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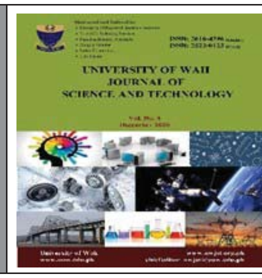

An Extensive Study on Condition Monitoring of Distribution Transformer under Transients

Najeeb Hussain, Kashif Imdad, Haseeb Faisal and Ijaz Hussain

***Abstract*-The faults on high voltage power lines are mainly due to high frequency transients. The Fast Fourier Transform (FFT) is an effective technique in analyzing the effects of high frequencies on a power system components whereas Frequency Response Analysis (FRA) provide computational support in diagnosis and detection of deformation in transformers that occur due to high frequency surges. One of the aims of this study is to analyze the incorporation of frequencies on the basis of resonating core of a particular transformer. Using transfer function method, a change in impedance is observed when transformer is subjected to high voltage surge. Another major issue that arises in power distribution transformer is determining the condition of transformers of different ratings. Some author have proposed single and dual resonance model that are applicable on transformers of 50 and 100 kVA rating. Whereas, in industries there is a need of designing protection schemes for devices/equipment's which are of different ratings. A modified model is proposed which has the capability to operate on single and dual resonance frequencies. Moreover, proposed model is effective in diminishing the transients or surges, which occur at High Voltage (HV) to Low Voltage (LV) lines. Surge model is based on T or Pi model and its design is validated by comparing the results with the two selected reference papers through transfer function method. The simulation results in time and frequency domain show better performance as compared to selected reference models.**

***Index Terms* - Single and Dual resonance, Transients, High Frequency Modeling, Transfer Function Method and Condition Monitoring.**

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I. Introduction

TRANSFORMER is one of the fundamental component of a power system as it provides a voltage level transformation. Transients are of high voltage; occur in a short period of time, so bucholz relay and other protecting devices are not able to detect it. In order to provide protection to customer as well as transformer itself a high frequency model is required. Deformation in transformer winding is mainly occurred when transformer is transported from manufacturing plant to the operational field [1-5]. Diagnoses on the bases of inter-turn faults need modeling of transformer winding. The modeling of a transformer winding depends on the construction and study of the electrical stresses. In general black box analysis is used for the diagnosis of a transformer. Transformer models were developed to estimate transferred surges from High Voltage to Low Voltage lines. Some Models are valid for unloaded conditions only [6-8]. However, there are models that were functional for both loaded and unloaded conditions, and are effective in the case of electromagnetic transients [9-10]. In order to calculate the transferred surges, distributed and lumped parameters models were used [11-19] for bandwidth up to 1MHz, lumped parameters analysis were used. It was observed that for satisfactory results, distributed parameter models were preferred by researchers of the discipline of power system. A single resonance and dual resonance behavior model of transformer is investigated by researcher [7-8]. However, no one has precisely elaborated the dual and single core resonating frequencies with respect to the transformer rating. For evaluating the mechanical deformation of a transformer core, the sweep frequency analysis was performed and it came into notice that the frequencies less than kHz are much more operative in intensifying the mechanical efficiency of a transformer. The loading and unloading conditions of the model were also taken into account [20]. It was perceived that transformer primary side was dominating capacitive while secondary behavior was inductive at higher frequencies [21]. A fault, which occur in the core of a transformer during its transportation. Therefore, primary testing is done before and after the transportation of a transformer. So, the secondary voltages are the main source of inspection as single or dual frequencies are directed toward magnetizing core of the transformer.

Another concept which has been develop in this paper is to examine the effects of high frequencies on the core of a transformer which are in the form of a resonance under the influence of a high transient faults. The idea is based on the modeling of the equivalent circuit at low frequencies. In an Open Circuit (OC) test of a transformer at low frequencies, core resistance and reactance are calculated. In an OC test, it is observed that when the impulse voltage was injected on primary and secondary side, the core voltage is resonating and its characteristics are changing.

This research is basically two dimensions in nature. In first phase, an experimental approach is developed and the concept is competitive in terms of defining single or dual resonance with respect to transformer ratings. In the second phase, a modified model is developed, which has a similarity in terms of the task performance with the selected reference models from [7, 9]. The loading and unloading conditions of the model are taken into account. It is observed that transformer primary side is representing dominating capacitive behavior while secondary have an inductive behavior on high frequencies.

II. Research Methodology

Impulse test has been performed by using two-port network theory and then transfer function is applied in term of impedance to see the core impedance behavior.

The transfer function method is helpful to identify that what will be the behavior of the core when impulse voltage is transferred or transformed towards output side of a transformer. The transfer function *TF* as shown in equation (9) represents the effective transformation of output voltage in term of input current that is known as transformed impedance. The equations for the two-port network shown in *Fig. 1*.

$$V_P = Z_{11} * I_P + Z_{12} * I_S \tag{1}$$

$$V_S = Z_{21} * I_P + Z_{22} * I_S \tag{2}$$

$$Z_{12} = \frac{V_P}{I_S} \quad \therefore I_P = 0 \tag{3}$$

$$Z_{21} = \frac{V_S}{I_P} \quad \therefore I_S = 0 \tag{4}$$

$$Z_{11} = \frac{V_P}{I_P} \quad \therefore I_S = 0 \tag{5}$$

$$Z_{22} = \frac{V_S}{I_S} \quad \therefore I_P = 0 \tag{6}$$

For the analysis of the experimental data under open circuit test, frequency domain analysis is performed by using Fast Fourier transform, represented by the equation as:

$$X(k) = \sum_{i=1}^{n} x(j)\omega_n^{(j-1)(k-1)} \tag{7}$$

Where,

$$\omega_N = e^{-2\pi i/N} \tag{8}$$

$$TF = \frac{V_{out}}{I_{in}} = \frac{V_{secondary}}{I_{Primary}} \tag{9}$$

$$T_{sample} = \frac{\mathrm{L}}{\mathrm{N}} \tag{10}$$

Where, T_{sample} is representing sampling time, which is dependent on the selection of the samples matched closely to each other. Moreover, *L* is the length of a signal and *N* representing the number of samples.

III. Experimental Setup

The experimental setup is comprised of 11kV/440V step down distribution transformer of 50 kVA having 3-phase; delta-star connection as shown in *Fig. 2*.

The experimental configuration of the transformer is based on the model as shown in *Fig. 3*. All phases of the primary side of a transformer are kept short circuit, for examining the impedance change in a core, the corresponding phase input voltages and currents are measured. The mutual induction phenomenon in all the phases affects the core; in this case it is presumed that all phase has same windings for magnetization. For analyzing the behavior of a core under open circuit test, secondary was kept open. Finally, using transfer function method after the injection of impulse voltage on primary side, the primary current I_P and secondary voltage V_S is find out.

A surge voltage is applied on the high voltage (primary) and low voltage side (secondary) of the transformer. Output voltage is measured via configuration shown in *Fig. 3*. Changes in current injections and output voltages are observed with the changing magnitude of surge voltages on the primary side. The configuration of *Fig. 3* for the test of HV and LV. On the oscilloscope the channel 1 is for the measurement of V_1, while channel 2 is for the measurement of I_1 and channel 3 is allocated for the measurement of V_2. As secondary is open therefore I_2 is zero. The injected voltages and currents are shown in the *Fig. 4* and *Fig. 5*.

Fig. 1. Two port network representation.

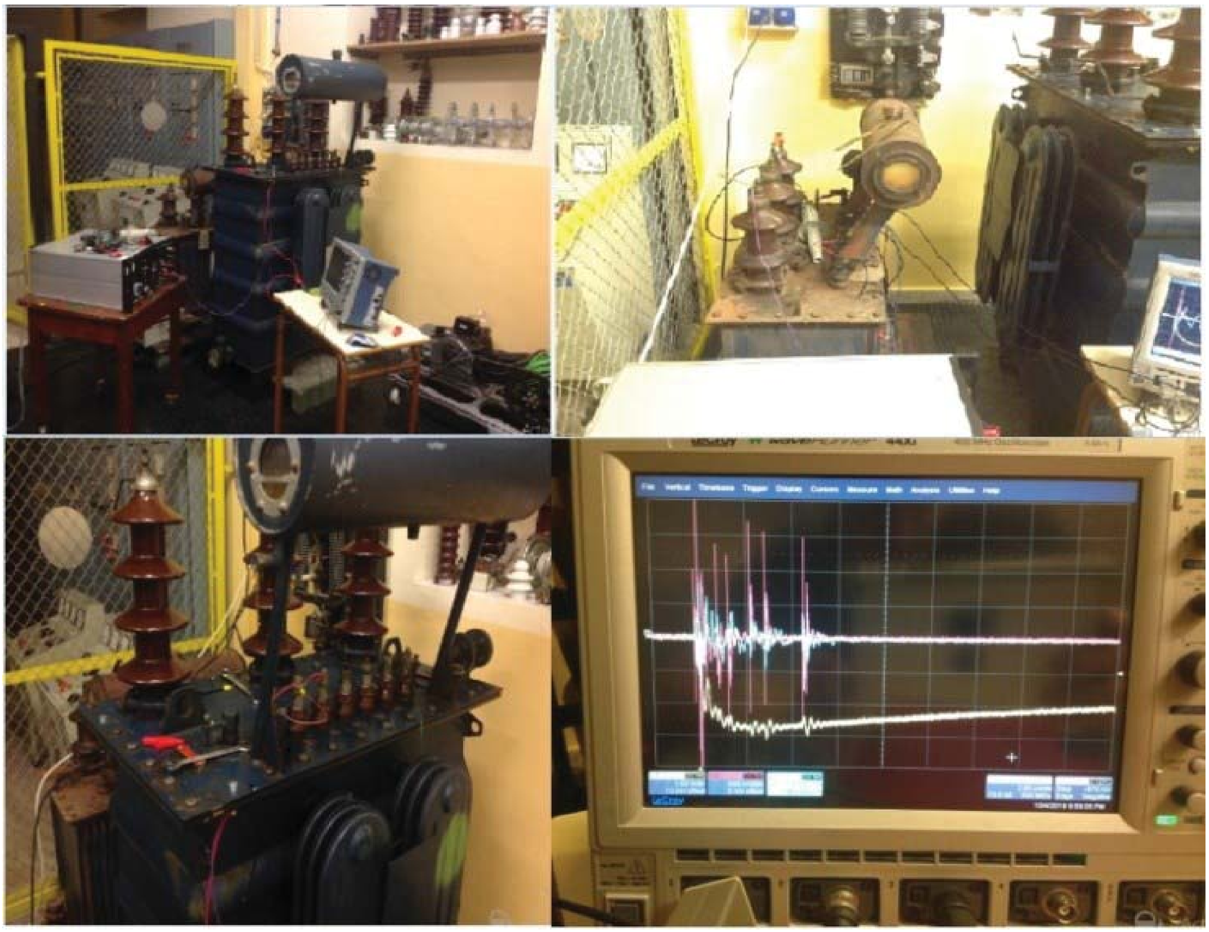

Fig. 2 Experimental setup for 50kVA transformer.

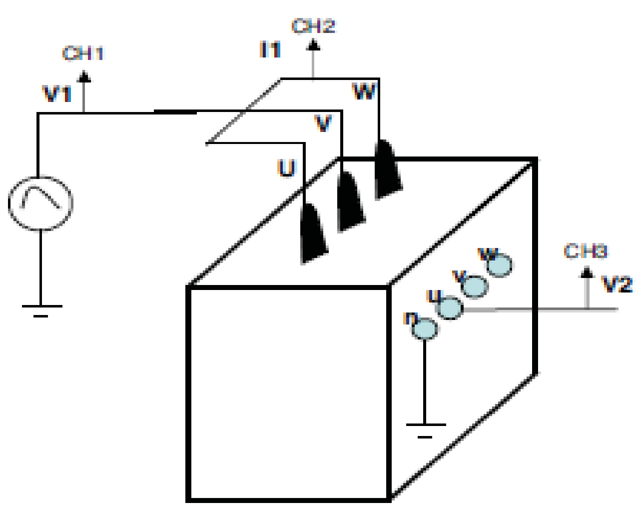

Fig. 3. Experimental configuration of 50kVA tranformer.

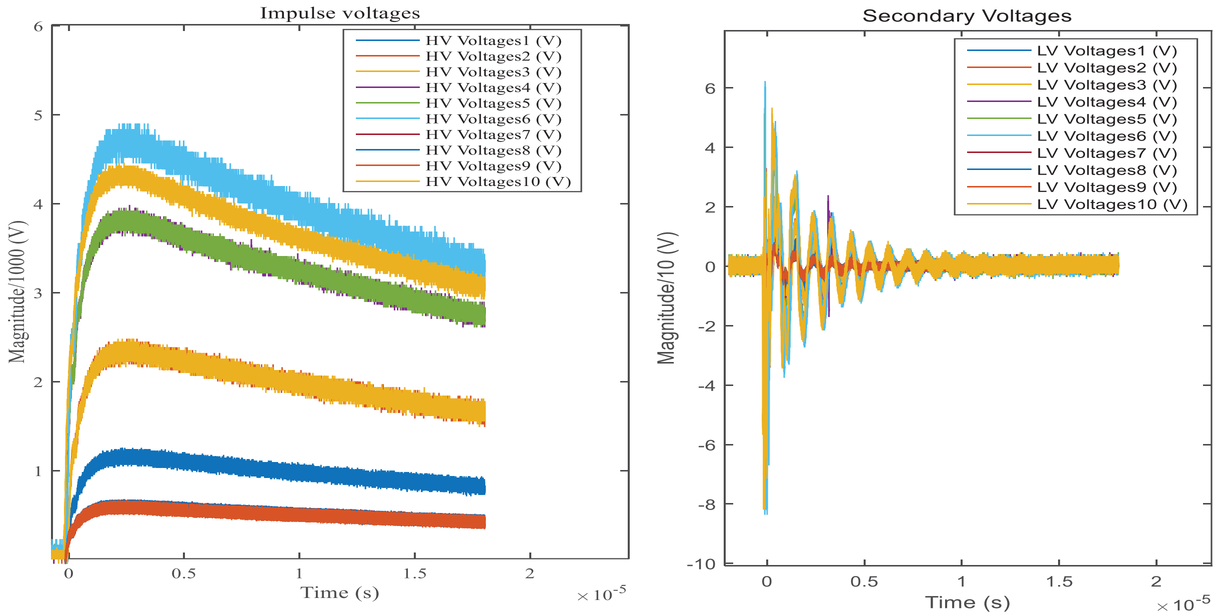

Fig. 4 Different impulse voltages at HV and Secondary voltages at LV.

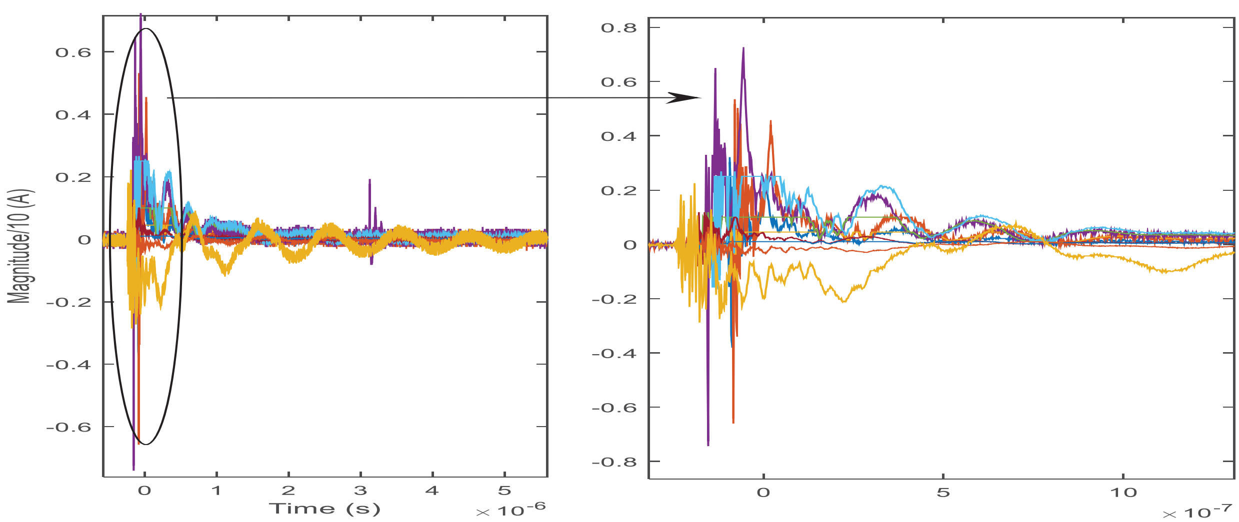

Fig. 5 Different currents injected at primary side.

IV. FREQUENCY RESPONSE ANALYSIS (FRA)

FRA is an effective tool in observing the core resonance when fault occurs at the HV side of the 50 kVA or less than 50 kVA transformer. As the resonating frequencies have low weight so they are not capable of affecting the core. Hence, their effect cannot incorporate as far the concern of developing a protection scheme model.

The obtained discrete data taken from the experiment performed is imported to MATLAB and then FFT algorithm is applied to inspect the behavior of a core in term of resonance of a core. Analysis was done on frequency bandwidth of 100 kHz and 1 MHz as in [7] [8] which discussed in section V.

Fig. 6 shows zone 1 has highest current injection at which core resonates on primary side of a transformer with frequency 1.05×10^6 where Z is 130 Ω. When the value of injecting current is decreased the impedance is increased and due to this frequencies increases, here at this point, frequency is 1.15×10^6 and Z is 441.9 Ω.

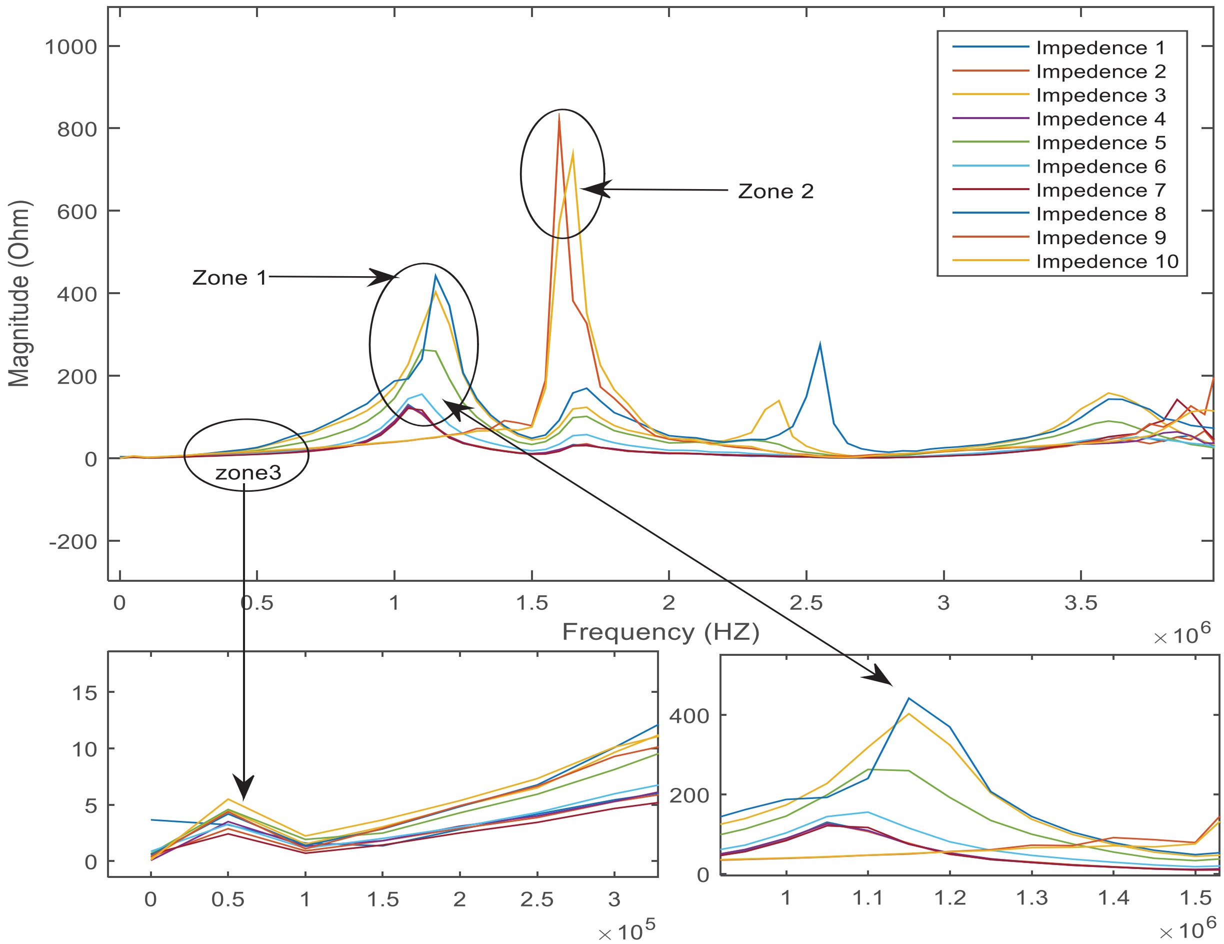

Fig. 6 Frequency vs magnitude response of transfer impedance

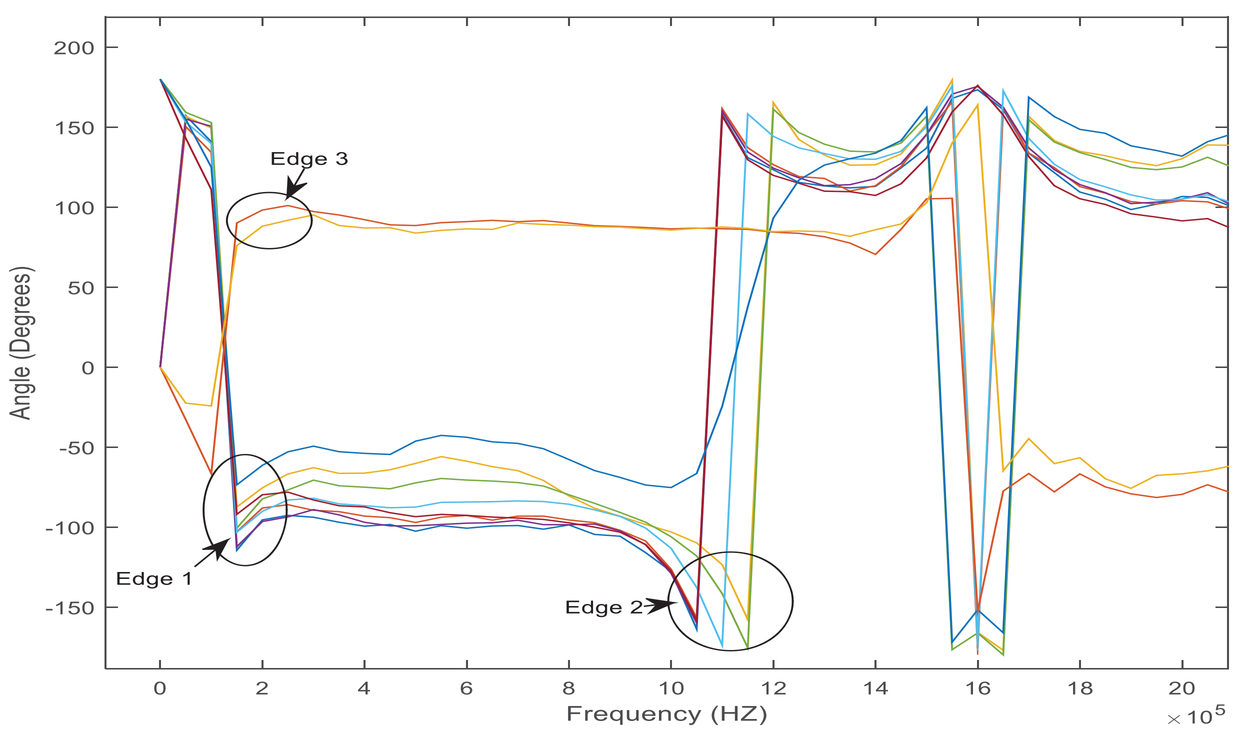

Fig.7 Frequency vs. Phase angle response of transfer impedance.

When the current is decreased at HV side in zone 2 at shown in *Fig. 6* then frequency response is slide towards dominating resonance frequency. At frequency of 1.65×10^6 Hz, the impedance value is increased to 736.7Ω.

On every value of injected current, there is a resonating frequency but due to low weight of frequency involvement, it has no effect on the core in zone 3 as shown in *Fig. 6*. The core of a transformer resonates when frequency reaches 1.277×10^5 Hz. At this frequency, the current response changed from capacitive to inductive. It is also observed that domination of high frequency is directly linked with the resonance of a transformer core. At the resonance frequency, the impedance and current have inverse relation, therefore in increase in impendence causes current to decrease and frequency to increase.

It is observed from FRA that only single core resonating frequency is dominating to affect the core of a transformer.

Three edges were considered for the analysis of a core resonance to study the relation between frequency and phase angle for different transfer impedances as shown in *Fig. 7*.

For the low resonating frequencies, the response of a core is shifting from inductive to capacitive as on edge 1. The resonating frequencies are considered negligible that have low weightage in term of magnitude. The response of dominating frequencies above 1 MHz have a changing behavior from capacitive to inductive and this resonance on edge 2 is actually responsible of increasing the aging of a transformer core.

On edge 3, the current is very low whereas the surge voltages and impedances are high, thus increases the dominating resonance frequency.

From phase angle response it is clear that 50-kVA transformers in a defined bandwidth has only single dominating resonance frequency.

V. HIGH FREQUENCY MODELLING

In this section, the proposed methodology is presented by testing on two transformer models of ratings 100 kVA and 30 kVA as shown in *Fig. 8*. Simulation is performed on MATLAB by proposing a modified model. The proposed model parameters is shown in Table I.

Firstly, a surge voltage of 450V 0.8µs/50µs is injected on HV side. From the value of V_1, I_1, V_2 and I_2 the behavior of transfer voltage in time domain and in frequency domain is find out by Fast Fourier Transform (FFT) algorithm. Secondly, a surge voltage is also injected on LV side and same procedure is repeated.

TABLE I
ELEMENTS OF A PROPOSED MODEL

Elements	Values	Elements	Values
C_1 (µF)	0.02103	L_2 (mH)	0.00856
C_2 (µF)	0.021063	L_3 (mH)	0.036897
C_3 (µF)	0.00512	L_4 (mH)	0.048296
C_4 (µF)	0.00022167	R_1 (Ω)	500
C_5 (µF)	0.0004221	$R_{\_switch}$ (Ω)	5e3
C_6 (µF)	0.00019152	R_3 (Ω)	1000
L_1 (mH)	0.00856	R_4 (Ω)	1e-6
		R_5 (Ω)	50

A. Single and Dual Resonance Testing

In *Fig. 8*, when the value of R switch is increase to a specific limit or higher, then the flow of current through the series branch is less; ultimatly parallel branch leads to the resonating effect and causes single resonance frequency.

Whearas, R switch is shifted towards low resistance then the series branch came into action and cause the signal to switch on dual frequencies. After certain bandwidth second resonace frequency starts to resonating the core.

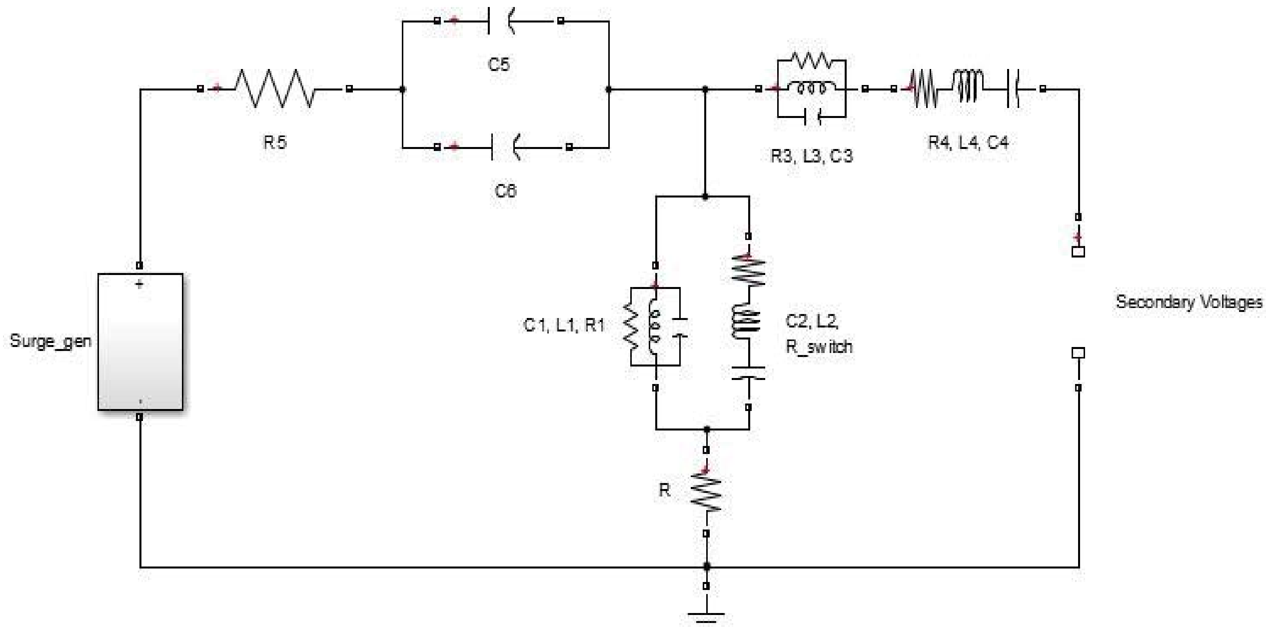

Fig. 8 Modified model for Single or Dual resonance frequencies.

B. Adjustments of Frequencies and Bandwidth

Frequencies can be adjusted by setting the values of L_1, L_2, C_1, and C_2. When decreasing the values of L_1 and L_2, the frequencies increases.

To set the bandwidth corresponding to the resonaces; increase the value of C_1 and C_2, it is observed that the narrowing in the bandwidth effect the location of frequencies; so optimizations are required to increase the capacitances and decrease the inductances.

According to the above model features, the proposed system provides flexibility that it could be a good possible option for a new transformer modeling by just single element variation to change the frequencies according to desired requirement.

C. Time and Frequency domain Response

Transient voltages flow from primary to secondary of transformer. In this section, effective secondary voltages (time and frequency domain) is taken into account under single and dual resonance frequencies.

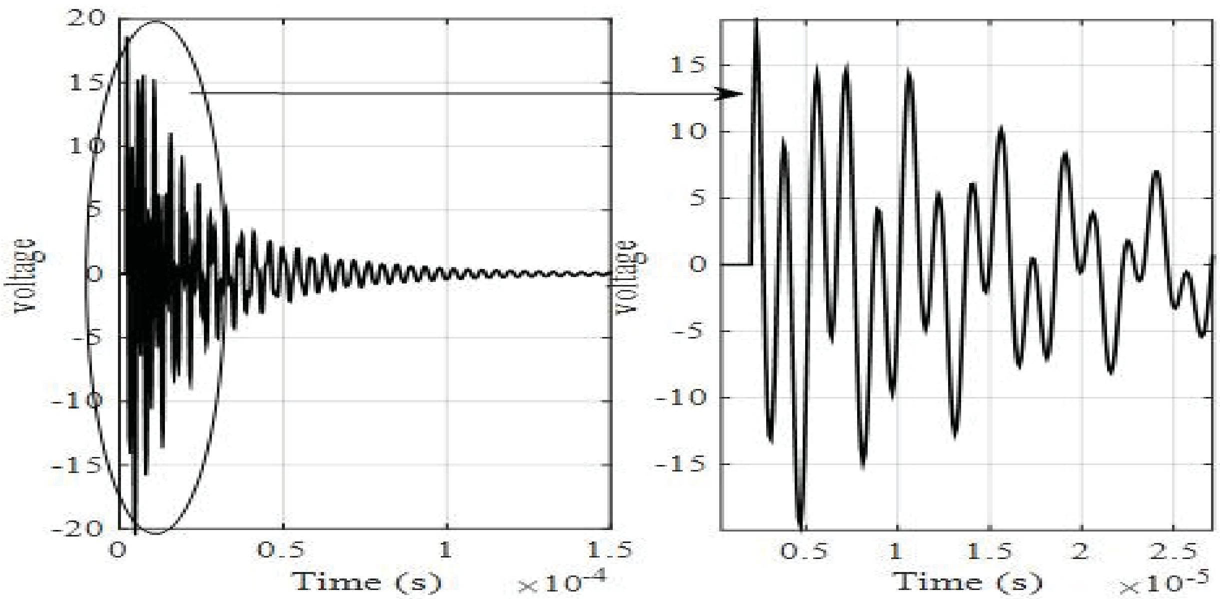

Fig. 9 Secondary voltage for dual resonance frequency.

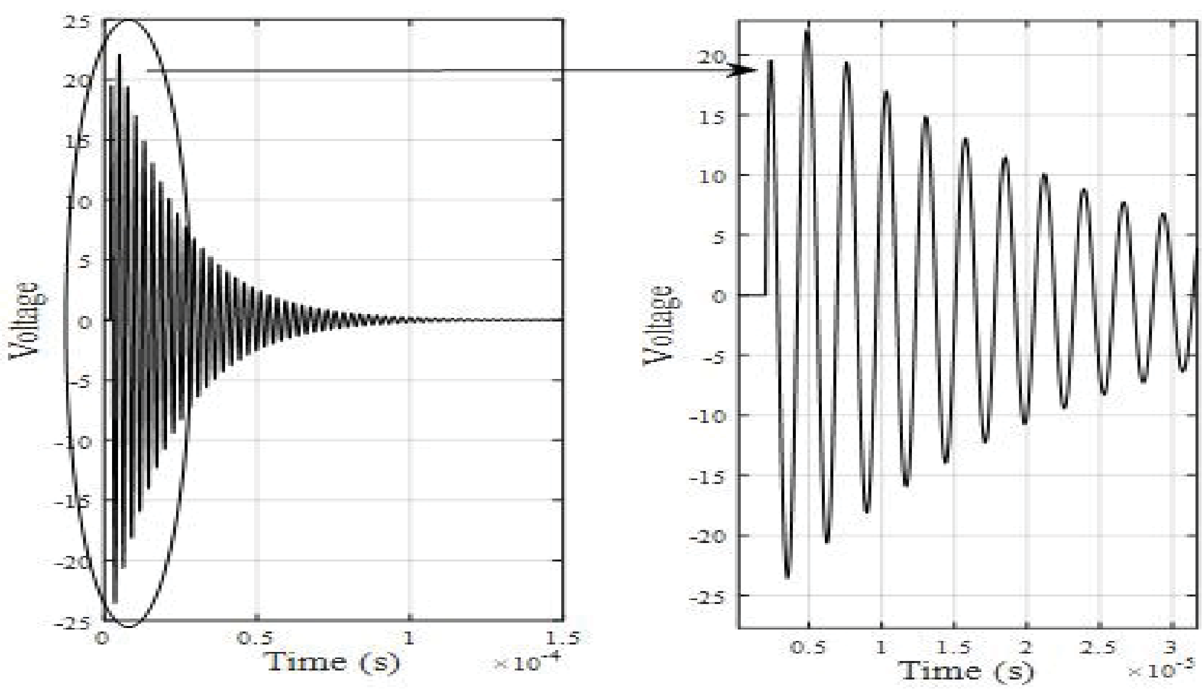

Fig. 10 Secondary voltage for single resonance frequency.

The study focuses on how the responses are closer to the response of model present in selected research articles [7-8]. Frequency domain analysis was carried out to check the weights of frequencies incorporation and the effective values of the frequencies which are actually affecting the core to resonate. For dual resonance, the time domain response of the transformer is shown in *Fig. 9.* If zoom in on this plot, it is very clear that the secondary transformer contains a dual frequency that resonates the core. These frequencies are similar to those arising as the frequencies occurring in the transfer impedances. The main observational goal is actually the number of times the core resonates and can be determined by the time response and transfer impedance. In *Fig. 10*, for a single resonance, the secondary voltage in the time domain is shown. A voltage of a certain value will tells that the transformer contains only a single frequency which causes the core to resonate at once and leads to the second behavior of the model if the transformers have different low ratings.

D. Transfer Function Method

In practice to find the behavior of transformer under surges in HV-LV and LV-HV, the transformer behavior can be verified by the angle of transfer function using FFT analysis. Equation 11 is used to find the both parameters of input and output.

$$G(s)=V_o / V_{in} \tag{11}$$

Fig. 11 presents the transfer function response which shows the degree to which the ratio of input to output is actually transferred to the secondary side. From the outset, it can be seen that the high inductive dominating ratio is on the secondary side and continuous to decrease. The magnitude of the transfer function decreases but the angle is equal to the angle of Z_{21}. It is a factor that indicates that the response of the core is the same, but magnitude of its voltage ratio decreases over time. When comparing *Fig. 11* and *Fig. 12* it can be seen that the both transfer functions are homogeneous to each other for dual resonance frequencies and the single resonance frequency, which satisfies the two network port theory in terms of the transfer function. The main emphasis in the proposed model presented in *Fig. 9* is to develop the impedance of the magnetizing side of the transformer for single and dual resonant frequencies.

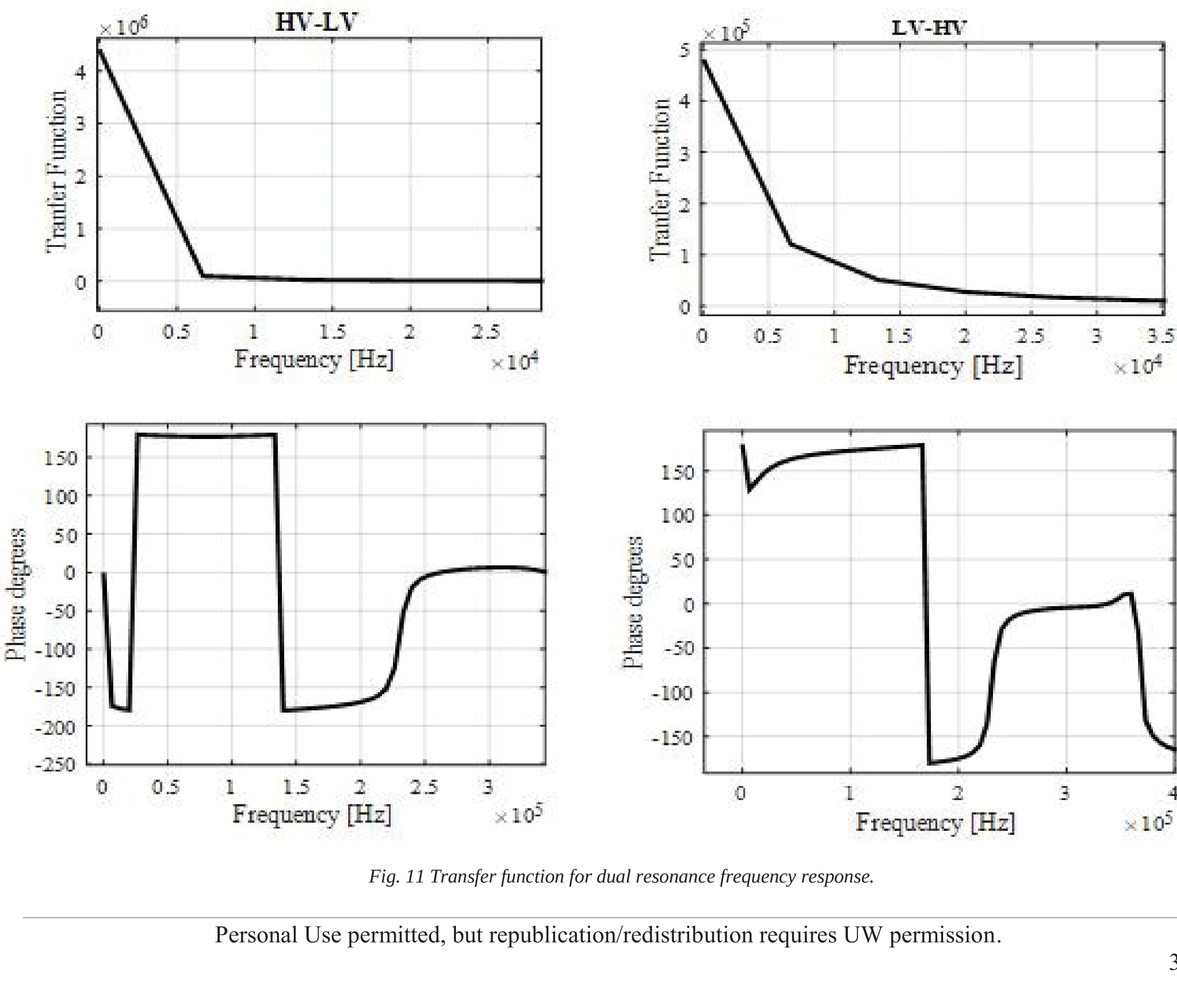

Fig. 11 Transfer function for dual resonance frequency response.

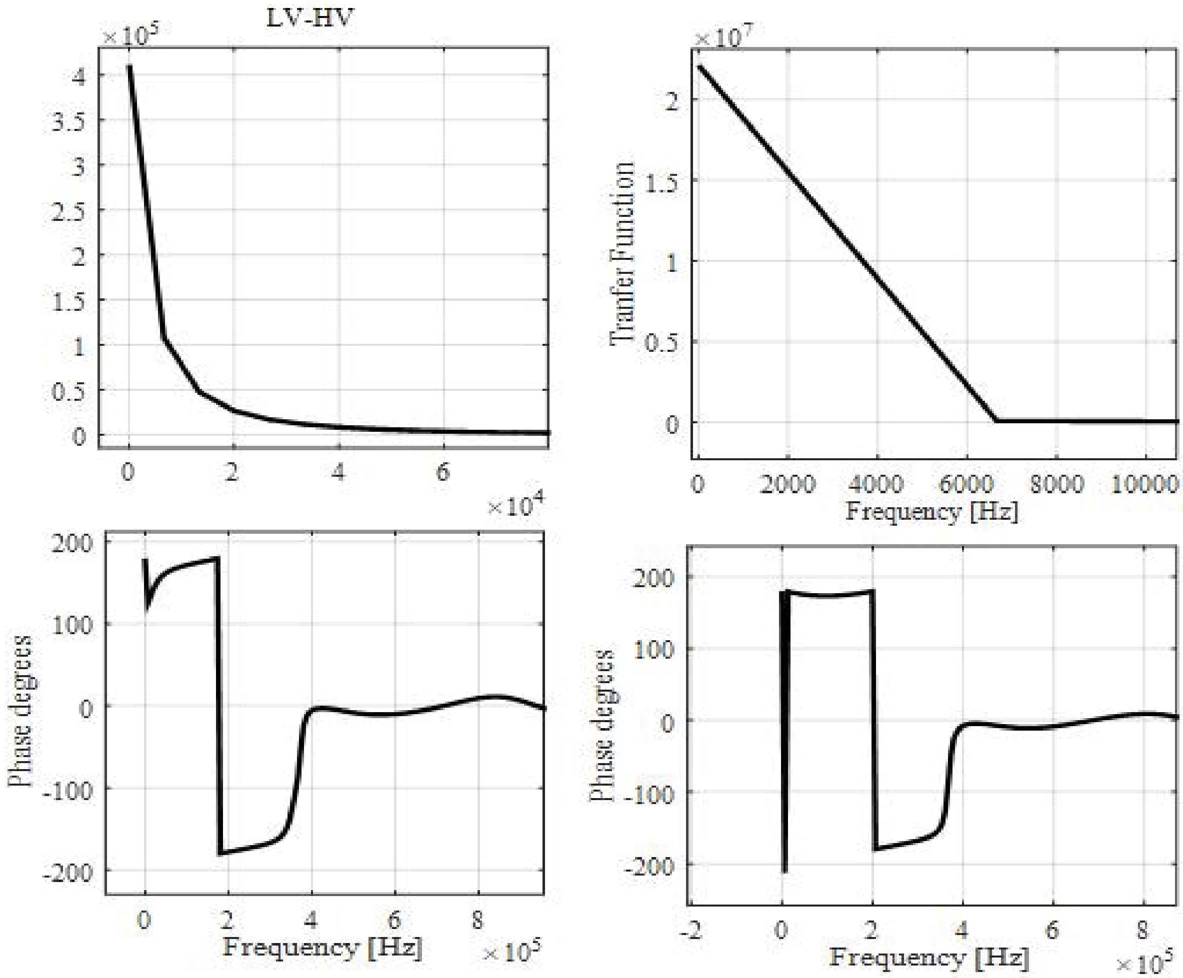

Fig. 12 Transfer functions for single resonance frequency response.

VI. Conclusion

The transformer models investigated were 30 kVA, 50 kVA and 100 kVA. The discussion of transformer model took into account that it was based on winding and was tested under no load condition. In this paper, a valid high-frequency model for unloading and loading for single and two resonant frequencies is presented. The proposed single model leads to other two models which can be verified by two port network theory, unloaded transfer under time domain and frequency domain analysis, transformer loading under different loads and transfer function method. Presented model is an option for any distribution transformer protection scheme, as it provides the flexibility to adjust resonance frequencies according to situation and need. In the experimental results, it was observed that the output cannot exceed two or more resonances. The model is capable to carry maximum dual resonance frequencies and also capable of carrying single resonance loading which is modification of the model presented in the recent literature.

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