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Transformer Fault Diagnosis Through Transient Voltage Analysis

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ABSTRACT:
Faults in the transformer can be diagnosed through Transient voltage basedFrequency response analysis (FRA).The fault detection was attempted in PSPICE simulation on 3Ø, 50hz, 315 KVA, 11 KV/433V, Dyn11, ONAN transformer modelled as a multi stage RLC ladder networkand hardware experimental works were attempted in 1Ø, 50 hz, 1 KVA, 240V/240V laboratory transformer to validate the efficacy of Frequency response analysis (FRA) in transformer fault diagnosis. The investigations are carried as per IEC 60076 PART-III and IEEE standard on FRA. Different short circuit faults and mechanical faults like axial and radial deformation on transformer winding were experimented and short circuit self impedance(SCSI) transfer function plots were obtained. In hardware, different short circuit faults were made artificially by shorting tappings provided in one of the windings and the results obtained were compared with signature FRA plot of the transformer in healthy condition, to assess the faults, their severity and its location in the transformer. Various results obtained during simulation and experimental investigations revealed that the type of the fault, its severity level and location could be identified through lightning and switching transient voltage frequency response analysis.

1. INTRODUCTION:

FRA is one of the very sensitive diagnostic techniques, which is used for detecting changes in the electrical characteristics of the transformer windings, which arise from different types of electrical and mechanical stresses.[1]

Lightning impulse and switching impulsebased frequency response analysis are techniques based on the fact that every transformer winding has its unique frequency characteristics that will change with respect to changes that happens in the electrical parameters of the winding, mainly its equivalent inductance and capacitance. If the winding is damaged due to any mechanical stress and electrical stress, the position, shape of the winding or characteristics of the winding will change according to the fault. This in turn alters the electric parameters of the winding and its frequency response characteristics.

IFRA is one of the methods in FRA. In this method the wide range of frequencies required is applied as lightning (or)switching impulse voltage signal into the one terminal of a winding and the response is obtained in the another terminal of a winding which may be voltage or current passing through the winding of the transformer. The input and response signals are filtered to remove unwanted disturbances like noise, sampled and stored in the time domain. FFT is then applied to the signals to analyse them in frequency domain. The impedance (or) admittance (or) transfer voltage ratio at different frequencies is then calculated from the FFT values of input and response signals. Short Circuit Self Impedance (SCSI) plots are obtained by finding 20 $\log_{10}$ (V/I) at different frequency levels from FFT data and plotting the same against frequency [2]. Fig (1) represents the procedure followed in FRA approach to Transformer fault diagnosis.

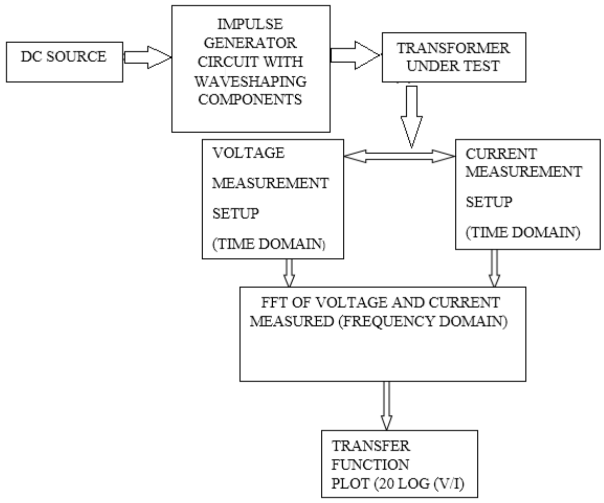

Fig 1-Block diagram representation of frequency response analysis (FRA)

The lightning and switching impulse voltages developedfrom the impulse generator was applied to the transformer under test. The voltage applied and the current response were measured in time domain and converted into frequency domain for analysis. Transfer function plots are obtained by plotting 20 $\log_{10}$ (V/I) versus Frequency. Transfer function plots obtained for transformer winding under healthy conditions was referred as signature (or) base plot. Plots obtained for transformer with fault windings were then compared with these signature plots. The deviation between signature transfer function plot and transfer function plot for faulty transformer winding was used to identify the fault, assess the severity of the fault and to identify the fault location within the transformer.

2. METHODOLOGY:

2.1) SOFTWARESIMULATION:

Softwareanalysis was done using PSPICE SOFTWARE (16.6 OrCAD Lite Capture& PSpice roducts2014). In PSPICE software the lightning and switching impulse generator was modelled as single stage MARX circuit. The output from the lightning and switching impulse generator are impulse waves of standard shape 1.2 µsec/ 50 µsecwith a tolerance of ±30% in Time to peak and ±20%Time to half peak value and 250 µsec/2500 µsec with a tolerance of ±60% in Time to peak and ±20%Time to half peak value respectively.(as per IEC 60076 standard part-III, part-IV)[3]

2.1.1) PSPICE MODELLED TRANSFORMER CIRCUIT

The 315 KVA, 11 KV/433 V, Dyn11, ONAN, 3Ø, 50Hz, distribution transformer under investigation is modelled as a RLC ladder network using the lumped R, L and C measured from the windings. The per phase equivalent circuit simulated for obtaining short circuit self impedance transfer function is shown in fig(2.1.1). The winding under test is modelled as a five stage RLC ladder network, each stage covering 20% of the windings.

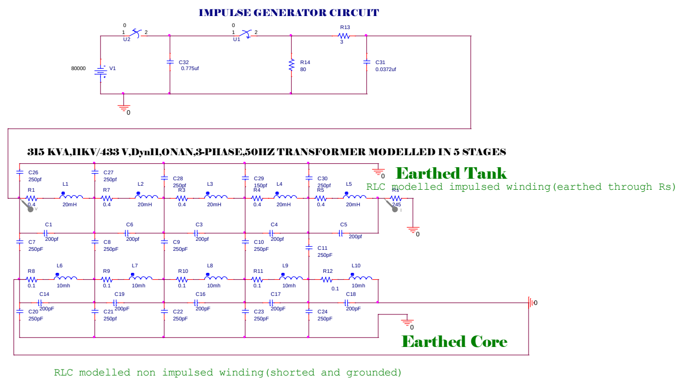

Fig (2.1.1) Simulation circuit for lightning impulse based SCSI transfer function analysis.

The mutual inductive effects between inductors are not considered in the modelled per phase equivalent circuit and the frequencies with range 5 KHz to 20 MHZwere used for the FRA based investigation.

For switching impulse based frequency response analysis (SIFRA), the software analysis was done in the same manner as LIFRA with transformer modelled as RLC ladder circuit with HV and LV windings divided into 5 lumped stages (each stage representing 20% winding). The diagram for SIFRA is shown in fig (2.1.2)

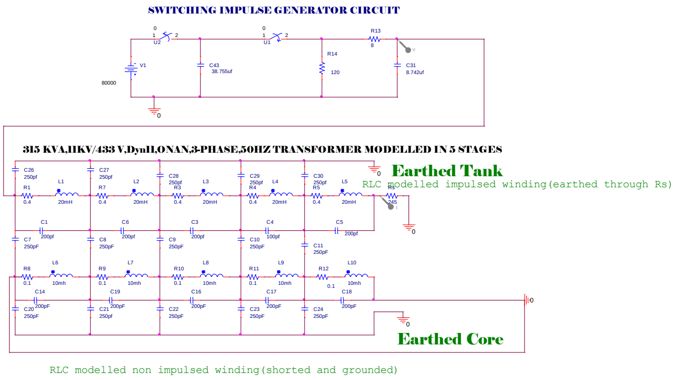

Fig (2.1.2)-simulation circuit for switching impulsevoltage based SCSI transfer function analysis

The test circuit was configured as per IEC 60076 PART III [3], with the non impulsed winding shorted and earthed for lightning impulse voltage test and kept opened for switching impulse voltage test, as per IEC 60076 PART III [3]

2.2) HARDWARE WORKS:

The Hardware test was based on applying a short low voltage impulse to one winding and recording the applied impulse and its response current on another winding (or) the winding current (or) output voltage as per IEEE standardC57.149 (2012)[4]. Changes in capacitance between windings as well as changes in the inter turn winding parameters R, L & C (caused by winding movement) are reflected in the change of the wave shape of the measured voltage or current. A Fourier transform was done on the recorded data. The Fourier transform of the measured output current or voltage is divided by the transform of the input voltage. SCSI transfer function plot was obtained by plotting 20 $\log_{10}$ (V/I) in dB for different frequency components obtained through FFT of voltage and current waves captured against frequency in Hz

By comparing the results (signature) plots recorded initially with the records recorded later or with results recorded on an identical transformer different type of faults like short circuit in the windings, mechanical movements of windings like axial and radial deformation etc.., were detected.

To cross validate the efficacy of FRA technique, a lightning impulse and switching impulse voltage test was alsoconducted on a 1 KVA, 1Ø, 50 HZ transformer (240V/240V)available in the High Voltage Laboratory at SASTRA University as per the IEC 60076 PART III & PART IV[3].

Fig 2.2.1 represents the circuit used for conducting SCSI transfer function through LIFRA.

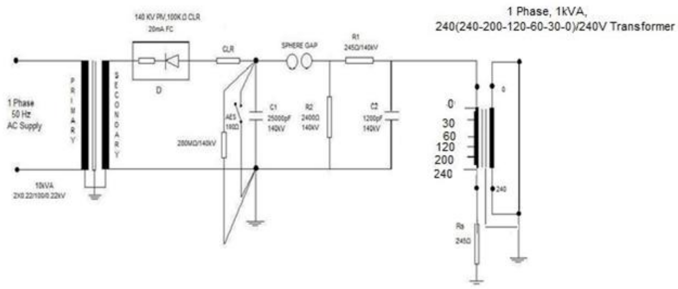

Fig (2.2.1)-circuit diagram for LIFRA experimental setup

Fig 2.2.2 shows the circuit used for obtaining OCSI transfer function through SIFRA

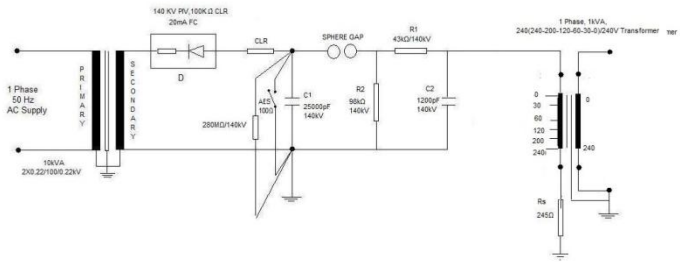

Fig (2.2.2)-circuit diagram for SIFRA experimental setup

All non impulsed winding terminals are shorted and earthed during LIFRA and they are kept open in SIRFA with neutral terminal, tank and core earthed in all these cases as per IEC 60076 recommendations [3]

Fig 2.2.3 represents the photographic view of LIFRA setup used

Fig (2.2.3) LIFRA setup for testing of 1-Ø, 1KVA, 240V/240V transformer

Fig 2.2.4 represents the transformer used for hardware experimental works with tappings on one of the winding at 0 V, 30 V, 60 V, 120 V, 200 V and 240 V levels.

Fig (2.2.4)Transformer under test (1-Ø, 1KVA, 240V/240V transformer)

3) RESULTS AND ANALYSIS:

3.1) SIMULATION WORKS

SCSI transfer function plot was obtained by plotting 20 $\log_{10}$ (V/I) in dBfor different frequency components obtained through FFT of voltage and current waves captured versus frequency in Hz.

SCSI PLOT FOR 315 KVA TRANSFORMER– LIFRA

Fig 3.1 shows the SCSI transfer function plots obtained through LIFRA of the 315KVA transformer modelled

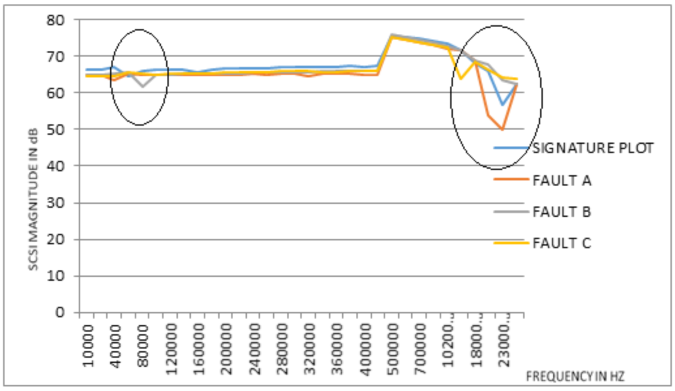

Fig (3.1.1) SCSI transfer function plot obtained through LIFRA on 315 KVA transformer model

The transfer function plots are drawn in MICROSOFT EXCEL (cramped scale) with frequency in X axis and dB magnitude of transfer function (SCSI) in the Y axis. Only critical frequency responses are covered and indicated in the graphs shown to highlight the major changes in the frequency response between signature plot (no fault case) and plots for different fault conditions.

SIGNATURE PLOT-refers to the SCSI transfer function (magnitude) plot obtained under no fault condition

FAULT A- refers to the short created near the impulse end of the winding.(shorting in one section near input end)

FAULT B-refers to the short created in the middle section. (Centre section of the winding)

FAULT C-refers to short created at the far end of the winding (i.e. the fifth section of the winding grounded through a 245 Ω resistor

The value of resistance used for grounding the far end (which is used to measure the response (I) in terms of voltage drop) can affects magnitude or response low frequency levels only, however the responses above 10000 Hz alone are considered for diagnosis in the FRA works

SCSI transfer function plots of faulty cases (obtained for various 20% shorts) with SCSI transfer function plot of normal case (no fault case), changes in both magnitude and location of the corner frequencies which corresponds to changes in (short circuit self impedance of the winding).These regions frequencies with considerable variations in Db magnitude were shown encircled for reference.The deviation in the SCSI transfer function magnitude is more predominant in the fault which was close to the impulsed end (FAULT A). When the fault is very near to impulsed end major deviations occurs between 30 KHz to 40 KHz, second major deviation occurs around 1MHZ to 1.2MHZ and third major deviation occurs at 1.8 MHZ to 2 MHZ.

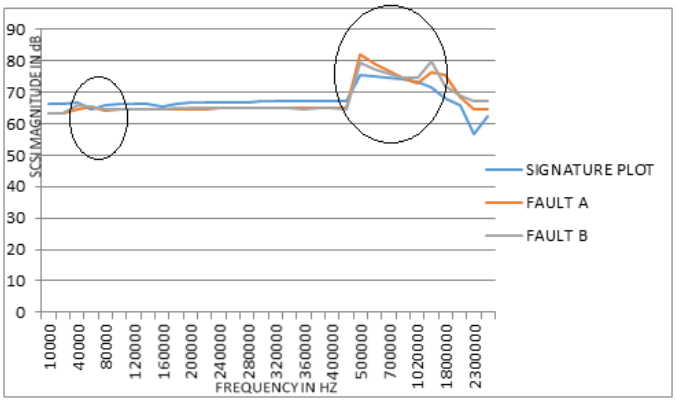

Fig (3.1.2) SCSI transfer function plot LIFRA-double section shorts

SIGNATURE PLOT-refers to the plot obtained under no fault condition

FAULT A- refers to the fault created by shorting two sections near the impulse end of the winding.

FAULT B-refers to the fault created by shorting two sections near the far end of the winding (near the end grounded through a 245 Ω resistor.

The frequency response for larger shorts were not clearly distinguishable between 80 KHz to 400 KHz.. The shift in locations of major changes in plots indicated that the different levels of shorts on the locations could alter the effective R, $X_L$and XC of the transformer winding to different levels. This flattening effect at the mid high frequencies was predominant (clearly distinguishable) when the fault was very near to the impulse end.

MECHANICAL FAULT DETECTION SIMULATION WORKS WITH LIFRA

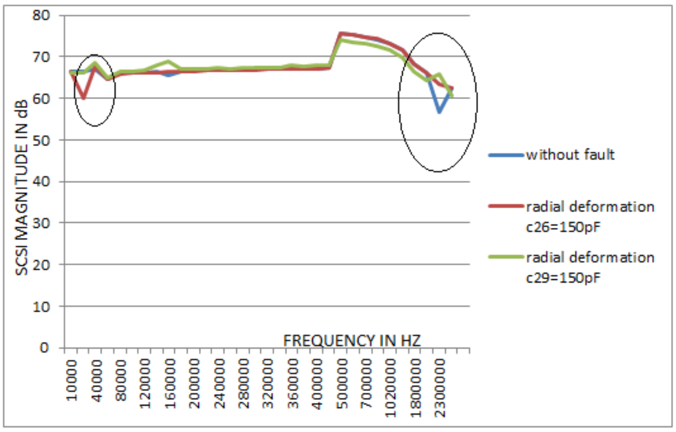

Fig (3.1.3) Lightning impulse voltage based transfer function analysis for radial deformation diagnosis.

For the radial winding displacement which results in alterations of effective thickness of major insulations, there was no appreciable changes in the location of critical frequencies, but there was appreciable changes in the magnitudes of SCSI at these critical frequency levels.

When the deformation occurs near to the impulsed end, the deviation in the SCSI plot at the critical frequency levels in between 30 KHz to 40 KHz. At the mid frequency ranges the deviation in the responses were not appreciable, again at the high frequency ranges of 1 MHz to 2 MHz, there is appreciable variations.

ELECTRICAL FAULT DETECTION- SIMULATION WORKS WITH SIFRA

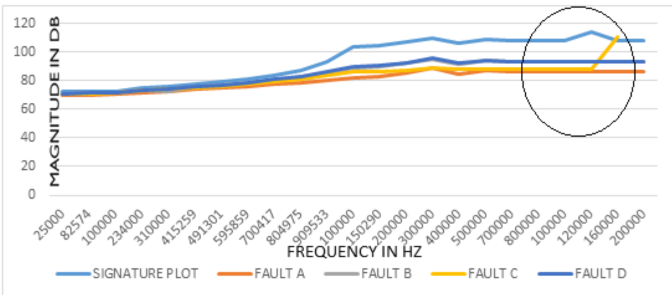

Fig (3.1.4) switching impulse voltage based transfer function analysis-40% of the winding shorted

SIGNATURE PLOT-refers to the plot obtained under no fault condition

FAULT A- refers to the fault created by shorting two sections near the impulse end of the winding.

FAULT B-refers to the fault created by shorting second and third sections near impulse end of the winding.

FAULT C-refer to the fault created by shorting fourth and fifth section near the far end of the winding.

FAULT D-refer to the fault created by shorting middle third and fourth section of the winding.

From switching impulse voltage based SCCI plot for double shorts, the major deviation occurs only in high frequency regions from 8 MHz to 12MHz and no deviation occurs in low frequency regions.

SCSI PLOT FOR AXIAL DEFORMATION IN 5 STAGE MODEL-SIFRA

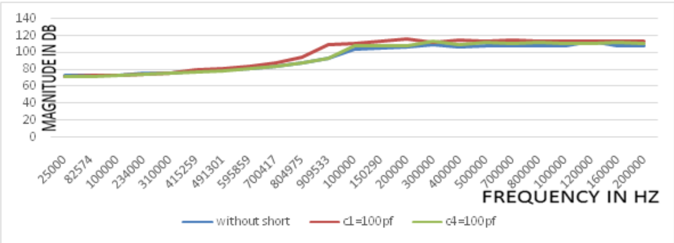

Fig (3.1.5)switching impulse voltage based transfer function analysis-axial deformation

From SIFRA SCSI plot for axial deformation all the curves are similar and one deviation occurs in 12 MHz to 15 MHzand in radial deformation plot some changes occurs in small frequency ranges of 700Khz to 900Khz.

3.2) EXPERIMENTAL WORKS

OUTPUT VOLTAGE AND CURRENT WAVEFORMS FOR LIFRA.

The primary winding of the 1-Ø, 1KVA, 240V/240V transformer having tappings at 240 V-200 V-120 V-60 V-30 V-0 Vat one of the winding was used for experimental works conducted for cross validating the efficacy of LIFRA and SIFRA based approaches in transformer fault detection. Different shorts circuit faults are artificially made by shorting any of the tappings. Example 0-30 short, 0-60 short etc.. The waveforms were captured in real time using a Digital Storage Oscilloscope DL1620D, 2 channel, 200 MHZ, 2GS/sec.

The fig 3.2.1 shows the input (voltage) and response (current) waveforms for normal transformer and fig 3.2.2 shows the input and response waveforms for a fault case (shunt between 0 V- 30 V tapping).

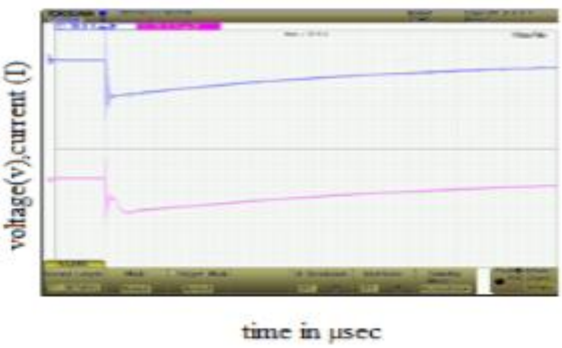

Fig (3.2.1) signature plot-LIFRA

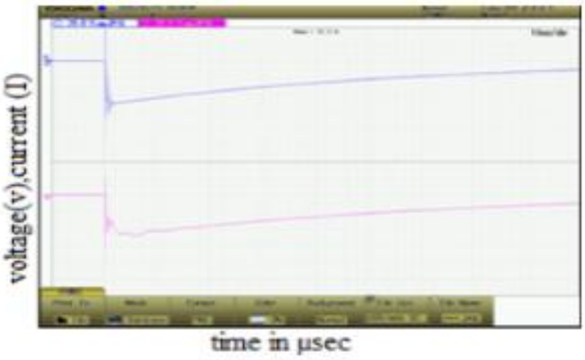

Fig (3.2.2) 0%-30% short – LIFRA

Waveforms obtained in time domain-UPPER waveform denotes the voltage (v) and LOWER waveforms denote the current (I).

SIFRA-OUTPUT VOLTAGE AND CURRENT WAVEFORM

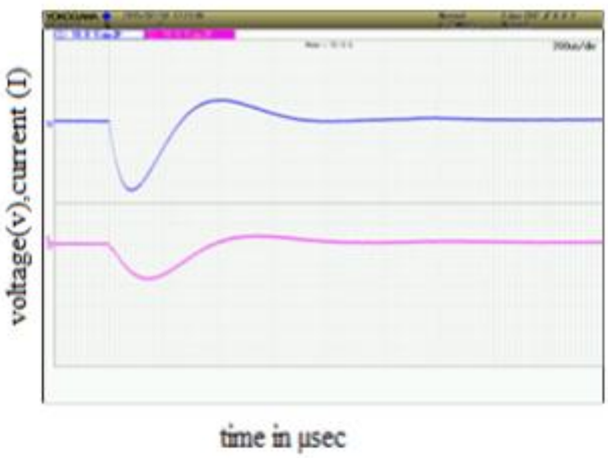

Fig (3.2.3) signature plot- SIFRA

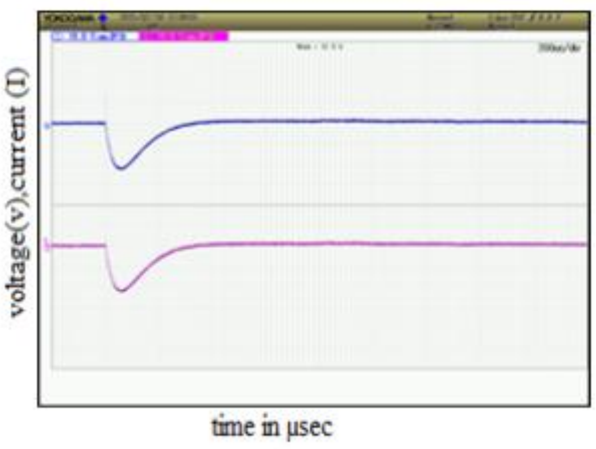

Fig (3.2.4) 0%-30% short (far end)-SIFRA

The fig 3.2.3 shows the input (voltage) and response (current) waveforms obtained in DSO for normal transformer and fig 3.2.2 shows the input and response waveforms for a fault case (shunt between 0 V- 30 V tapping).
The Fast Fourier Transform for the time domain input and response waveform were obtained in the MATLAB. Fast Fourier transform for the input and response waves were done in MATLAB. The dB magnitude transfer function for the normal transformer and for the faulty transformer were also done using MATLAB coding and then FRA analysis was carried out.
Fig 3.2.5 shows the LIFRA based experimental investigation for Electrical fault diagnosis

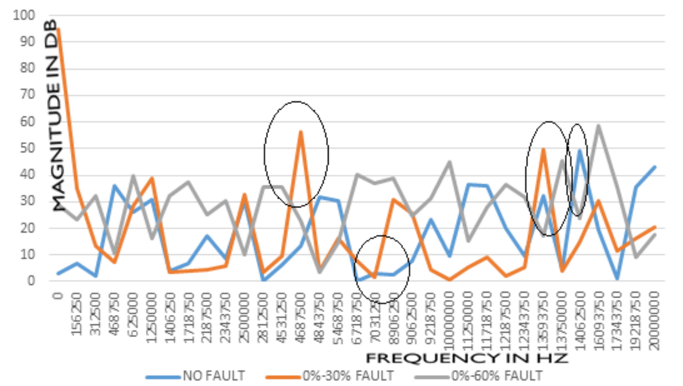

Fig (3.2.5) Lightning impulse voltage based transfer function analysis-LIFRA for electrical fault diagnosis.

NO FAULT CASE- refers the transfer function plot of transformer with no fault
0 V-30 VFAULT CASE- refers the transfer function plot for transformer with a shunt between 0 V-30 V tappings of the impulsed winding. In this 0 V- 30 V fault case major peaks occurs in the frequency range between 4 MHZ to 5MHZ and between 12 MHZ to 13 MHZ.
0 V-60 VFAULT-refers the transfer function plot for transformer with a shunt between 0 V-60 Vtappings of the impulsed winding. In this 0 V- 60 V tapping shunt casefrequency major deviation occurs between 4 MHZ to 5 MHZ and peaks occurs between 13.5 MHZ to 17.5 MHZ.
These major deviation areas (shown encircled) which were shown at different frequency ranges in the plot were indicative of the type & severity of the faults.
Fig 3.2.6 shows the SIFRA based transfer function obtained during experimental investigation on 1KVA transformer.

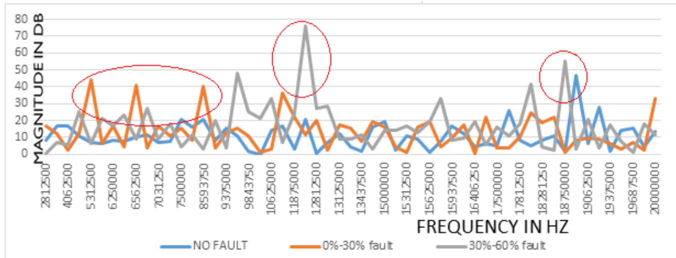

Fig (3.2.6) SIFRA based transfer function analysis for electrical faults

NO FAULT-refers transfer function plot of transformer with no fault.
0%-30% FAULT-refers the transfer function plot for faulty transformer with shunt between 0 V-30 V tappings on the impulsed winding. In this plot major peaks occurs in frequency range of 5 MHZ, 6.25 MHZ and 8.5 MHZ.
30%-60% FAULT-refers the transfer function plot for faulty transformer (with shunt between 30 V-60 V oftappings on the impulsed winding. In this plot peaks occurs in the frequency range of 1.1 MHZ to 1.28 MHZ and between 1.85 MHZ to 1.9 MHZ.

4. CONCLUSION

1. The LIFRA and SIFRA is capable of identifying even small fault, their severity and their location through the variations observed in the transfer function plot 20 $\log_{10}$ (V/I) versus Frequency in Hz.
2. Different types of faults like short circuits, axial and radial deformation can also be identified and located with LIFRA and SIFRA. We also studied that time domain to frequency domain conversion is necessary to identify the faults clearly.
3) Online IFRA can also be done using the same arrangements to detect the faults
4) LIFRA and SIFRA based approaches can also be attempted for fault diagnosis in rotating machines.

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