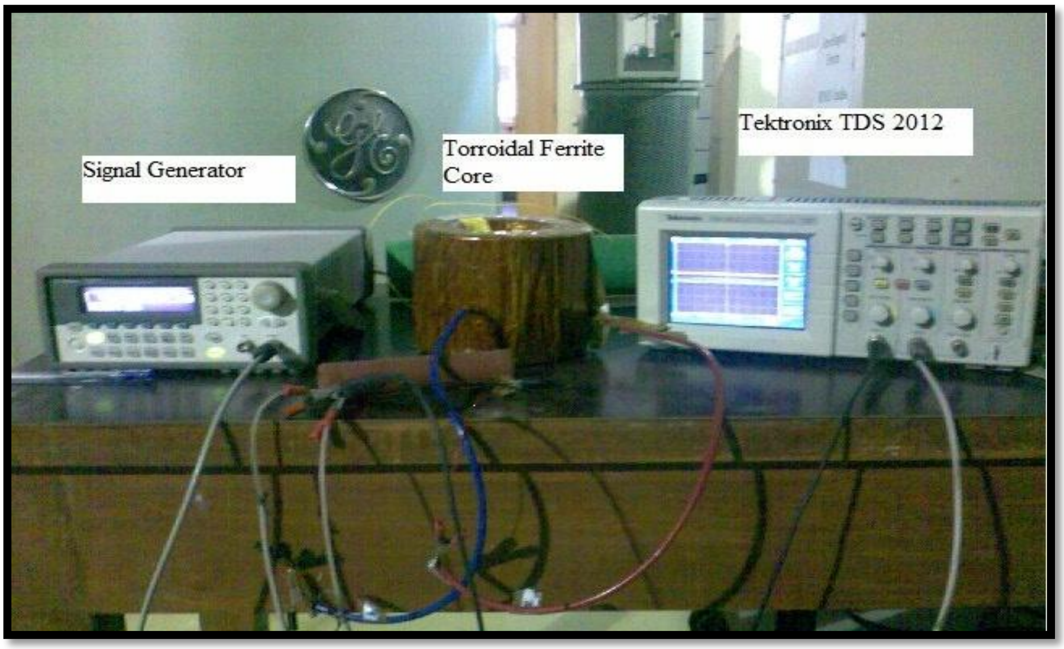


Fig 8 Test Setup

Table no. 2 component and specification

Sr.No.	Component	Specification
1	SignalGenerator	Agilent, 33250 A, 80 MHz,
2	CRO	Tektronix,TDS2012,Two Channel,Digital
3	Resistance'R'	50Ohm,100W,50E,±5%.
4	FerriteCore Transformer	Toroidal core, Primary- 4 turns, Secondary-24 turns turns ratio 24/4

Test setup consists of a Ferrite Core Transformer, which can be called the system, the analysis of which has to be done, a Signal Generator for applying sinusoidal input, A CRO for measuring the input & output voltages, i.e., the dB gain & the phase difference in degrees.

$$dB = 20\log_{10}(V_2 / V_1)$$

$$Deg = \frac{360 \times TimeDifference}{TotalTimeofOneCycle}$$

Table no. 3 Readings

Sr. No.	ω =Frequency (in radian/second)* 10000	Gain (in dB)	Phase (Degree)
1	4.0	35.000	24.000
2	4.2	35.072	24.000
3	4.4	35.052	24.200
4	4.6	35.091	31.524
5	4.8	35.095	31.753
6	5.0	35.102	31.902
7	5.2	35.152	31.971
8	5.4	35.091	31.990
9	5.6	35.189	31.999
10	5.8	35.102	32.021
11	6.0	35.202	32.420
12	6.2	35.172	34.860
13	6.4	35.195	34.860
14	6.6	35.200	34.860
15	6.8	35.250	34.890
16	7.0	35.125	34.900
17	7.2	35.152	30.124
18	7.4	35.172	30.325
19	7.6	35.107	31.823
20	7.8	35.211	31.823
21	8.0	35.295	31.824
22	8.2	35.199	31.824
23	8.4	35.386	31.824
24	8.6	35.362	31.824
25	8.8	35.252	32.002
26	9.0	35.250	32.001
27	9.2	35.356	30.000
28	9.4	35.325	24.000
29	9.6	35.402	24.006
30	9.8	35.382	22.003
31	10.0	35.256	18.009

MATLAB PLOTS FOR EVALUATION OF TRANSFER FUNCTIONS

The command used to plot the frequency response data is plot (mag, freq) & plot (phase, freq), where 'mag' consists of a vector containing the dB gain, 'phase' is a vector containing the phase differences & 'freq' consists of a vector containing the frequencies. These commands give us graphs with 'x-axis' as frequency & 'y-axis' as magnitude & phase respectively. But the 'x-axis' is still linear & not logarithmic as is desired in the Bode Plot method. So, the property of the 'x- axis' needs to be changed. Hence, we change the 'x-axis' property from linear scale to logarithmic scale.

This gives us the desired Bode Plot of the system. Now, we will use this Bode Plot to calculate the Transfer Function of our system. An alternate method to obtain the Bode Plot is to use the command 'semilogx(ω, mag) & 'semilogx(ω, phase)'. This directly gives us the Bode Plot in one step.

$$H(s)=\frac{B(s)}{A(s)}=\frac{b(1)s^{n}+b(2)s^{n-1}+\dots\dots\dots\dots+b(n+1)}{a(1)s^{m}+a(2)s^{m-1}+\dots\dots\dots\dots+a(m+1)}$$

BODE PLOTS

The following plots are evaluated by MATLAB Programming

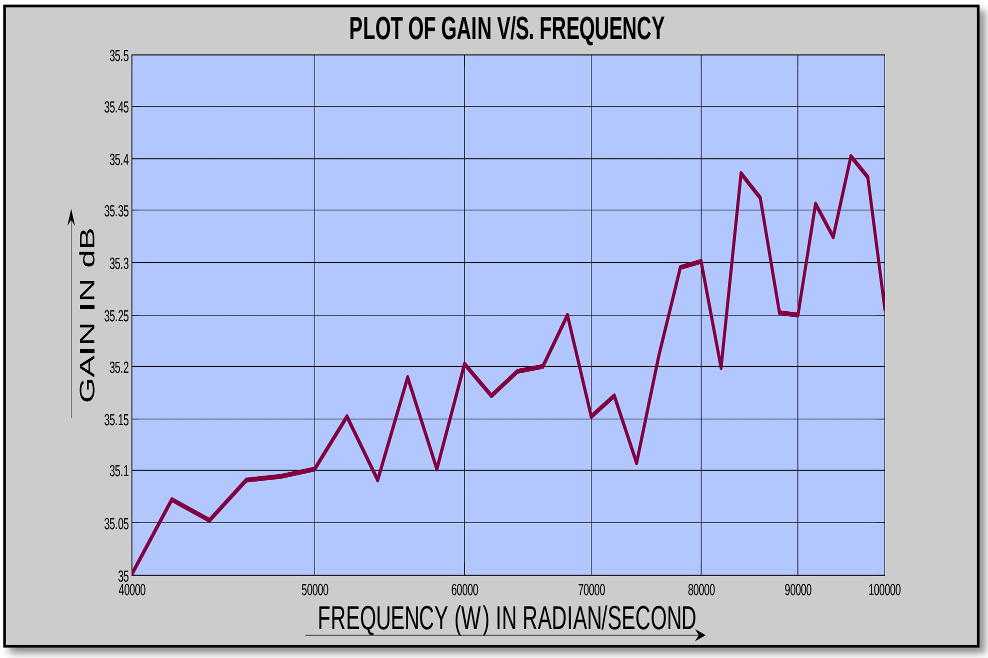


Fig. 9 Bode plot of Gain v/s. frequency

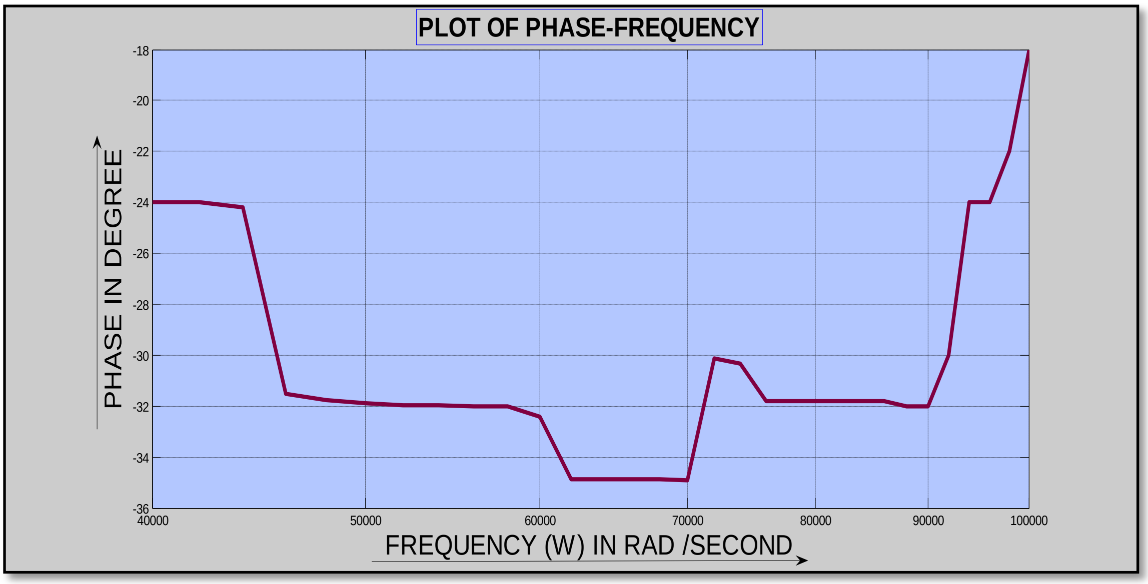


Fig. 10 Bode plot of phase v/s. frequency

VALUES OF [a] & [b] THROUGH MATLAB PROGRAMMING

When MATLAB program is applying with putting the different values of (n,m) , the result has come-out in the form of different values of polynomials of 'b' and 'a' with their coefficient term are obtained .all are listed below in following table These all values will used to obtain values of transfer functions.

Table No. 4 Final Values.

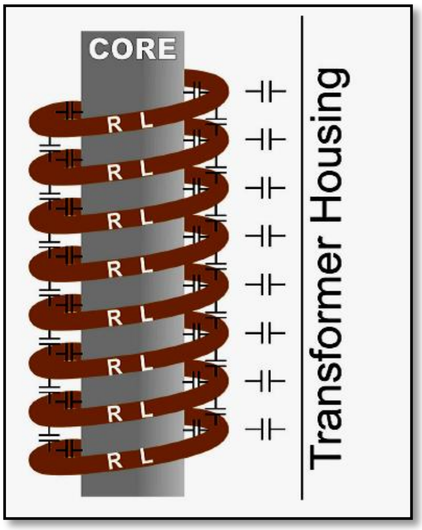
Sr. No.	(n,m)	[b]	[a]
1	**(1,1)**	1.0e+0005 **0.001 2.0539**	**1.0000 111.2937**
2	**(1,2)**	1.0e+009 **0.002 3.7190**	1.0e+009 **0.0000 0.0000 5.2405**
3	**(1,3)**	1.0e+014 **-0.001 -7.8597**	1.0e+013 **0.000 -0.000 0.0006 -0.0436**
4	**(1,4)**	1.0e+019 **-0.001 1.9744**	1.0e+019 **0.0000 -0.0000 0.000 0.0000 -**

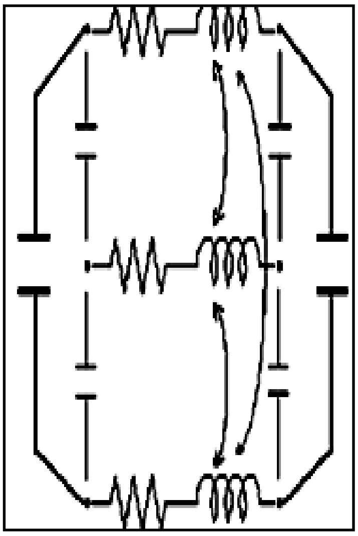
			1.0436
5	**(2,1)**	1.0e+005 **-0.000 0.0001 -5.5089**	**1.0000 -298.5092**
6	**(2,2)**	1.0e+010 **-0.000 0.0001 -5.5089**	1.0e+009 **0.0000 - 0.0000 5.2856**
7	**(2,3)**	1.0e+015 **0.000 0.0000 3.2956**	1.0e+013 **0.0000 0.0000 6.0006 4.3842**
8	**(2,4)**	1.0e+020 **0.000 -0.0000 1.7347**	1.0e+019 **0.000 0.000 0.000 0.000 2.6911**

The final equation of transfer function of the system accordance the change of value of (n,m) are describe in table.(mentioned in last page).

RESULT ANALYSIS FROM T.F.

The RLC circuit is developed in transformer core and windings, when induction process.





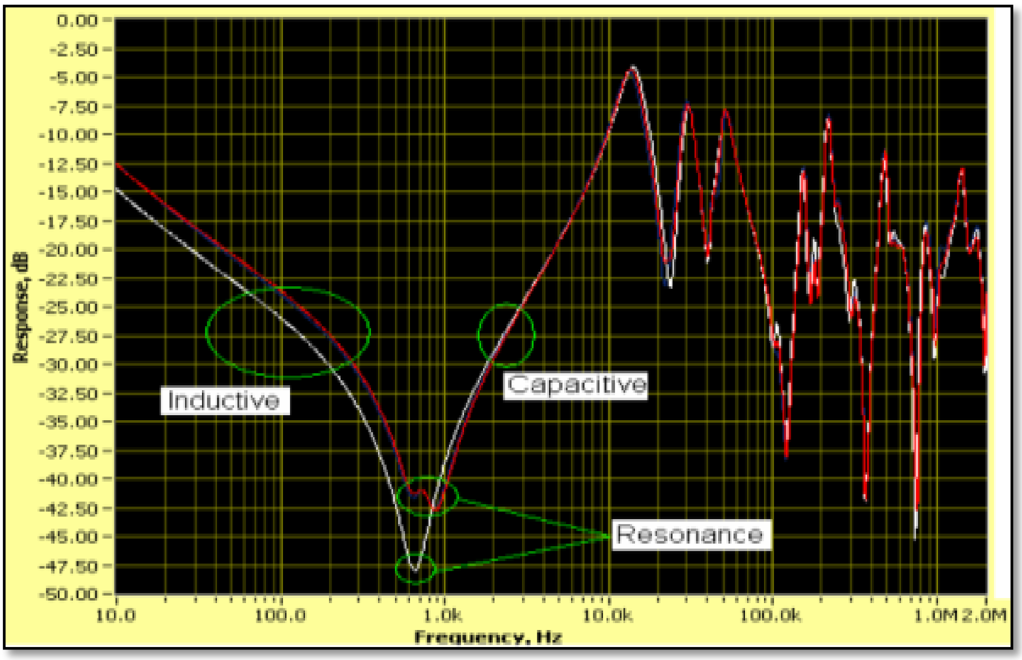


Fig. no. 11 RLC component in transformer

RESULT

- In between the range of 50000 to 60000 radian/second 'fg' ,' hi', ' jk' are the upward slope so that capacitive component dominating. and 'gh' ,'ij' is down slope so that inductive component is dominating. and resonance is obtained at point 'h' and 'j'.
- In between the range of 60000 to 70000 radian per second 'kl', 'no' is inductive components dominating. 'lm', 'mn' are capacitive. Resonance obtained at at point 'l' and 'o.
- In between the range of 70000 to 80000 radian /second 'op', 'qr', 'rs' capacitive and 'pq' is inductive.. resonance at point 'q'.
- In between the range of 80000 to 90000 radian /second 'st', 'uv' 'vw' are inductive. 'tu' is capacitive. Resonance at 't' and 'w'.
- In between the range of 90000 to 100000 radian/second 'xy', 'z$' capacitive.' yz' and '@^" are inductive. Resonance at point 'z'.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

SFRA has proved to be a sound diagnostic technique.SFRA is a powerful tool for use in analyzing transformer health and mechanical integrity. The reliability

&repeatability of the response curves obtained, regardless of the varying test conditions such as tap position, short/open circuit windings, weather, electromagnetic interference and contact resistances etc., is too high to dispense this method. The test is easy to perform and operate ,however measurements must be made confidently and conscientiously to ensure reliable and meaningful diagnosis. By focusing on its ability to detect winding movement we under emphasize the fact that measured responses are capable of providing an indication when no winding movement has occurred. This ensures that a transformer is returned to service quickly and avoids a costly internal inspection.

The networks obtained by SFRA give a good insight of the transformer winding orientation. A good interpretation method can give the exact location of fault inside the transformer.

An effort to extend this technique to a level as to see the effect of fault on each turn can prove to be a milestone. An advantage is that reference responses are not required to make an accurate decision as a comparison of response to the different phase of the same transformer and a comparison of response from sister transformer are used successfully to diagnose the mechanical integrity of the transformer.

Final values of all transfer function

Table no. 5 Final Result in terms of Transfer Function.

Sr.No.	(n,m)	T.F.	Final value of T.F.
1	**(1, 1)**	$\frac{10^5(.0001\boldsymbol{S}+2.0539)}{1.0\boldsymbol{S}+111.2937}$	$\frac{10S+(2.0539\times10^5)}{1.0S+111.2937}$
2	**(1, 2)**	$\frac{10^9(0.002\boldsymbol{S}+3.7190)}{10^9(0.000\boldsymbol{S}^2+0.0000\boldsymbol{S}+5.2405)}$	$\frac{0.000381\boldsymbol{S}+0.7096}{1}$

3	**(1, 3)**	$\frac{10^{14}(-0.001S+1.9744)}{10^{13}(0.000S^3+(-0.00)S^2+0.0006S-0.0436)}$	$\frac{0.01S+19.744}{0.0006S-0.0436}$
4	**(1, 4)**	$\frac{10^{19}(-0.001S+1.9744)}{10^{19}(0.0000S^4+-0.0000S^3+0.000S^2+0.000S-1.0436}$	$\frac{0.00095S-1.89}{1}$
5	**(2, 1)**	$\frac{10^5(-0.000S^2+0.0001S-5.5089)}{10^9(0.000S^2-298.5092)}$	$\frac{10S-550890}{1.0000S-298.5092}$
6	**(2, 2)**	$\frac{10^{10}(-0.000S^2+0.0001S+5.5089)}{10^9(0.000S^2-0.000S+5.2856)}$	$\frac{.001S-55.089}{5.2856}$
7	**(2, 3)**	$\frac{10^{15}(0.000S^2-0.000S+3.2956)}{10^{13}(0.0000S^3+0.0000S^2+6.0006S+4.3842)}$	$\frac{329.56}{6.0006S+4.3842}$
8	(2, 4)	$\frac{10^{20}(0.000S^2-0.0000S+1.7347)}{10^{19}(0.000S^4+-0.000S^3+0.000S^2+0.000S+2.6911)}$	6.4460

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