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High Frequency Modeling of Transformer Using Black Box Frequency Response Analysis

Mubasher Hussain, Naeem Arbab, Adeel Khan

***Abstract*—**Lightning Surges consequently induce high frequency overvoltage to transformers. Therefore, it is alluring to study the transfer voltage of lightning surges from primary to secondary side of transformer. Keeping in mind the end goal to do lead this review, high frequency Siemens power transformer of rating 25KVA, 25KV/400V is to be examined. In this paper, an advanced and modified high frequency model of transformer is presented for protection of load against lightning transients. Suggested model is modified form of N.A Sabiha model and based on black box, two ports four terminal network theory. For No load condition, Transformer parameters are calculated on two resonance frequencies of 450 KHz &1 MHz using fast Fourier transform. Matlab/Simulink is used for simulation analysis. Both Time and frequency domain validate the accuracy. Resemblance between the measured and calculated results confirms the precision of proposed model when an impulse of 1.2/50µs is applied to transformer terminals.

***Index term*—**Power transformer, Black box analysis, Frequency response analysis, resonance frequency.

I. Introduction

Lightning surges shifted to consumer low voltage side through the interwinding capacitance of transformer. So, it is paramount importance to design the transformer to withstand the high voltages and high frequency stresses during lightning. Lightning impulse test devised to proof the high frequency behavior of transformer [1]- [3]. Different high frequency protected modelsform lightning are Proposed to study the transient behavior of transformers for both loaded [4]- [6] and unloaded conditions [7]- [10]. The high-frequency behavior can be model by different ways.

In mechanical way computing a lumped electrical system in the light of geometry, winding stresses during transients and material properties, yet requires mechanical detailed data like winding material, gap between windings, physical structure, material properties including dimension and core size, about the transformer [11]- [12]. Winding deformation can be calculated by FRA using finite element method. Conditional monitoring of large power transformer using SFRA is presented in [13]. Using frequency analyzer, the values for L, R and C were calculated for equivalent model of transformer. When inductance increases then disk deformation and local breakdown occur. Value of resistance is dependent on resonance frequency. The desirable mechanical data is hardly ever provided by the transformer manufacturer.

When detailed data and internal structure of transformer is not present, black box model is appropriate to acquire high frequency behavior of transformer [4]- [5], [9]- [10], [14]- [16]. In [17] M Heindl compares white box, gray box and black box model. In White box model complexity is high; bandwidth is low as compared to gray and black box. But it allows deeper system view. While gray box lies between white and black box model. In [18] artificial method is used for gray box analysis of transformer parameter calculations. The numbers of unknown parameter are reduced using both Weibull Distribution function and exponential function. In [19] capabilities of a black box model were analyzing to characterize the transformer at high frequency. Measured values and simulated values in EMTP-RV for transmitted over-voltages are compared.

Black Box model has several terminals and based on terminal measurements. While in [4] N.A Sabiha presented transformer model for dual resonance frequencies which is based on two ports four terminals network theory. Aforesaid model is modified form of [9] Piantini model, based on single resonance frequency. In aforesaid model resonance frequency is calculated by transfer function. The high frequency behavior of power transformer based on several resonance points in a wide frequency band is due to inductive and capacitive behavior of transformer [15]. Frequency band is divided into low, medium and high frequencies but these levels do not have distinct boundaries. The transformer equivalent T or Pi model is based on lumped parameters.

In [20] transfer of surges form primary to secondary side and effect of internal capacitance on winding skin effect of transformer were determines. In proposed model, the parameters were determined by frequency-characteristic measurement using an impedance analyzer. Hysteresis and saturation effect not discussed because CIGRE WG suggested that the hysteresis effect can be neglected in lightning surges. Similarly, Penetration of magnetic flux can be neglected at 1MHz frequency or for higher frequencies. In his model, various surges calculation is carried out by EMTP.

Mubasher Hussain: Research Scholar at University of Engineering and Technology, Peshawar, Pakistan. Email:mubasher_hussain921@yahoo.com Cell: 0092-3455606120.

Naeem Arbab: Professor at University of Engineering and Technology, Peshawar, Pakistan.

Adeel Khan: Research Scholar at University of Engineering and Technology, Peshawar, Pakistan. Email: adeel_khan182@yahoo.com Cell: 0092-.3347354535

In [7] PTM Vaessen proposed transformer model for high frequencies. The Proposed model was for no load condition and based on black box analysis. For value of inductance (L) the value for frequency ω will be minimum or nearly equal to zero and for the value of capacitance (C) the value of frequency ω is very high nearly equal to infinity. The value of L and C determined from imaginary part of Z(ĩω).

In [21] transformer winding parameters like R, L and C matrices were found using numerical method for lightning test. In [22] the transformer modeling is optimized using genetic algorithm and one of important application in fault detection is discussed. Some recent models of transformers have been developed in [23]- [26] to study the transferred surgeries and fault diagnostic techniques by using a program of transition electromagnetic called EMTP/ATP and Orcad-Pspice.

However, all these models need some sophistication. So, modified model of power transformer at two resonance frequencies is presented here.

II. Two Ports Network Theory

Two ports network theory is used to determine the Z-Parameters (impedances), Y-parameter (Admittance), H-parameters (Hybrid) and T-Parameters (Transmission). In this theory two ports have four terminals and Network is represented by black box. The driven source may be voltage or current. But here the driven source is impulse voltage. Based on connection of impedances, two ports network can be classified into T or π (Pi) network. Using open circuit test, we determine the different parameters of T-model transformer. The linear T-network equations are

$$Vp = Ip * Z11 + Is * Z12 (1)$$
$$Vs = Ip * Z21 + Is * Z22 (2)$$

When impulse is applied on primary side of transformer and secondary remain open then we find the following quantities.

$$Z_{11} = \frac{V_p}{I_p} |\ I_s = 0,$$
$$Z_{21} = \frac{V_s}{I_p} |\ I_s = 0$$

Similarly, when impulse is applied on secondary and primary remain open then we obtain

$$Z_{12} = \frac{V_p}{I_s} |\ I_p = 0\ ,$$
$$Z_{22} = \frac{V_s}{I_s}\ |\ I_p = 0$$

III. Experimental Setup

The experiment was executed in High Voltage Lab ESEIAAT_TRI of Universitat Politècnica de Catalunya (UPC)-Technological University of Catalonia, Barcelona Spain. The rating of test transformer was 25KVA, 25KV/400V DYn5 (Delta start connected with earth neutral).

Fig1. Experimental setup for transformer testing

Impulse of 4KV applied to primary side of transformer while secondary side remained open and find out the primary current (Ip), primary voltage (Vp) and secondary voltage (Vs) as shown in Fig2. Fours channel oscilloscope was used for captures the wave foams and save their data in time domain.

After taking the values of Vp, Ip, and Vs, convert these wave foams into discrete values. Then find out the transfer function

$$T(s) = Vout/Vin$$

From this T(S), find the two resonance frequencies. The resonance frequencies are at 450 KHz and 1 MHz. For these resonance$Z11$shows capacitive behavior.

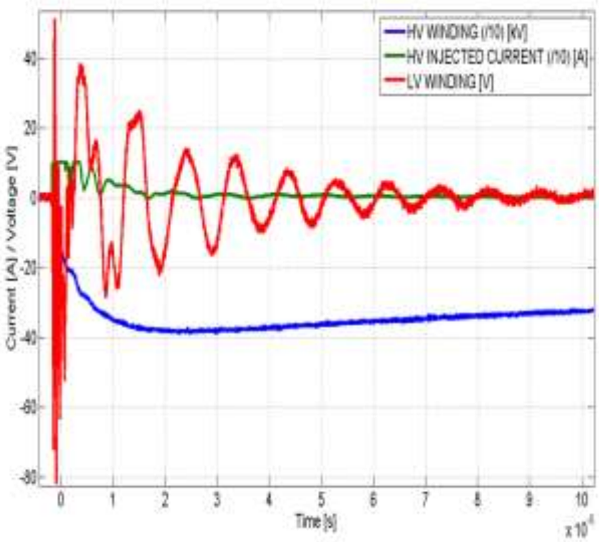

Fig2. Impulse Voltage on HV side, Impulse current On HV Side, and Secondary voltage.

Similarly, when impulse applied on secondary side of test transformer and primary side was kept open circuit then calculate the value of Vs, Is, and Vp as shown in figure 3.

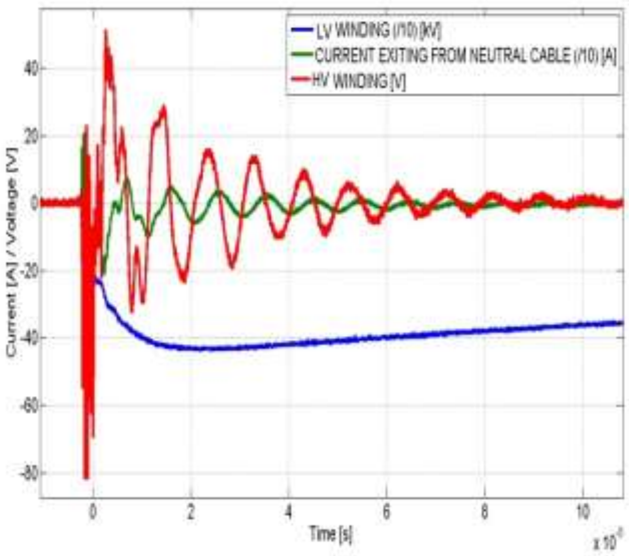

Fig3. Impulse Voltage on LV side, Impulse current on LV side, and Primary voltage

When impulse applied on secondary, transfer function for secondary side was calculated. T(S) verifies that Z12 and Z21 both resonate on same frequency as shown in fig 4. From this T(S), find the two resonance frequencies for which $Z21$ have inductive behavior.

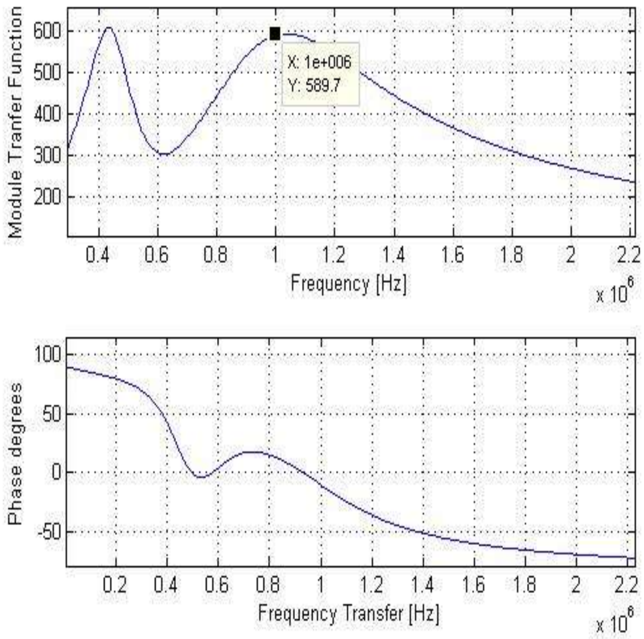

Fig 4: Transfer Function for Z12 and Z21

Apply the Fast Fourier transform to the discrete data of these currents and voltages wave foams and using transfer function method find out the values of parameters. Amplitude of Z11 and phase angle is given in figure 5.

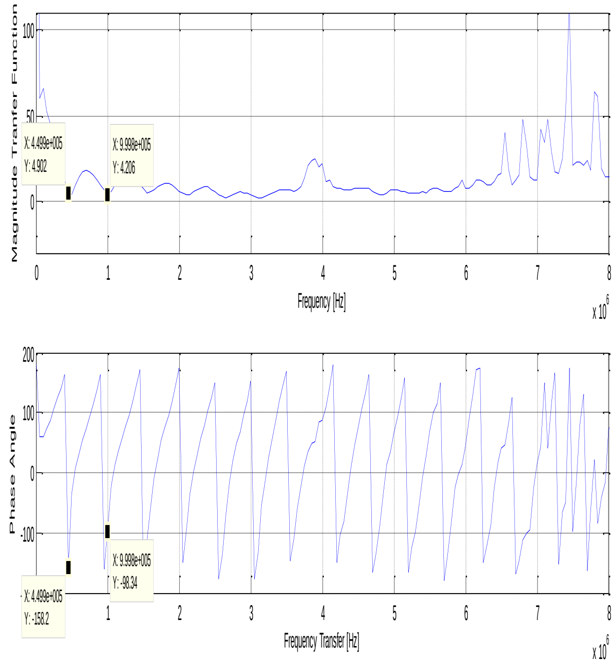

Fig 5: Magnitude and Phase angle for Z11

Negative value of the imaginary part of Z11-Z12 shows capacitive behavior of the transformer.

Similarly, the value of Z12 is shown in figure 6.

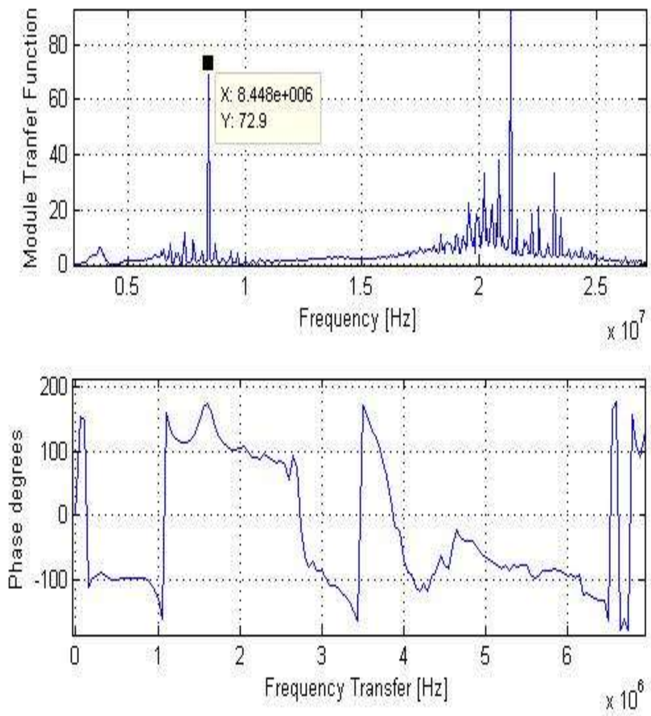

Fig6: Magnitude and Phase angle of Z12

The value of Z22 is shown in figure 7.

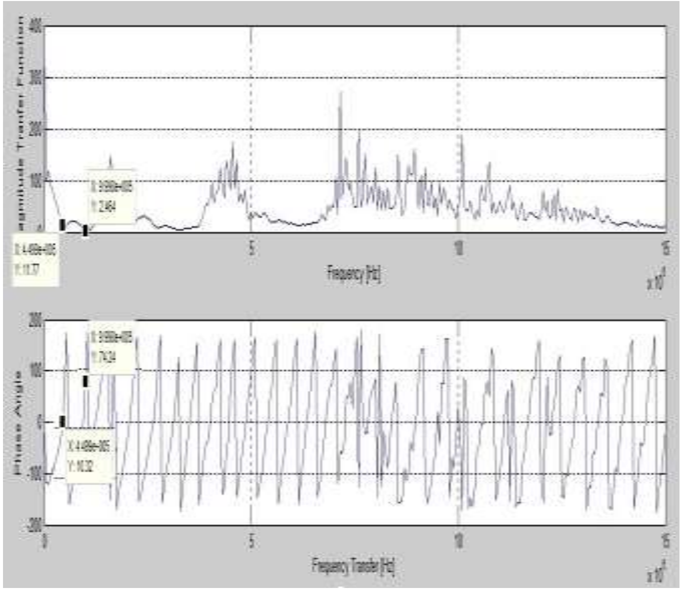

Fig7: Magnitude and Phase angle for Z22

Positive value of Z22-Z21 shows the inductive behavior of secondary side of transformer.

The value of Z21 is shown in figure 8.

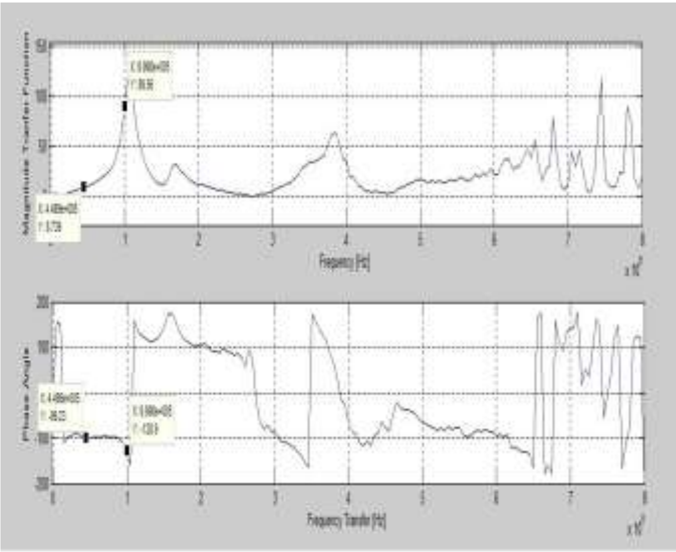

Fig8: Magnitude and Phase angle for Z21

From the impedances equations at resonance frequency calculate the values of R, L and C using the resonance equations.

TABLE I. THE VALUES OF PARAMETER OF PROPOSED TRANSFORMER

Elements	Values
R1	3.013 Ω
C1	0.20657315e-7
R2	0.624 Ω
L2	3.70244e-9H
R3	558.5405 Ω
L3	0.058967e-3H
C3	0.00043e-6F
R4	500 Ω
L4	0.067305e-3H
C4	0.001859e-6F
R5	12.54 Ω
L5	0.3748e-5H
R6	53.213 Ω
L6	1.123656e-5H

IV. PROPOSED MODEL

The proposed T- Model of the power transformer is shown in figure 9.

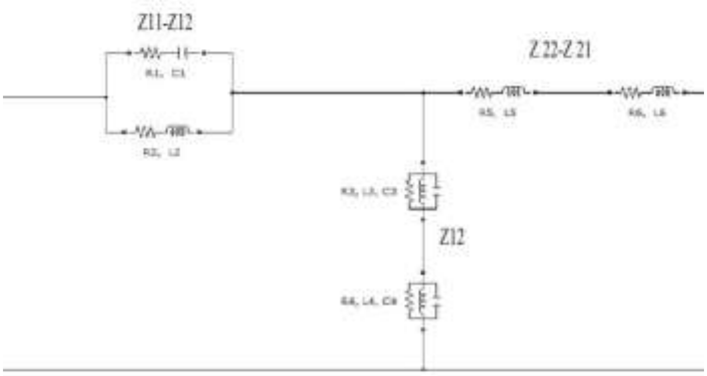

Fig9. Proposed T-Model for Transformer

The secondary transfer voltage of the propped model for unloaded condition with impulse is

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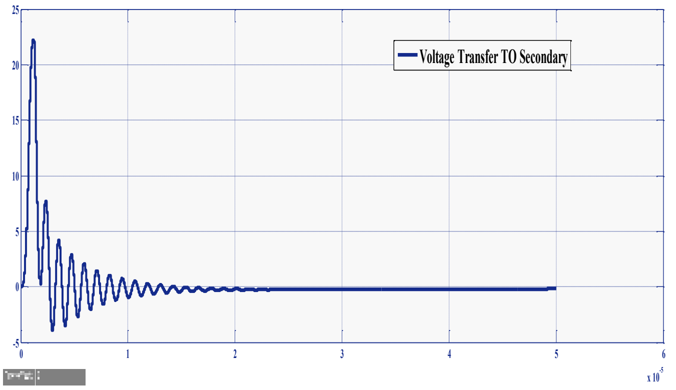

Fig10. Transfer voltage from primary to secondary side

CONCLUSION

The modified model for transformer load protection from lightning surges of specific frequency is tested at 4KHz and 1 MHz.The resonance frequency for both Z12 and Z21 is same which validate the proposed model. Therefore, it can be very easily realized that the transformer model for protection of load from transients or lightening signal is very efficient. The proposed technique can be used for online conditional monitoring of transformer in future.

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Engr. Mubasher Hussain is a post-graduate research scholar in Department of Electrical Engineering, University of Engineering and Technology Peshawar, Pakistan. He received his BS degree from COMSATS Institute of Information Technology Abbottabad in 2012. His research area includes operation of power system and transformers. Mubasher_hussain921@yahoo.com

Engr. Muhammad Adeel Khan is a post-graduate research scholar in Department of Electrical Engineering, University of Engineering and Technology Peshawar, Pakistan. He received his BS degree from COMSATS Institute of Information Technology Abbottabad in 2012. His research area includes Power system reliability and power system protection. adeel_khan18a@yahoo.com 0092-3347354535