Power Transformer Faults Identification using SFRA

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Abstract — Power transformer is one of the most imperative equipments in a high voltage electric power system. This dissertation aims at the Power transformer faults analysis using Sweep Frequency Response Analysis (SFRA). SFRA is condition monitoring technique for expensive power equipment. It measures the frequency response of passive element (RLC) of the apparatus. In a power transformer it measures the fault current of the winding over a wide range of frequencies. The SFRA measurement is done using sweep frequency of 20Hz – 20MHz applied to transformer of 16MVA, 33KV/11KV under normal as well as faulty conditions.
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Index Terms—Power Transformer, Winding movement, Partial Discharge, Transient faults, Sweep Frequency Response Analysis

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1 INTRODUCTION

Power transformers play an awfully grave role in the efficient and effective transmission of power. They are the crucial connection between the generating station and distribution station. Now a day's generating station capacity is almost to reach GW range. This much of power production and transmission equipment should have high grade of insulation strength. Especially power transformer insulation strength is very important one. Because of power transformers are not only contribute to transmission and distribution of power, its play isolation between the low voltage and high voltage equipment. In generating station generating power is low as compared to transmitting power. This much amount of power is obtained from step up transformer in the generating station. But in consumer side transformers are doing step down action due to equipments operating power is low. Any defect in generation unit power transformer its will leads to the huge power transmission loss. The budding technology of condition monitoring and diagnostics testing of power transformers and other major equipment has come to the forehand is increasingly being considered to predict the condition of the equipment before it forces outages and/or major breakdowns. So many predictable methods are available that are namely transformer oil analysis, winding resistance measurement, tan delta measurement etc. But above tests are not able detect the winding movement of power transformer. Sweep Frequency Response Analysis is tool [1], [2] which can be use to access the mechanical integrity of the power transformers. Whenever a power transformer is subjected to high fault currents, the mechanical structure and windings are subjected to dish up mechanical stresses because winding movement and deformations. It may also

result in insulation damage and turn-to-turn fault. As a power transformer ages, the insulation shrink, and the clamping pressure lost which reduces it's withstand strength and also causes winding movement. Deformation results in relative changes to the internal inductance and capacitance of the winding. These changes can be detected externally by Sweep Frequency Response Analysis method (SFRA). Partial discharges (PD) are the type of electrical discharges, which do not establish electric conduction between electrodes. But if it occurs with sufficient discharge magnitudes relevant to the portion of electrical equipment can cause failure of insulation of equipment. This type of discharge is detected and analyzed by frequency response analysis [3]. Whenever a switching device is sudden opened or closed, it can cause high-frequency voltage transients in the system. Furthermore natural lightning hit of the transformer, the insulation suffer because of the high amplitude of the voltage [4]. These faults are analyzed by using Seep Frequency Response Analysis.
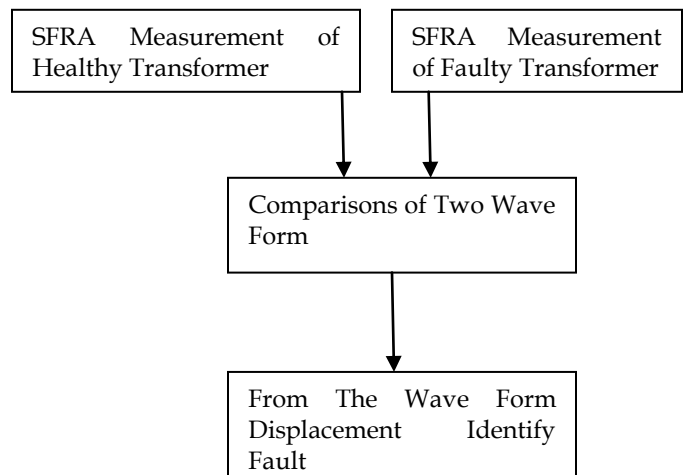
2 PROPOSED MODEL

Fig. 1 Proposed model

SFRA techniques are now a day, widely used by the electric

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utilities. It is especially for detecting winding displacements inside the transformer and is based on the fact that something occurs inside the transformer.

The four steps of diagnosis method are listed:

1. A measurement in the healthy state of the transformer is made.

2. Another measurement is carried out in the supposed fault state.

3. Two responses are compared.

4. Any difference between them means fault has occurred.

3 METHODOLOGY

3.1 Frequency Response Analysis (FRA)

The loss of mechanical integrity in the form of winding deformation and core displacement in power transformers can be attributed to the large electromechanical forces due to fault currents, winding shrinkage causing the release of the clamping pressure and during transformer transportation and relocation. These winding deformation and core displacement if not detected early will typically manifest into a dielectric or thermal fault. This type of fault is irreversible with the only remedy been rewinding of the particular phase or a complete replacement of the transformer. It is therefore imperative to check the mechanical integrity of aging transformers periodically and particularly after a short circuit event to provide early warning of impending failure. Hence an early warning detection technique of such a phenomenon is essential. Frequency response analysis is recognized, as been the most sensitive diagnostic tool to detect even minor winding movement and core displacement [5].

3.2 Low Voltage Impulse (LVI) method

In this method, a low voltage impulse with short front and tail time is applied to one end of the winding. The winding current is measured with the help of a shunt connected at the other end of the winding [6].The input & output responses are measured simultaneously with digitizers and frequency response is calculated using Fast Fourier Transform Method. The main advantages of the LVI method is its shorter measurement time in the order of few seconds, however, the method suffers from several disadvantage, Shape of the   impulse, limit the frequency range. Disposition of test leads affects the repeatability of measurement.

3.3 Sweep Frequency Response Analysis (SFRA)

Sweep Frequency Response Analysis (SFRA) is a tool that can give an indication of core or winding movement in transformers [7], [8]. In this method, measurements are performed at frequency can be varied typically from 20Hz - 20MHz. As compared to LVI method, SFRA method offers the following first one is wide range of frequency and good frequency   resolution can be obtained. Better signal to noise ratio and the results are high.

4 SIMULATION AND ANALYSIS

4.1 Mechanical Faults

Mechanical fault in transformer mainly contributes to the following reason [9]

1. Winding deformation & winding displacement
2. Movement of clamping pressure
3. Partial collapse of winding

4. Hoop buckling
5. Short and open circuit in winding etc

At this juncture following turn faults are analyses by SFRA

1. Inter turn fault
2. Turn to turn fault.
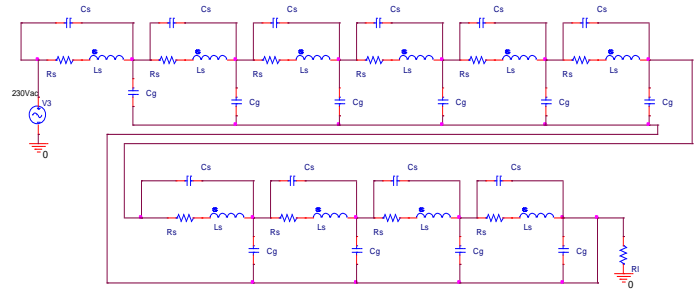3. Turn to ground fault.

4.2 Measurement of SFRA using PSPICE

Fig. 2 Transformer model

Transformer model is developed by using PSPICE software. Following model is no fault condition. Take Cg=0.011nF, Cs=0.914pF, Ls=0.3655mH, R=0.01942E
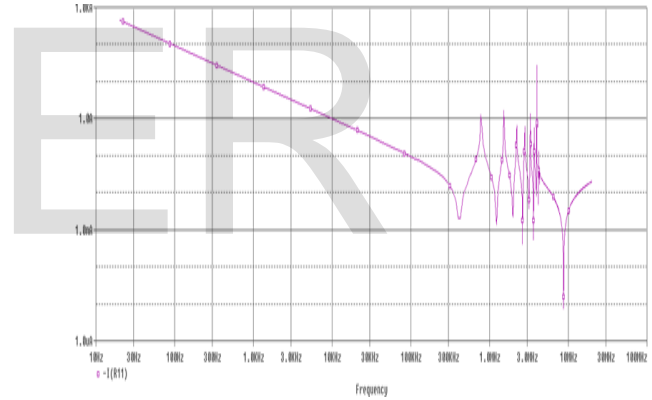
4.3 Unfault Condition Result

Fig 3. Frequency Vs Time (unfault condition)

The above response shows the unfault condition response. The response is simulated without making any fault in Fig 2. For a wide range of frequency the equivalent circuit of the transformer winding   includes numerous inductance and capacitance element and moreover, there are mutual inductive and capacitive coupling between the winding elements, which are effectively determine the features of FRA responses of windings, including multiple resonance and antiresonances.

The first resonance is occurring at 399.139 kHz.   Beyond this resonance point inductance of the transformer winding dominates. After first resonance point magnetic effect of the winding is tries to increase but winding inductance effect screened. This process continuously repeats several times, so that medium frequency range has more number of resonance points. After medium frequency range, winding inductance effect is completely cancelled due to series and shunt capacitance of the windings. The current measured from the wave form occurs at the value 451.645A. Further analyzing can be considered from first resonance point.

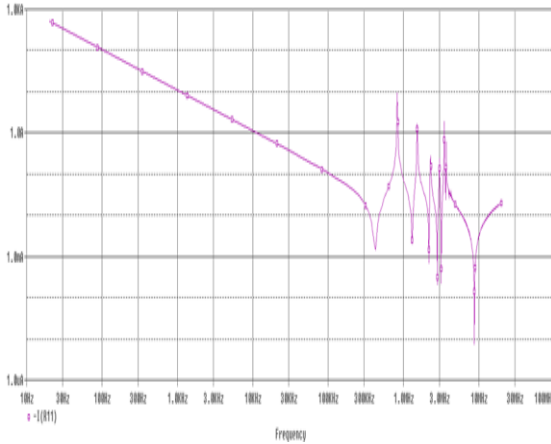## 4.5 Inter Turn Fault Result

Fig 4. Frequency Vs Current (inter turn fault)

This simulation is being done by inter turn fault condition. The fault is artificially created in fourth turn of transformer windings in Fig 4. From the above Fig 4 notices that significant wave form displacement occurs compared to no fault wave form. The first resonance point is occurring at 429.068 kHz. Also in medium frequency range there is a slight wave form displacement compare to normal condition wave form. But from 2MHz to 4.2378MHz range big displacement occurs. The current is measured at inter turn fault condition is 500.925A. Compared to no fault condition 49.28A will be increase. The increasing current produces an abnormal heat which will affect the transformer insulation and also leads to winding burn out.
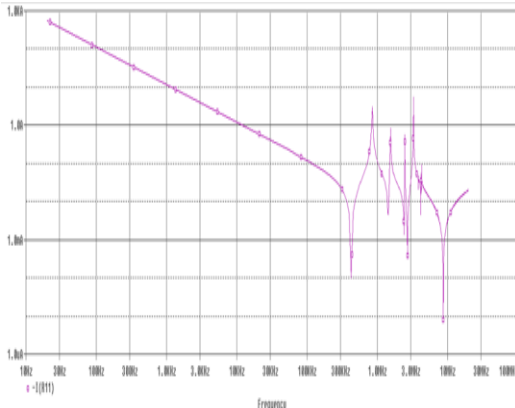
4.6 Turn to Turn Fault Result

Fig 5. Frequency Vs Current (Turn to Turn fault)

This simulation is being done by inter turn to turn fault condition. The fault is artificially created in between the third and fourth turn of transformer windings in Fig 2. From the above Fig 5 notices that significant wave form displacement occurs compared to no fault wave form. Also this wave form is compared to previously discussed fault. The first resonance point is appearing at the 427.471 kHz. At turn to turn fault condition the wave form obtained get completely displaced from 1.4417 MHz to 4.3697MHz compared to reference set. The current measured at inter turn fault condition is 562.264A which compared to no fault condition, the increased current

will be at a range of 110.619 A. Which is thermally stresses the insulation to be used in transformer winding. Due to this un expected thermal stress the insulation degraded.
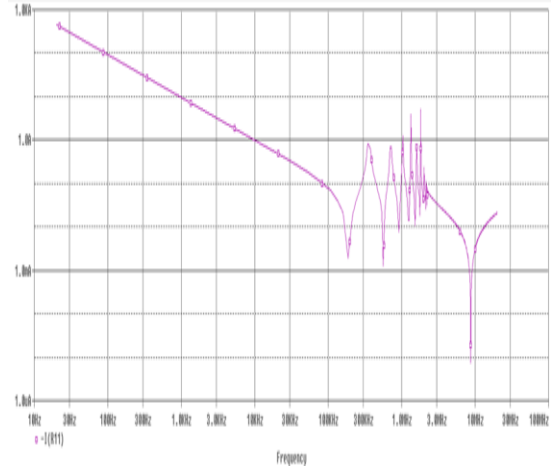
4.7 Change of Ground Capacitance

Fig 6. Frequency Vs Current (Change of Cg)

The simulation is being done by change of turn to ground capacitance value. This is due to radial displacement of the transformer winding. For no fault condition the value of the ground capacitance is 0.011nF. For analyzing purpose choose the turn to ground capacitance value as 52.6pF. Comparison of Fig 2 and Fig 6 significant wave form displacement occurs in Fig 6. Notice that above Fig 6 wave form is entirely collapsed because of capacitance which is inversely proportional to the frequency. The first resonance point is appearing at 187.008 KHz. From 187.008 KHz to 2.2124MHz wave form displacement occurred.
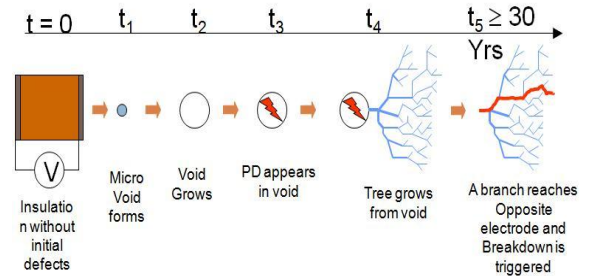
4   PARTIAL DISCHARGE (PD)

Fig 7. Stages of Partial Discharge

Above Fig 7 clearly shows the stages of insulation degradation. Due to inadequate insulation design micro void is formed during the service. This micro void is growing as big voids. In case of electro mechanical stresses reaches the critical value, PD appears inside void. After PD is developed inside void conducting trees are formed outside the void circle which has weak insulation. This treeing effect approaches the opposite electrode. It will leads to breakdown of the insulation medium between two electrodes. To reach this stage it will take few numbers of years. Integrity of the insulation of HV equipment should be confirmed using Partial Discharge Analysis during its manufacturing, its commissioning, and during its life time.

PD is one of vital phenomena to causes the degradation of transformer winding insulation. Due to this location of PD is important. There is the number of methods are use to detect the PD that are conventional electrical technique, UHF Light emission, Chemical methods, Acoustic emission techniques. But here location of PD by changing the alpha values. In this method helpful to location of PD as well as severity of PD. Severity is obtained from measurement of peak value at the instant of PD occurred time. Also changing alpha value which value gives exact location and time required to location of PD at particular alpha value is less. Location of partial discharge is accurately by travelling wave method.

5.1 Unit Step Signal

The unit step signal is generated (Fig 8) by using PSpice software. Time taken for pulse signal to reach a unit voltage is 5ms and its pulse width is 5ms, total time period of unit step pulse is 10ms [10]-[11] and its raise time and fall time is 1ns.

Fig 8. Step signal

5.2 Simulation of partial discharge

The model winding used in lumped model .consisting of 10 sections, The lumped parameter model consisting of internal winding capacitance Cs (e.g. inter turn, inter disc capacitance, the earth capacitance (stray capacitance) Cg, the inductance L and the resistance For simulation reason step pulse signal is injected corresponding position of the transformer winding i.e. supply end as well as load end in Fig 2.
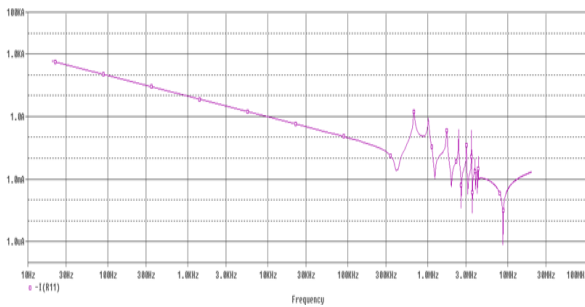

Fig 9.PD on transformer winding

The above wave form is obtained at the time of PD occurred on transformer winding. The above wave form is deviated from fundamental wave form Fig 3. The obtained wave form displacement entirely different from turn faults wave form displacement. The first resonance point is appearing at 409.600 KHz. when the PD occurred on the transformer winding there is a huge deviation in wave form displacement in between 409.600 KHz to 4.4266MHz.

5.3 PD location methodology

For PD detection rationale the supply voltage is removed, resistances are connected at supply and load end in Fig 2. Now PD is injected at any one of the end (supply or load end) and collected output from two resistances at instantaneously. Location of PD fault can be measured by means of peak value of the load and supply side.
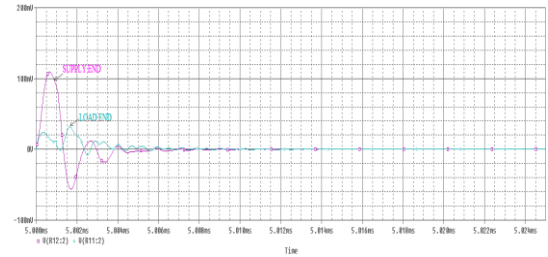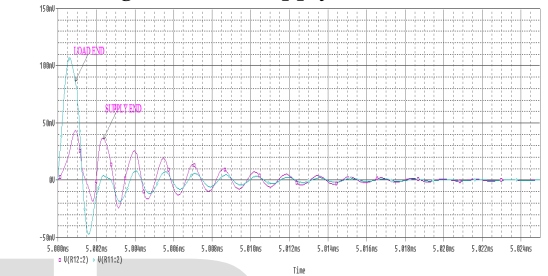

Fig 10. PD at Supply End

Fig 11. PD at Load End

Now PD is injected at load end and collects the output from individuals two resistance. From the wave form peak voltage is observed from load end, so the discharge is occur at load end. The above two Fig 10 and 11 is shows only weather PD is occur on supply end or load end only. Improving accuracy of PD location different alpha values are chooses. This analysis use the three alpha values are 3.4, 12 and 18. To obtain diverse alpha value by changing ground capacitance value only all other values are maintained at constant.
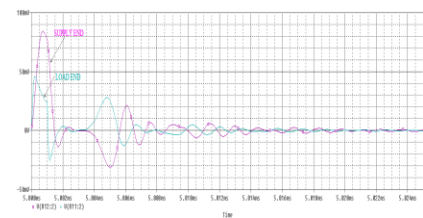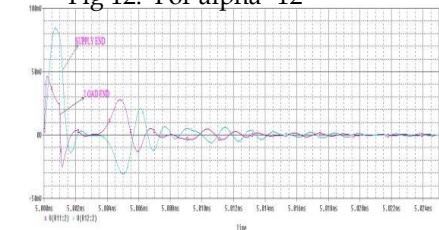

Fig 12. For alpha=12

Fig 13. For alpha=18

The above response is obtained under PD signal is injected at supply end. Above wave form is harmonic less wave form. Measure the first peak corresponding to time taken for reach the first peak. The measured readings are tabulated.

Table 1 for alpha=12

S.L. N.O	Voltage in mV (supply end)	Time in ms (supply end)	Voltage in mV (load end)	Time in ms (load end)
1	75.464	5.0003	30.220	5.0004
2	84.172	5.0007	45.533	5.0002
3	84.298	5.001	61.03	5.0005
4	72.581	5.0011	70.382	5.0006
5	56.818	5.0015	74.203	5.0006
6	55.716	5.0017	75.377	5.0007
7	55.148	5.0020	75.464	5.0006
8	53.484	5.0021	75.834	5.0007
9	44.024	5.0024	77.046	5.0007
10	43.814	5.0023	77.046	5.0007

Table 2 for alpha=18

S.L. N.O	Voltage in mV (supply end)	Time in mV (supply end)	Voltage in mV (load end)	Time in ms (load end)
1	72.581	5.0003	36.686	5.0005
2	76.617	5.0008	55.509	5.0003
3	70.516	5.001	60.415	5.0006
4	48.625	5.001	68.86	5.0008
5	40.482	5.002	71.572	5.0008
6	39.967	5.0023	71.956	5.0008
7	39.725	5.0026	72.062	5.0010
8	36.959	5.0029	72.096	5.0010
9	34.880	5.0033	72.708	5.0009
10	35.733	5.0039	78.133	5.0009

From the comparison of above two tables, higher alpha values give the accurate PD location (Table 1 alpha=12, Table 2 alpha=18). In addition above tables are help to find out in which turn PD is occurred.

6 TRANSIENT FAULTS

Magnetic relays are protective devices that are widely used in the electrical system in order to protect the electrical system from transients and over voltages. However, these devices generate switching transients and noise during normal operation. These switching transients can be high enough in magnitude to damage equipment and cause equipment malfunctions. The modern facility uses hundreds of relays during the course of daily operation. These relays Generate huge voltage transients. This transient severely affects the transformer winding [12].

On other hand lightning is the natural phenomena that is occurs in the atmosphere between the clouds. Sometime this lightning is hit on the transmission line and travel to the equipment and power system. This will leads to insulation degradation in the electrical equipment. Because of this lightning incident will propagates the over current and over voltages in the electrical system. This over voltage is travels to the transformer through transmission line severely affect the transformer. The inter turn insulation is particularly weak to high-frequency oscillation, and therefore, the study of the distribution of inter turn. Also to investigate how will affect different shape impulse (current and voltage) on transformer are important.
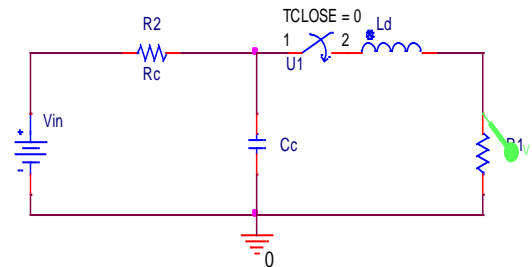
6.1 Lightning Impulse Generator

Fig 14. 8/20μs lightning impulse generator

The above Fig is 8/20μs impulse current generator [13],[14] circuit. Initially the capacitor need for charging, the charging voltage is 15.5kV. The capacitor is charging through charging resistor Rc. The inductance Ld is the damping resistor which is used to reduce the oscillation.
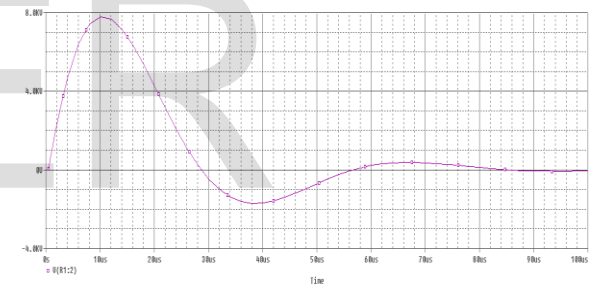

Fig 15. 8/20μs Lightning impulse wave form

The above Fig 15 is 8/20μs Lightning impulse wave form, this impulse is generated by using Fig 14. The front and tail time is taken from wave form is 7.5μs and 20.7μs, peak 7.8kV. The generated wave form is satisfies the tolerance limit.

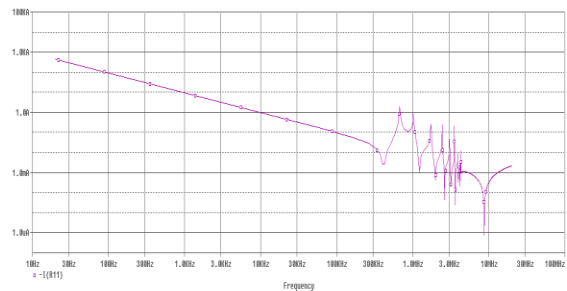### 6.2 Lightning Impulse on Transformer Winding

Fig 16. Lightning impulse on transformer winding

This wave form is obtained under lightning impulse current is applied at supply end of transformer winding Fig 2. The wave form is deviated from fundamental waveform. This wave form displacement is compared with reference set. It can

be notice that the wave form displacement is completely different from already discussed winding fault. This type of displacement will occurred at the instant lightning impulse hit time only. The first resonance point is appearing at 409.600 KHz. Notice that above Fig wave form displacement occurs at first resonance point to 20MHz. this will severely affects the transformer insulation.
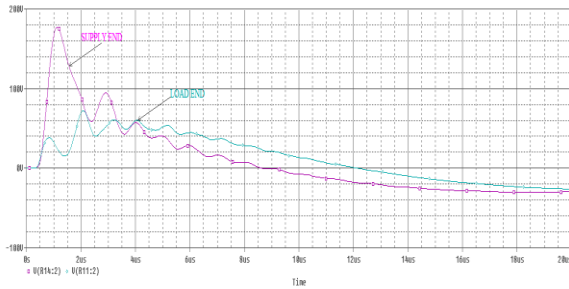
6.3 Lightning Impulse Detection Method

Fig 17. Lightning current impulse on supply end

The above Fig 17 is 250/2500μs impulse generator circuit. Initially the capacitor need for charging, charging capacitor Voltage is 15.5 kV applied to the capacitor.
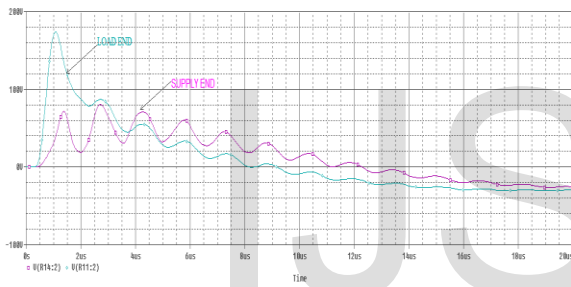

Fig 18. Lightning current impulse on load end

Notice above two Fig 17, 18 if lightning impulse on supply end peak is observed from supply end, if impulse on load end peak is observed load end. By using this technology location of impulse made easily.
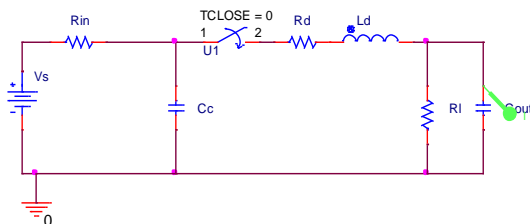
E. Switching Impulse Generator

Fig 19. Switching impulse generator

The above Fig 19 is 250/2500μs impulse generator circuit. Initially the capacitor need for charging, the charging capacitor Voltage is 15.5 kV applied to the capacitor.
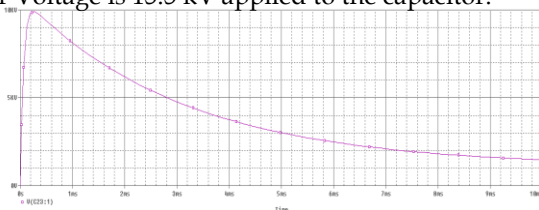

Fig 20. Switching impulse wave form

The above Fig 20 is the switching impulse wave form. The front and tail time is taken from wave form is 246μs and 2750μs. This switching impulse is applied to transformer winding through coupling capacitor at the same time supply is maintained at 230V. Output is collecting the out from RL.
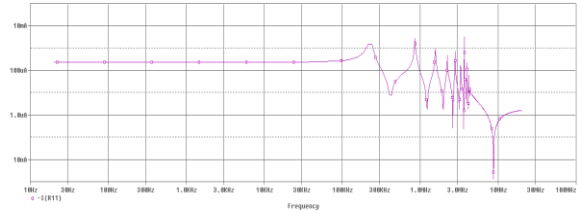

Fig 21. Switching impulse on transformer winding

The above response is obtained due to instant switching impulse fed on the transformer Fig 2. Obtained wave form is deviate from fundamental. This wave form displacement compared from reference set. From this comparison terminate the switching impulse which occurs on the transformer. Notice that above Fig up to 36.933 kHz wave form shows like almost straight line. First resonance point is appearing at 231.829 kHz. From this frequency to 4.4266MHz wave form deviation occurs. Switching effect will leads to the voltage increases exponentially but current decrease to mA. This unexpected voltage increases severely affect the transformer winding.
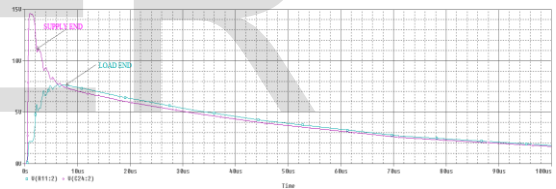
6.4 Switching Impulse Detection Method

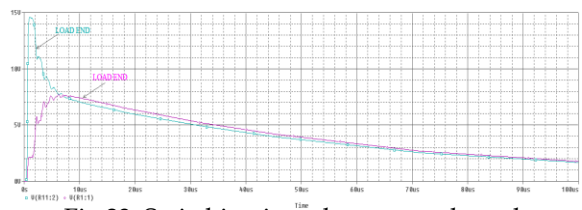Fig 22. Switching impulse on supply end

Fig 23. Switching impulse on supply end

In Fig 22 peak is observed from supply end due sudden closing the supply to transformer or disconnecting the supply during operation. In Fig 23 peak is observed from load end due to sudden disconnecting or connecting a heavy load to normal operating transformer.

7   CONCLUSION

In this effort, a method based on sweep frequency response analysis of the power transformer is presented which can successfully detect faults such as winding movement, PD and Transient fault. On the other side transformer faults like PD and transient where occur in the transformer winding can be easily identified using travelling wave method. In transformer PD fault can be exactly located at the transformer winding

very accurately, when the alpha value is around or more than 12. Transient fault in the transformer can be identified exactly weather the fault occur in the supply end or load end. It used to avoid catastrophic failure in power transformers and also help maintenance engineer to estimate time and cost for repairing the transformers after the fault occurred. In future transformer 3D model has to be developed by ANSYS. This is used to investigate magnetic and Thermal behavior of power transformer under Different fault condition.

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