PhD Thesis

High Frequency Modeling of Power Transformers under Transients

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Thesis Title

High Frequency Modeling of Power Transformers under Transients

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Declaration

I, Kashif Imdad, hereby declare that this Thesis neither as a whole nor as a part thereof has been copied out from any source. It is further declared that I have developed this thesis and the accompanied report entirely on the basis of our personal efforts made under the sincere guidance of my supervisor. No portion of the work presented in this report has been submitted in the support of any other degree or qualification of this University, if found we shall stand responsible.

Signature:______________

Name: Kashif Imdad

Acknowledgement

First of all, I would like to raise unlimited thanks to God, the Most Gracious, the Most Merciful, Who said in His Holy Quran:“It is He who shows you lightning, as a fear and as a hope (for those who wait for rain). And it is He who brings up (or create) the clouds, heavy (with water) (12). And the thunder glorifies and praises Him, and so do the angles because of His awe. He sends thunderbolts, and therewith He strikes whom He wills, yet they (disbelievers) dispute about Allah. And He is mightily in strength and severe in punishment (13).” Translation of the meanings of Surah Ar-R´ad (The thunder).

It is honor for me to acknowledge supervisor Joan Montanya for his great encouragement and motivational help to complete this research. I acknowledge Universidad Politécnica de Cataluña for providing me such a great platform for this research work.

Abstract

This thesis presents the results related to high frequency modeling of power transformers. First, a 25kVA distribution transformer under lightning surges is tested in the laboratory and its high frequency model is proposed. The transfer function method is used to estimate its parameters. In the second part, an advanced high frequency model of a distribution transformer is introduced. In this research, the dual resonant frequency distribution transformer model introduced by Sabiha and the single resonant frequency distribution transformer model under lightning proposed by Piantini at unloaded conditions are investigated and a modified model is proposed that is capable to work on both, single and dual resonant frequencies. The simulated results of the model are validated with the results of Sabiha and Piantini that have been taken as reference. Simulations have shown that the results of the modified model, such as secondary effective transfer voltages, transferred impedances and transformer loading agree well with the previous models in both, the time and frequency domains.

The achieved experimental and simulated objectives of this research are:

- Methodology for determining the parameters of a power transformer.
- High frequency modeling of a transformer in order to simulate its transient behavior under surges.
- Modification of high frequency model for single and dual resonance frequency.

The originality and methodology of this research are:

- High frequency transformer model is derived by means of the transfer function method. In the literature, the transfer function method has been used in many

applications such as the determination of the mechanical deformations or insulation failure of interturn windings of transformers. In this thesis, the parameters of the proposed model are estimated using the transfer function method.

- Modification of high frequency model for single/dual resonance frequency using the transfer function method. The transfer function can also be used to determine the state of the transformer. The modification in the developed model using the proposed technique has been validated (by simulations).

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LIST OF ABBREVIATIONS

LV	Low Voltage
HV	High voltage
Z11	Primary impedance
Z22	Secondary impedance
Z12	Transfer impedance from primary to secondary
Z21	Transfer Impudence from secondary to primary
I1	Primary current
I2	Secondary current
I12	Transfer current from primary to secondary
Vo	Output voltage
Vs	Surge voltage
L	Inductance
R	Resistance
C	Capacitance
HV-LV	High voltage to low voltage
LV-HV	Low voltage to High voltage
kV	kilo volts

Chapter ONE

GOALS AND OUTLINE

A transformer is a fundamental element of any electric power system. When under voltage, over voltage or lightning situations occur, it is known that the transformer's transformation ratio might experience unsystematic short-duration, deviating voltage transients, i.e. the rate of re-striking voltage depends on the magnitude of the transient voltage. Therefore, the common overvoltage protection is based on surge arrestors. But, in order to accurately design the protection to customers as well as the transformer itself, a high frequency model of the transformer is required.

To obtain the high frequency model, the transformer performance was analyzed in two ways, i.e. with normal (nominal voltage) and abnormal (surge voltage). The purpose of these tests was to estimate the transfer surges and behavior of a transformer under transients and under normal conditions. The complete analysis of a transformer in both of these conditions is described in chapter 3.

To understand the aforementioned problem of surges under transients, the proposed model is developed. Works in the literature related to high frequency models are based on three categories: 1- Black box modeling of transformers

2- Single resonance frequency modeling for transformer loading and unloaded condition analysis

3- Dual resonance frequency modeling for transformer loading.

In the literature, several methods for the estimation of the transformer parameters have been discussed but the transfer function method is only used for mechanical deformation or in turn fault analysis. In this research, for the first time, the transfer function method is used for the calculation of transformer parameter using the FFT.

1.1 Objectives

This thesis is focused on the high frequency modeling of power transformers and the use of the developed models to perform different types of analysis (described in the literature), distribution of voltages in the transformer windings under the presence of a surge voltage (lighting type impulse), and frequency response of the transformer under Frequency Response Analysis (FRA). Normally, a transformer under the influence of transients experiences uneven distribution of voltages. Since, for example, the distribution of the per-turn voltage fluctuates under transients, there are more chances of inter turn faults and, to monitor such faults, frequency response analysis is used.

In the same line, the transfer function method has been tested. This method consists of measuring the leakage current to ground during a transient voltage applied to the transformer, usually the connection of the machine to the grid. Since this transient produces a wide range of voltage frequencies, a transfer function can be obtained between voltage and current to ground. The study of this function (described in section 3-4.1) and its variation yields useful results to detect transient faults. The designed models are also validated by obtaining the same (in the proposed scheme of transformer parameter estimation) transfer function.

The following specific objectives are presented in this thesis:

1. Review of the 'State of the Art': study of the previously designed models and the applications given to them by other researchers.

2. Analysis of the limitations of the above models and selection of the one considered more suitable.

3. Implementation of the proposed model to the reference machines available at the UPC Electrical Engineering Laboratory.

4. Study of the transfer function method.

5. Experimental application of the transfer function method to a transformer.

6. Analysis of the results.

7. Debugging and improvement of the model.

8. Experimental verification of the development model or models.

9. Practical study in HV laboratory: analysis of lighting-type impulses and validation with the models.

10. Experimental verification of the transfer function method.

1.2. Phases of the thesis

The following steps are used to develop the high-frequency transformer model and the relation of each step and chapters is explained below.

Chapter two: In the second chapter the review of the literature studies is carried out, most of the research articles are presented in theses describing their novel idea on high frequency model development. The common problem found in the literature is that the proposed models are only designed on real time values (only for specific transformers on which they were tested) and they can only be valid for specific range of surges and for specific a transformer rating.

Chapter three: In this chapter, the surge generator with specific raise and fall time is developed and its response is described. The transformer behavior in the presence of surges is presented. The methodology of transformer parameters estimation and modeling are presented from experimental tests.

Chapter four: In this chapter, the transformer analysis under surges is described and in the same line, a transformer model is proposed that is designed using the transfer function method, its equivalent circuit/model is tested for magnetization impedance analysis and it is shown to be correct.

Chapter Five: In this chapter, a high frequency transformer model is proposed that is tested for single and dual resonance frequencies under transformer loading conditions. A complete comparison with a reference high-frequency model is presented and validated in all modes of operation, i.e., loaded, unloaded, etc. The mathematical expression of the transfer voltage is obtained from both sides, i.e., HV-LV and LV-HV.

Chapter TWO

BACKGROUND

In this chapter, a review of the literature related to high frequency modeling of transformers is discussed. There are three categories of transformer modeling: black box analysis, two resonance frequency and single resonance frequency analysis.

2.1 Previous Studies

To examine the high frequency behavior of a transformer, there are numerous techniques used to find out its characteristics. The RLC values can be examined by utilizing an impedance analyzer to determine the electromagnetic transient effects [1] [2]. The RLC values are also obtained by analytical and mathematical calculations of shell category power transformers by means of the finite element method (FEM) in [3]. A model of a distribution transformer represented by lumped parameters subjected to lightning stroke currents is explained in [4]. To determine the elements of a wideband transformer, the scattering matrix theory is used [5]. In [6] [7], frequency domain analysis of a transformer is performed to evaluate the results. Another method to estimate the transformer's parameters focuses on internal formation of the transformer, i.e. self and mutual inductances, windings resistance and effect of electromagnetic (the electromagnetic effect analysis needs to examine the eddy currents for the short-circuit case and hysteresis current for the open-circuit analysis using a finite element analysis tool) and are discussed in [8]-[14].A transformer model of distributed and lumped parameters with tolerable results under transients is presented in [15]-[23]. The finite element method (FEM) has been applied to find the parameters for electromagnetic analyses [24]-[25].

The review of the literature is not enough to determine the characteristics of distribution transformers as most of the results are obtained from the real time data of experiments on a particular test transformer.

The transformer behavior analysis using black box analysis for modeling of single resonance frequency was presented in [26]. The proposed model was valid for unloaded conditions. A modified model with two resonance frequencies was proposed [27],[28] that was valid both, for transformer.

Lightning surges shift towards the low voltage side through the inter winding capacitance of transformer. So, it is of supreme importance to design a transformer that copes with high frequency stresses and voltages during lightning. The high frequency behavior of transformers has been validated by lightning impulses tests as reported in [35]-[36]-[37]. Different high frequency protected models from lightning are proposed to study the transient behavior of transformers for both loaded [27]-[28]-[38] and unloaded conditions [39]-[40]. The high-frequency behavior can be modeled indifferent ways.

In mechanical way (in term of computing its deformation) computing a lumped electrical system in light of geometry, winding stresses during transients and material properties about the transformer [41]. Winding deformation can be calculated by FRA (frequency response analysis) using the finite element method. In [42], the conditional monitoring of large power transformers using SFRA (sweep frequency response analysis) is presented. Using a frequency analyzer, the values of L, R and C were calculated for the equivalent model of a transformer. When inductance increases, disk deformation and local breakdown occur while the value of the resistance is dependent on the resonance frequency. The desirable mechanical data are hardly ever provided by the transformer manufacturer. When the structural detail data of the transformer are not present, the black box model is appropriate to acquire the high frequency behavior of the transformer [39, 40, 43-45]. In [46]. Heindl compares the white, gray and black box models. In the white box model, the complexity is higher with lower bandwidth as compared to the gray and black box models but it allows a deeper system view. While the black box lies between white and gray box model. In [47], the artificial method is used for the gray box analysis of transformer parameter calculations. The number of unknown parameters is reduced using both, the Weibull distribution function and the exponential function. In [48], the capabilities of the black box model were analyzed to depict a transformer at high frequency. Measured and simulated values in EMTP-RV for transmitted over-voltages were compared.

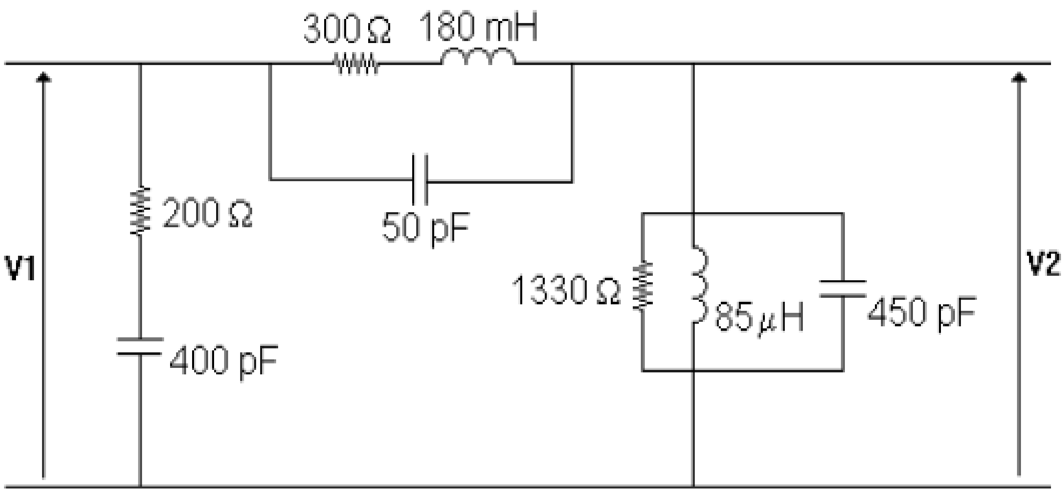
The black box model has several terminals, based upon terminal measurements based on experimental values. N.A Sabiha [28] presented a transformer model for dual resonance frequencies which is based on the two-port four-terminals network theory. The aforementioned model is a modified form of the Piantini model, based on a single resonance frequency. In the model, the resonance frequency is calculated by way of the transfer function. The high frequency behavior of power transformers based on several resonance points in a wide frequency band is due to the inductive and capacitive behavior of the transformer. The transformer equivalent T or Pi model is based on lumped parameters. Vaessen [39]proposed a high frequency transformer model for no load condition and based on the black box analysis. For inductance (L) determination value for frequency will be nearly approaches to zero as the inductance reflects the current, similarly the current is directly proportional to frequency and for the capacitance (C), the value of the frequency is very high, nearly equal to infinity. The value of L and C are determined from the imaginary part of Z (iω). The transfer of surges from the primary to the secondary side, the effect of internal capacitance on the winding and the skin effect of the transformer were determined. In the proposed model, the parameters were determined by frequency characteristic measurements through an impedance analyzer. The hysteresis and saturation effects are not discussed because the CIGRE WG standard suggested that the hysteresis effect and penetration of magnetic flux for 1 MHz or higher frequencies can be neglected in lighting surges. In [49], the transformer winding parameters like R, L and C matrices were found using numerical methods for lightning tests. In [31], the transformer modeling is optimized using genetic algorithms and an important application in fault detection is discussed. Recent transformer models have been developed in [50]-[52] to discuss the transferred lightning surges and fault diagnostic techniques by using a program of transition electromagnetic called EMTP/ATP and Orcad-Pspice.

2.1.1 One resonant frequency model

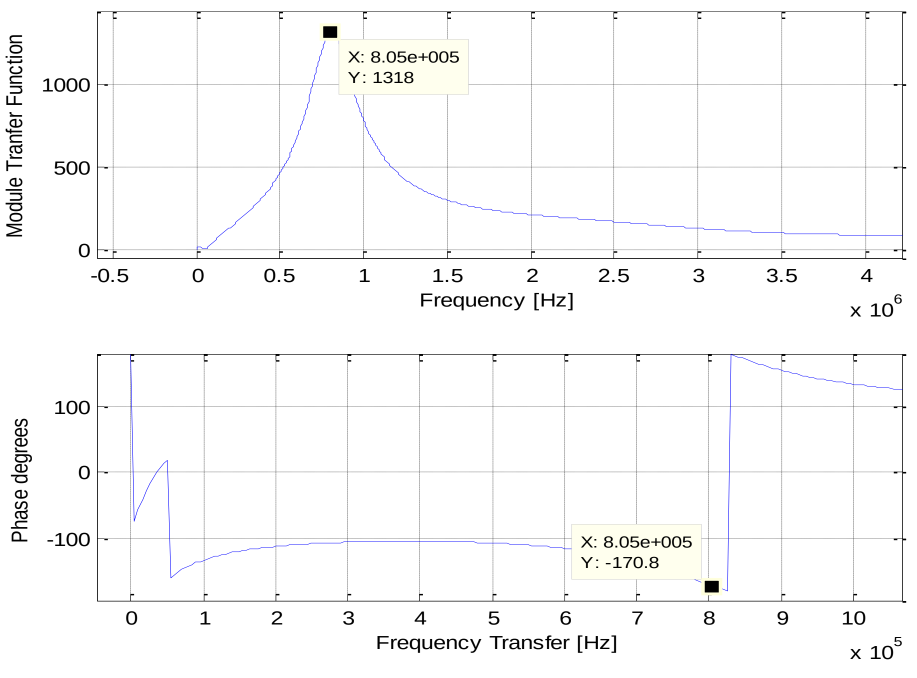
In Brazil, Professor Alexandre Piantini tested a distribution transformer having rating parameters of 30 kVA, 13.8 kV - 220/127 V. He proposed a model which validates the experimental results against theoretical results using a single resonance frequency [26].

On the basis of his experimental setup, he concluded that at high frequencies, the transformer's primary input behavior will be capacitive and the secondary will be inductive.

The model is very simple and it overcomes the problem of representing the transient response by using the black box analysis. The model given in figure 2-1(a) below is not valid for transformer loading. If the transformer has a full or partial load, the transformer model fails to scan the transients at particular resonance frequencies. In figure 2-1 (b) &(c) the (unloading and loading) impedance parameters are estimated using the proposed scheme presented in [26].



(a)



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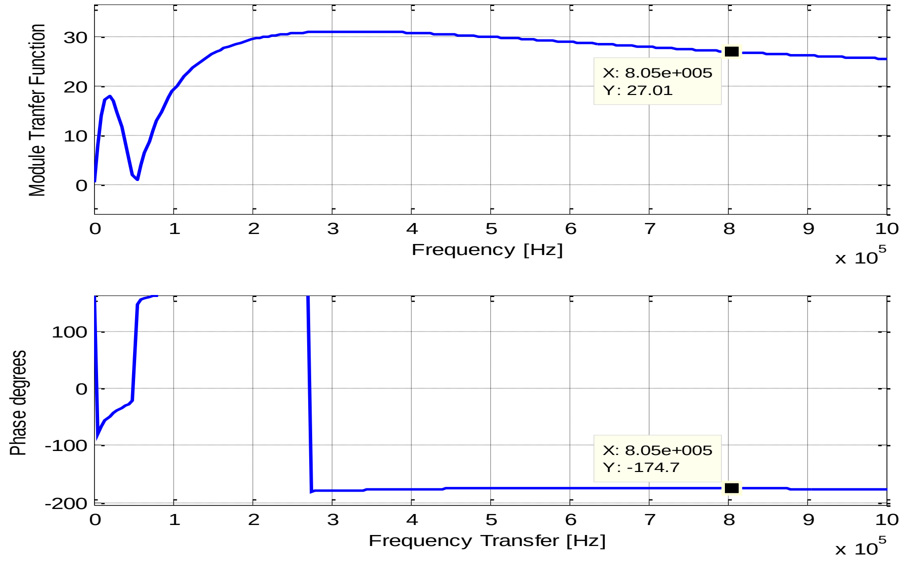


(c)

Figure 2-1(a) Single resonance frequency model [26], (b) Single resonance frequency magnitude and phase angle under unloading condition, (c) Single resonance frequency magnitude and phase angle under resistive load condition

2.1.2. Two resonant frequency model

In 2010, Nehmdoh, Sabiha and Lehtonen [28] studied the voltage transferred to the secondary terminal of a transformer due to a lightning current on the primary terminals. A high frequency model with two resonance frequencies was proposed by the researchers. The proposed model is based on two-port network theory. The parameters are calculated on two resonance frequencies. The designed model is suitable for both, loaded and unloaded conditions [27], [28]. Nehmdoh, Sabiha and Lehtonen modified Piantini's model and did the experimental verification of a distribution transformer under transients.

The verification of the model was based on the transferred effective secondary voltage by experimental results and simulated results. The model is capable for representing conditions of loading and unloading as well.

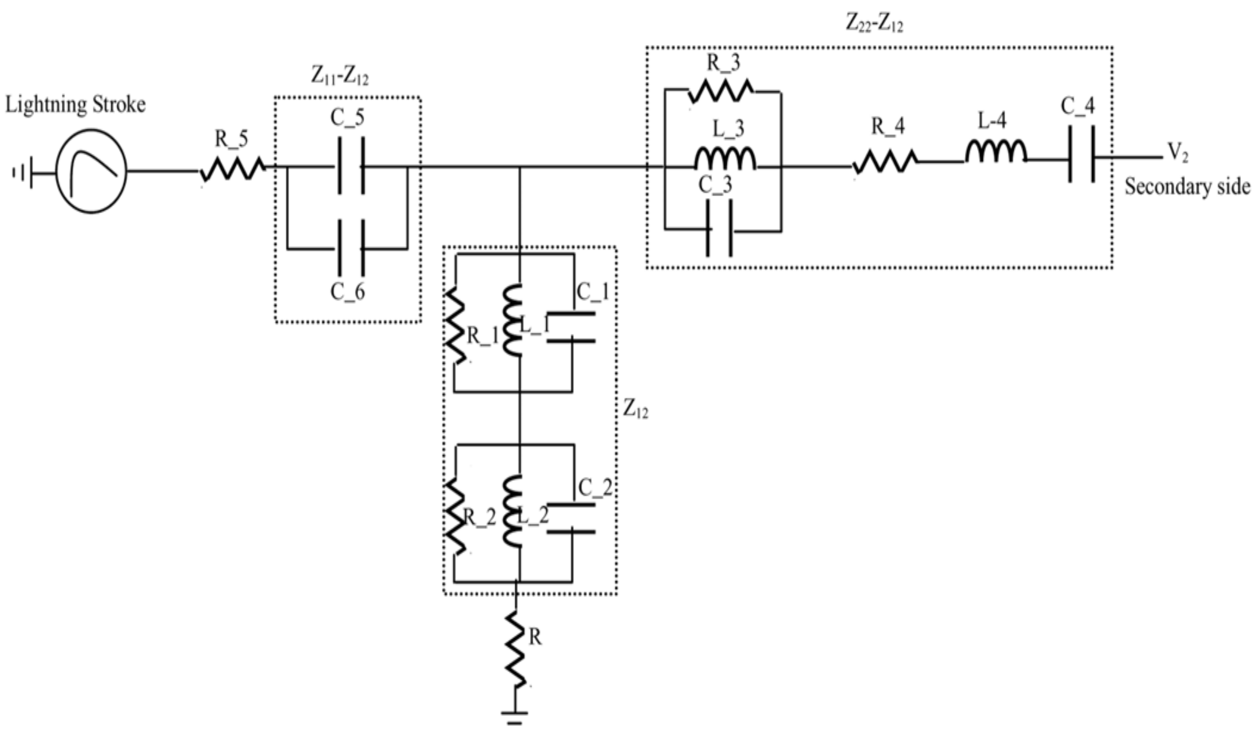


Figure 2-2 Two resonance frequency model proposed in [28]

2.1.3 Modeling Based On Black Box Analysis

In 2014, Carobbi and Bonci [29]derived values of parameters for an equivalent circuit of a surge generator in order to make the open circuit voltage and short circuit current according to the standard wave requirements in terms of peak amplitude, front time and duration [29].The time domain values of voltage and current are relatively close, indicating that the transformer parameters are fluctuating between the inductive and capacitive domains. These kinds of models are not suited for a broader frequency band analysis, i.e., most of the models are designed at 10 kHz frequencies.

In 2013, Carobbi [30]derived analytical expressions to find the measurement errors of parameters of the standard unidirectional impulse waveforms caused by distortion due to limited bandwidth of the measuring system [30]. The results obtained are very useful to correct errors and uncertainties of unidirectional impulse generators. In [31], analytical results are verified by means of numerical simulations.

In 2013, Bigdeli [31] presented the optimized modeling of a transformer in transient state with the use of genetic algorithms in order to estimate the transformer parameters. He proposed a model for transient analysis of transformers. His proposed model is capable of representing the impedance or admittance characteristics of the transformer measured from the terminals under different connections up to approximately 200 kHz. The estimation of the model parameters was obtained using genetic algorithms. The comparison between calculated and measured quantities confirms that the accuracy of the proposed method in the middle transient (the point where the first resonance reflects to resistive means that here is also the phase angle approaches to zero i.e. Xl=Xc) frequency domain is satisfactory. He also discusses the application of one of its proposed models in fault detection [31]. Genetic algorithms have demonstrated to be a very fast technique to approach the solution.

The frequency response of a power transformer by means of the impulse response method can be identified. The impulse response method requires a short evaluating time period. In the impulse frequency response, an impulse voltage that has enough frequency components is applied to the transformer and the resulting response voltages and/or currents are measured together [32].

An algorithm is established for FFT analysis of transfer functions which is valid for surge or transient analysis only. This algorithm is very useful for transformer parameter estimations under transients.

Lightning overvoltages propagating along transmission lines and entering substations are transferred from the high-voltage (HV) winding of the power transformer to the low-voltage (LV) winding and vice-versa by inductive and capacitive coupling. The capacitive effect depends upon the overvoltage and the inductive effect depends upon overcurrents flowing due to lightning currents [33].

In 2014 Paulraj, HariKishanSurjith and DhanaSekaran [34] used the Transfer Function Method (TFM) and Frequency Response Analysis method (FRA) to locate the fault in a transformer's winding [34]. The authors verified experimentally their results. The foremost fault that occurs in a transformer is the inter-turn short circuit fault through the winding. The authors showed the usefulness of the transfer function method and frequency response analysis method to detect partial breakdown between the windings, breakdown and mechanical displacement. [34]. The existing methods of transformer deformation analysis only use the transfer function method to compare the figure print of the reference transformer with the results of the transformer under examination.

Chapter THREE

METHODOLOGY OF MODELING

In the first part of this chapter a MATLAB®/Simulink surge generator is designed. In the second part, an experimental procedure is described and it is applied for the analysis of transfer surge overvoltages on the HV-LV & LV-HV lines of a transformer. The purpose of the surge generator design is to determine the impulse response of the transformer. Under transients, a transformer experiences a steady state condition for very short intervals of time in which transients can travel from the high voltage side to the low voltage side towards costumers loads. This surge generator is used for impulse response analysis of transformers, and their high frequency modeling under transients. The experimental procedure is carried out based on two-port network theory to determine the transformer parameters for its modeling.

3.1 Why is a surge generator required?

Researchers and engineers use standards (e.g. IEC) for the representation of surges. A standard lightning impulse has a waveform with a rise time of 1.2µs and a fall time of 50µs[60060-1].Its magnitude depends on the test or analysis, e.g. transformer rating. In this thesis, it is required to design an impulse generator which fulfills the above criteria.

3.2 Surge generator model

A surge generator is implemented in MATLAB®/Simulink. The model is shown in figure3-1. The output of the generator provides the lightning impulse waveform defined in most of the standards, shown in figure. 3-2. This surge generator is compared with Sabiha's surge generator [28].

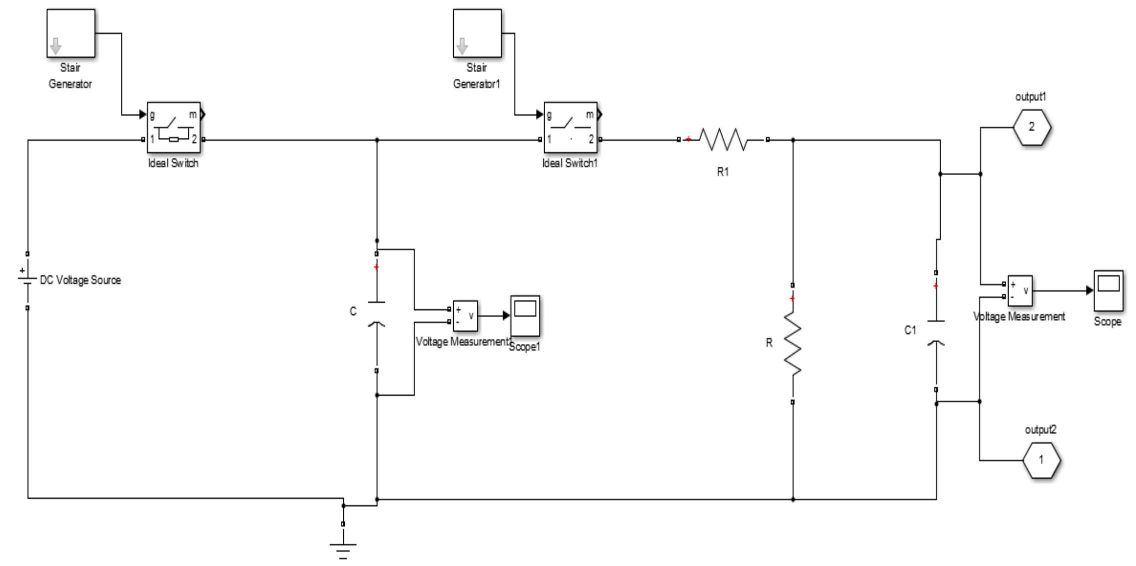


Figure 3-1 Surge generator model

In this model, we have used two switches. In real generators, those are commonly made with spark-gaps. The first step is to charge the capacitor C by means of connecting the DC voltage source to the capacitor bank C by closing switch S1. Once the capacitor bank C is charged, the surge is applied by closing the switch S2which allows C to discharge. The waveform is obtained by means of the shaping capacitor C1 and resistors R1 and R2. In this way, we got the required wave-front. WhenC1 is charging we get fall time on the discharge.

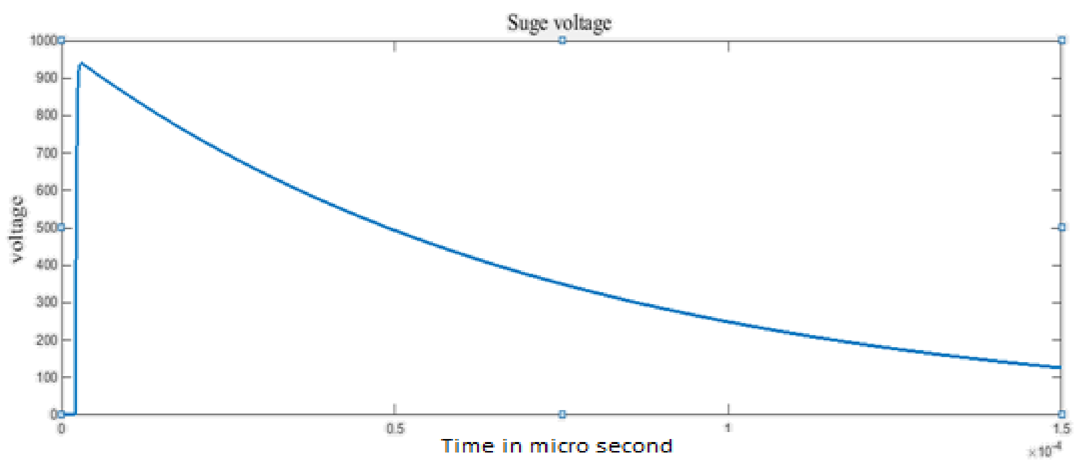


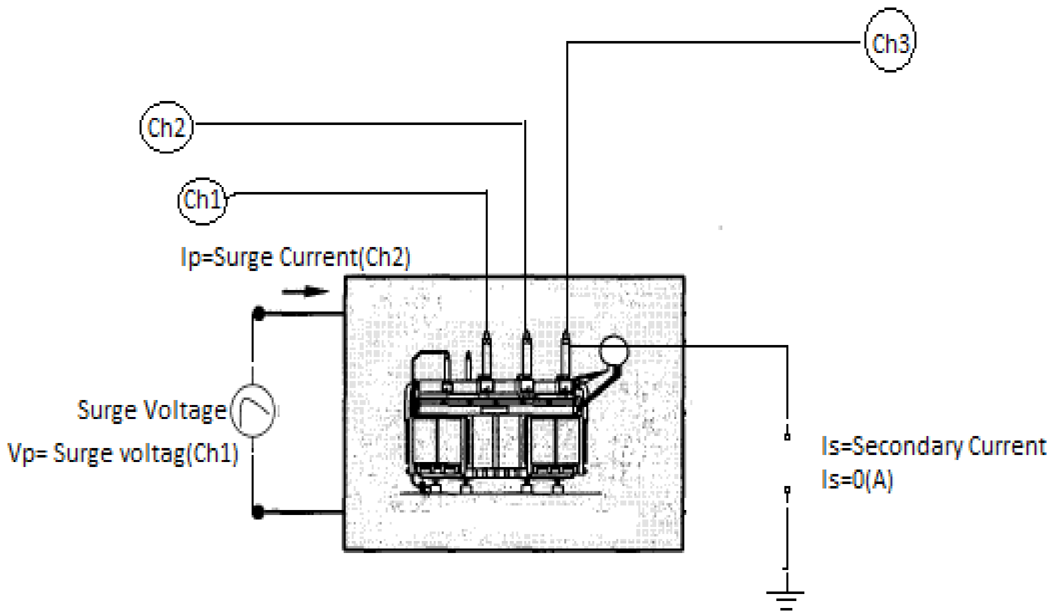
Figure 3-2 Surge generator output

3.3 Experimental procedure

The standard method to determine the transformer withstand strength is the impulse response analysis. The idea of applying an impulse voltage on the transformer is to estimate the frequency at which the transformer's natural frequency and the frequency of the impulse become equal, also called resonance frequency. The transformer modeling is carried out on two resonance frequencies specified from the impulse test. The complete procedure of the test is described in this chapter's section 3.4.1.

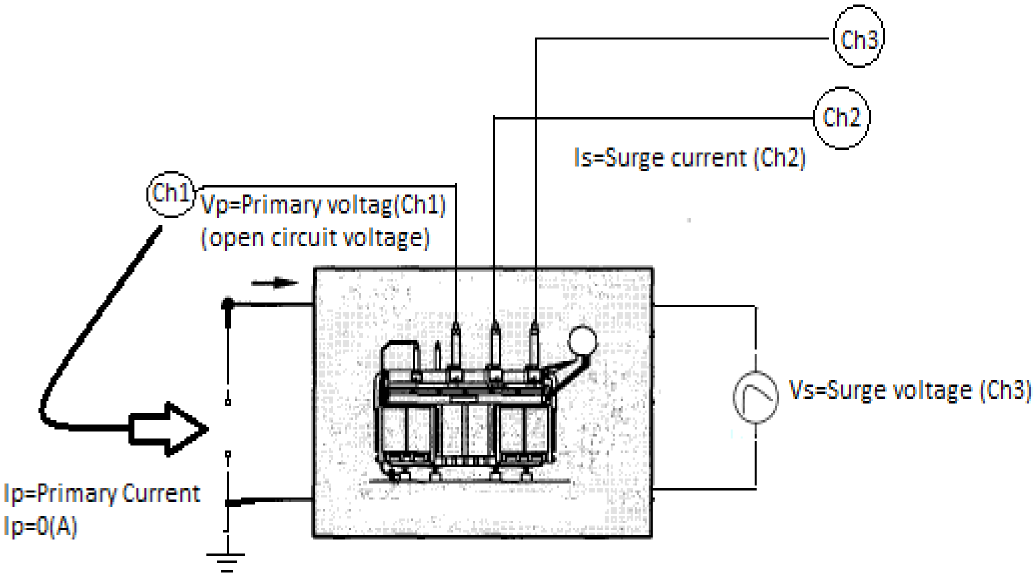
Transformers are tested in two ways; in the first test the primary side of the transformer is kept open and the surge is applied to the secondary side by means of an impulse generator. The purpose of this test is to obtain the transfer impedance on the magnetizing side of the transformer. In the second test, the transformer secondary side is kept open and the voltage surge is applied to the primary side; again, the transfer magnetizing impedance is calculated.

HV to LV experimental setup



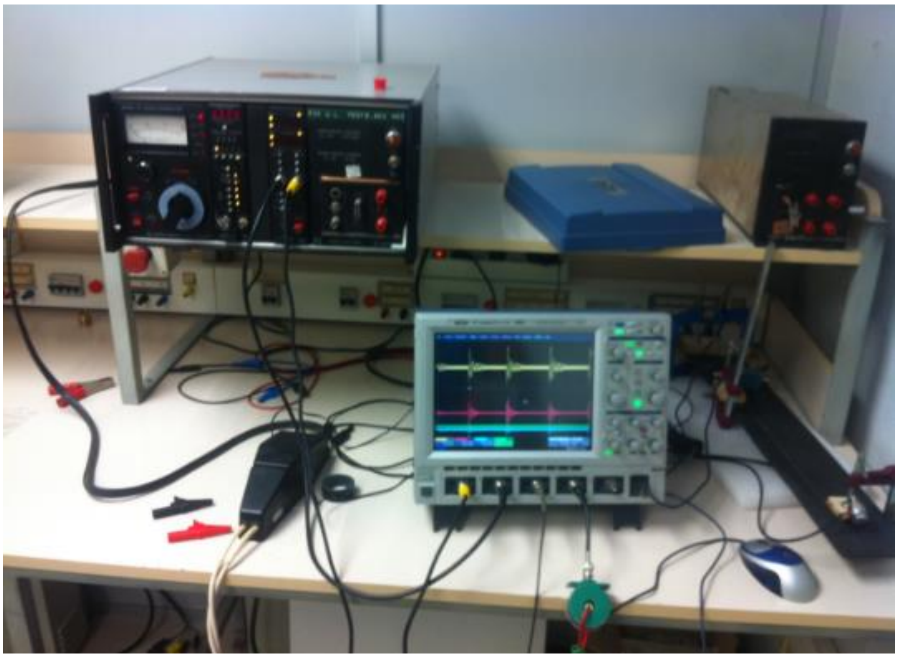
(a)

LV to HV experimental setup



(b)

Figure 3-3 (a) & (b) Schematic diagram of experimental setup [52]



(a)

(b)

Figure 3-4 (a) & (b) Experimental setup

The specific analysis given below was performed for each and every tested transformer, in order to obtain an optimized solution of high frequency modeling.

Parameter estimation: On the basis of experimental data under surges, the transformer parameters were estimated, i.e. at the primary side, the secondary side and the magnetizing side, (presented in section 3-4.1).

FFT analysis for range of resonance frequencies: The transformer is analyzed in frequency domain under surge or transient excitations, described in section 3-4.1.

Transfer function analysis: The transfer function allows to calculate the unknown values of impedances using output as voltage and input as current for every respective test in frequency domain.

3.4 Theoretical analysis of the expected model with surge voltage

The simulations of mathematically obtained impedance vs. frequency behavior with/without connecting surge are expressed in this section. The response of the model could be predicted by this method.

3-4.1Two-port theory network

The two-port 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 a black box.

The driving source may be a voltage or a current. Here, the driven source is the impulse voltage of the transient. On the basis of the connection of impedances, a two-port network can be classified into T or π (Pi) network. Using open-circuit tests, different parameters of the T-model transformer are determined. The resistive T-network equations are:

$$\mathrm{Vp} = \mathrm{Ip} * \mathrm{Z11} + \mathrm{Is} * \mathrm{Z12} \qquad (3\text{-}1)$$

$$\mathrm{Vs} = \mathrm{Ip} * \mathrm{Z21} + \mathrm{Is} * \mathrm{Z22} \qquad (3\text{-}2)$$

When an impulse is applied on the primary side of the transformer and the secondary side is kept open circuited, the Z11 and Z21 are found:

$$Z_{11} = \frac{V_p}{I_p} \mid I_s = 0, \qquad Z_{21} = \frac{V_s}{I_p} \mid I_s = 0 \qquad (3\text{-}3)$$

Similarly, when an impulse is applied on the secondary side and the primary side is kept open circuited, the following is obtained:

$$Z_{12} = \frac{V_p}{I_s} | \; I_p = 0 \, ,$$
$$Z_{22} = \frac{V_s}{I_s} \; | \; I_p = 0 \qquad (3\text{-}4)$$

In this section, the complete procedure of theoretical analysis is carried out for the estimation of the RLC elements.

<u>Step -1</u> Measurement of the HV voltage, HV current, and LV Voltage.

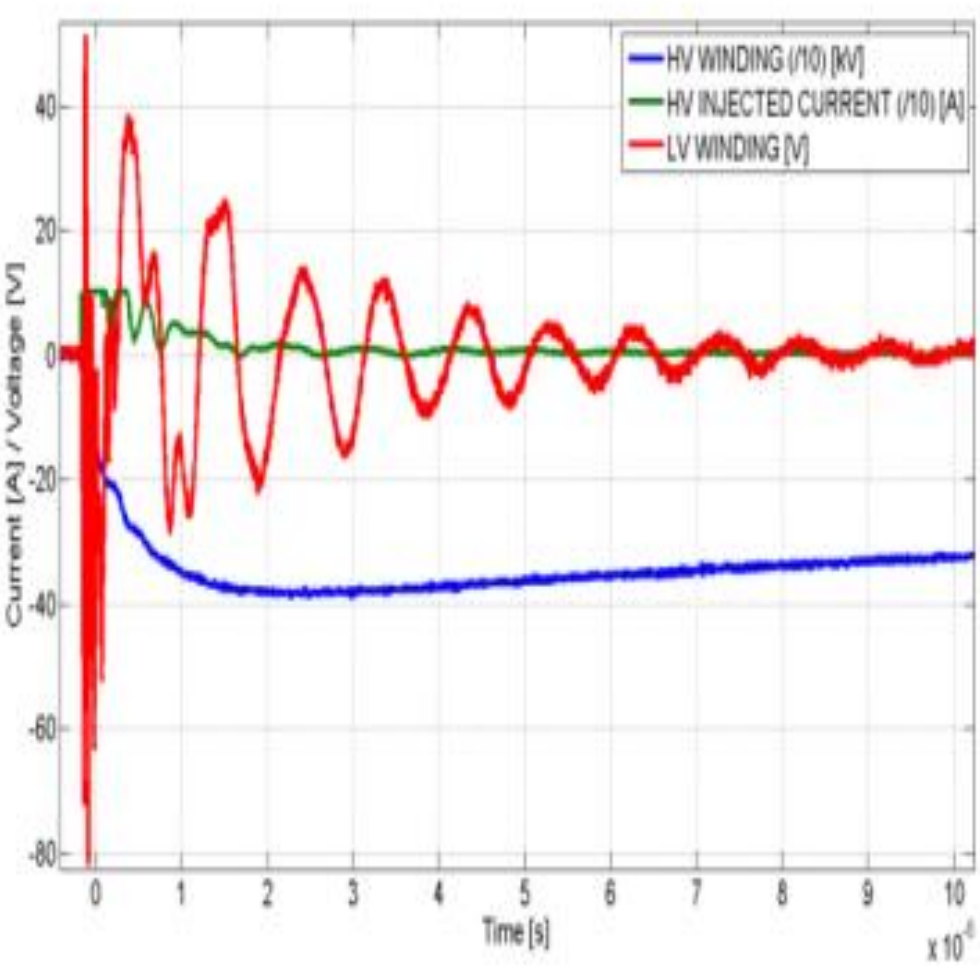
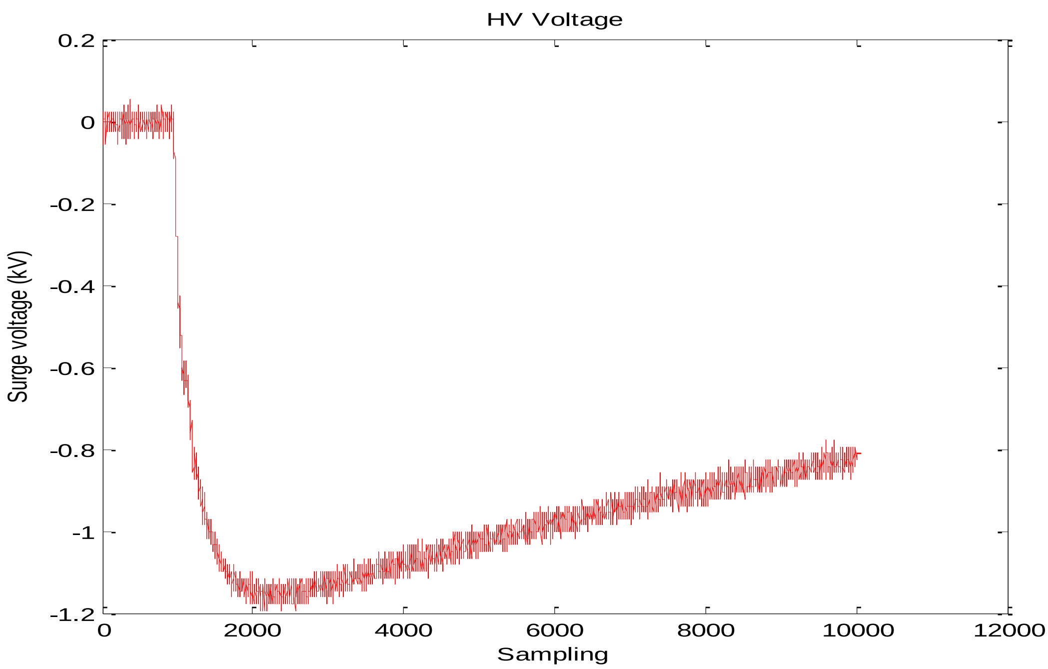
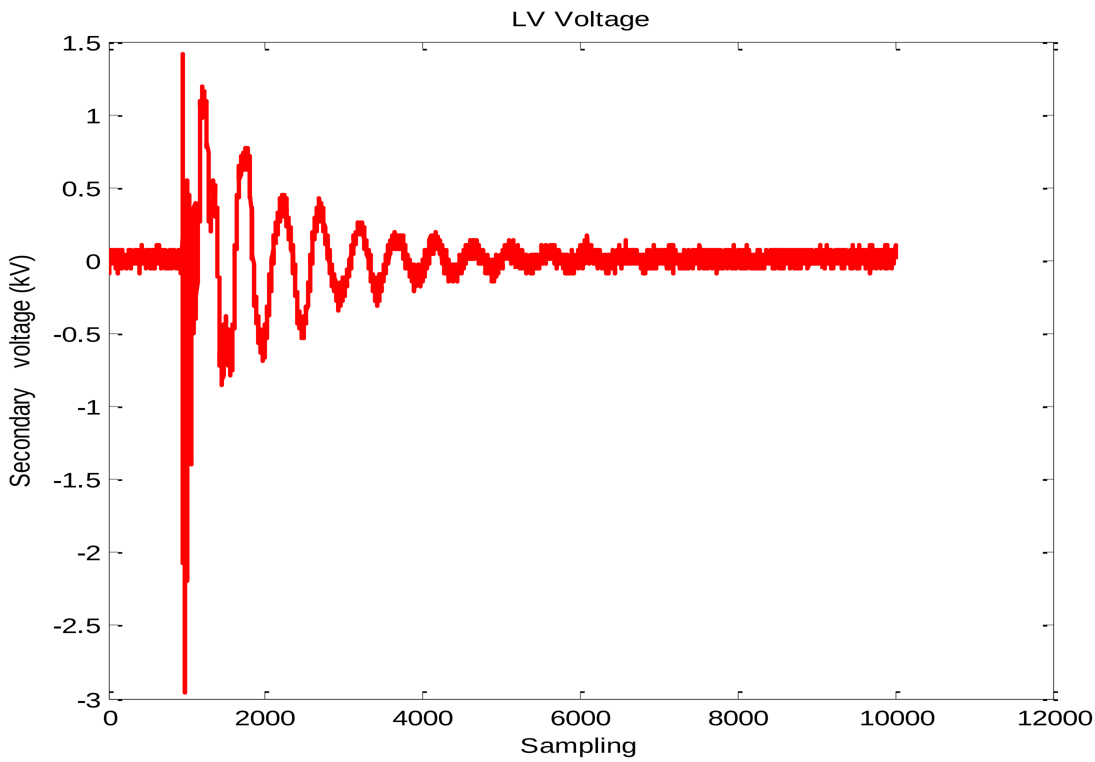


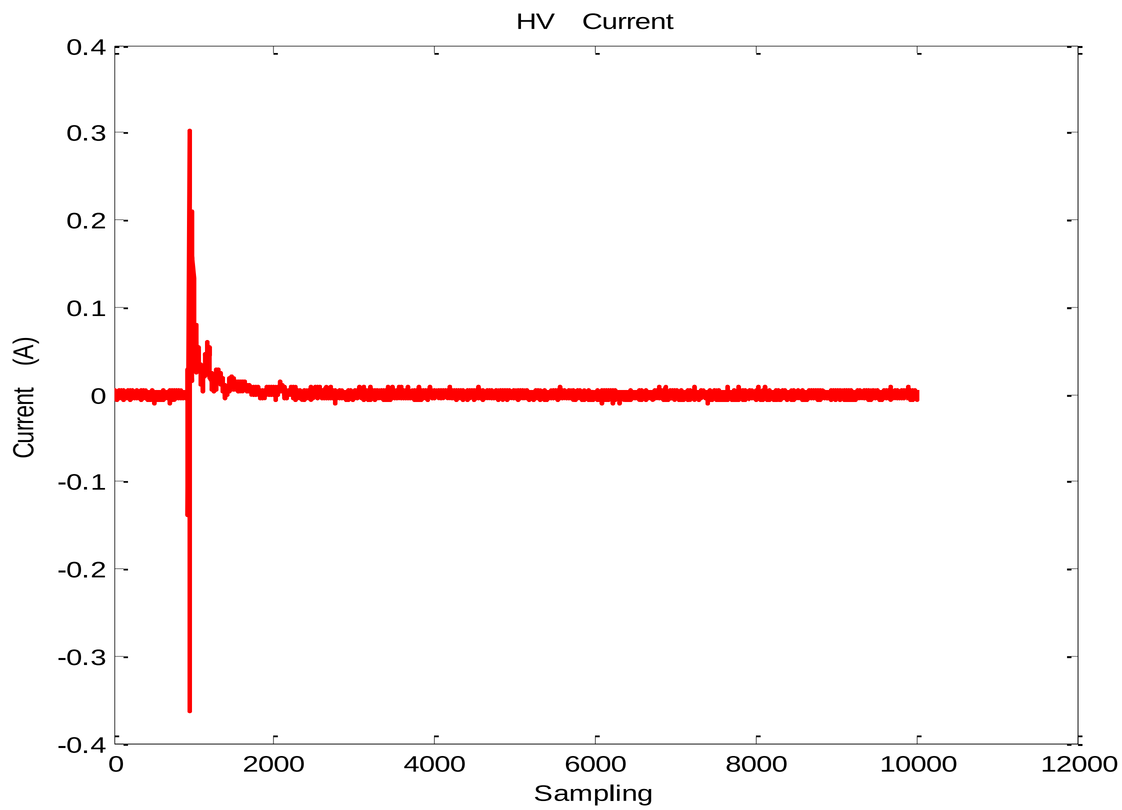
Figure 3-5 Experimentally obtained digital data of HV voltage, Current, and LV voltage


HV Voltage
Surge voltage (kV)
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0
2000
4000
6000
8000
10000
12000
Sampling

(a)


LV Voltage
Secondary voltage (kV)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
2000
4000
6000
8000
10000
12000
Sampling

(b)



(c)

Figure 3-6 (a) HV voltage, (b) Current, and(c) LV voltage

Step-2 The two-port network theory on a T model which is given in figure 3-7

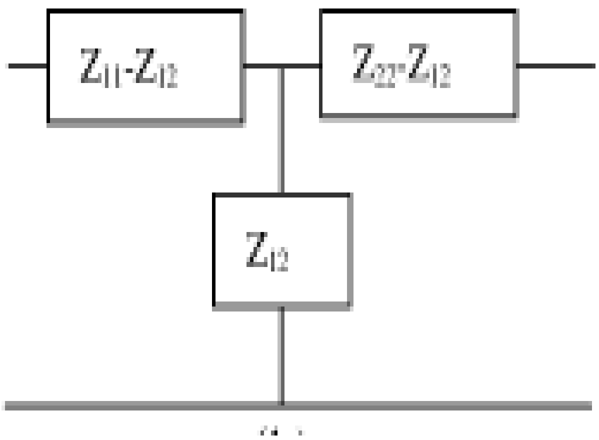


Figure 3-7 Two port network (T) model [28]

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix}.$$

where

$$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0} \qquad Z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

$$Z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \qquad Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

The impedance parameters are obtained in time domain and then are converted into frequency domain using the FFT algorithm described in Annex A.

Here, the circled impedance is determined using the data in figure 3-6.

V2=LV Voltage,

I1= HV Current,

Z21= This is called the magnetization impedance.

If the model is correct, it should prove the magnetization condition that is Z12=Z21

As example the result of the procedure is given in figure 3-8.

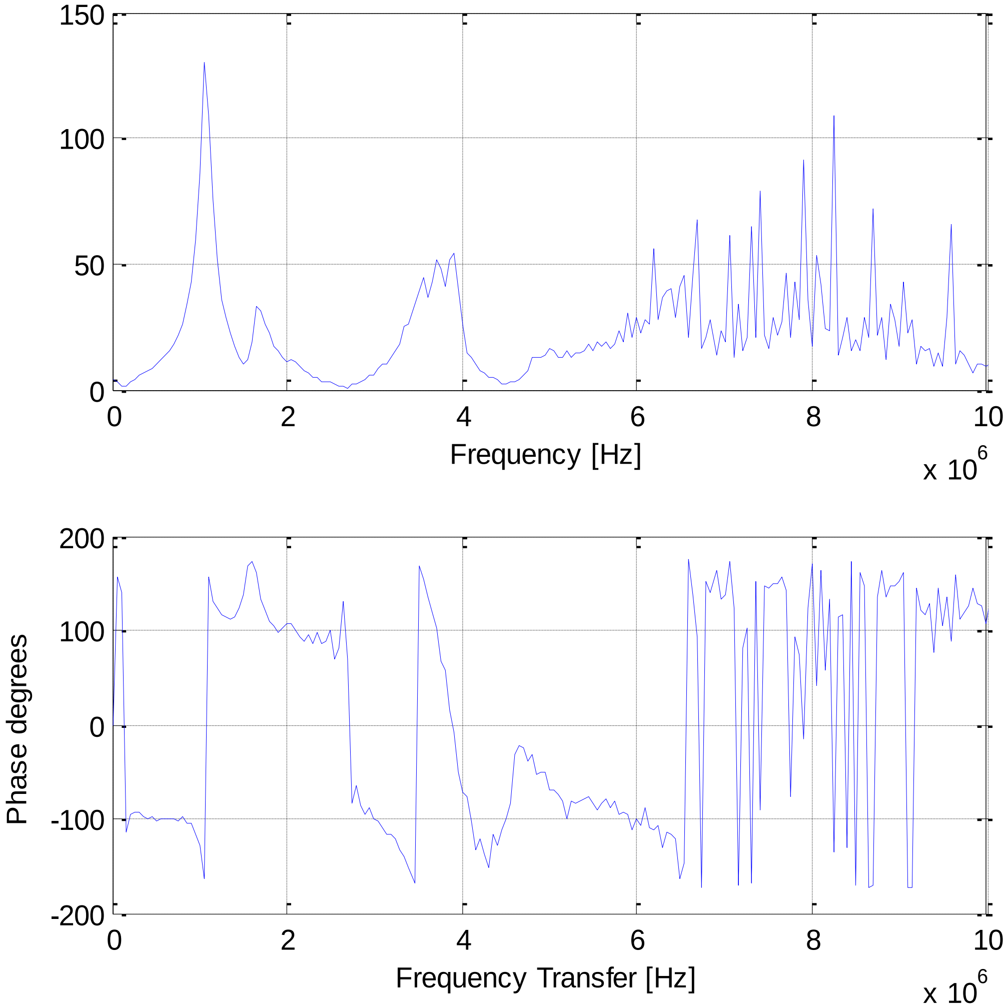


Figure 3-8 FFT response at magnetizing impedance magnitude and phase angle

<u>Step -3</u> Select the different magnitude (of impedances) and their respective phase angles from all these selected frequencies between 1 MHz – 10 MHz, the purpose of the random selection of these frequencies is to estimate the parameters of the transformer on all these selected frequencies.

The selection of the bandwidth at the different frequencies is based on experimental data, i.e. the points on which the maximum resonances occurring.

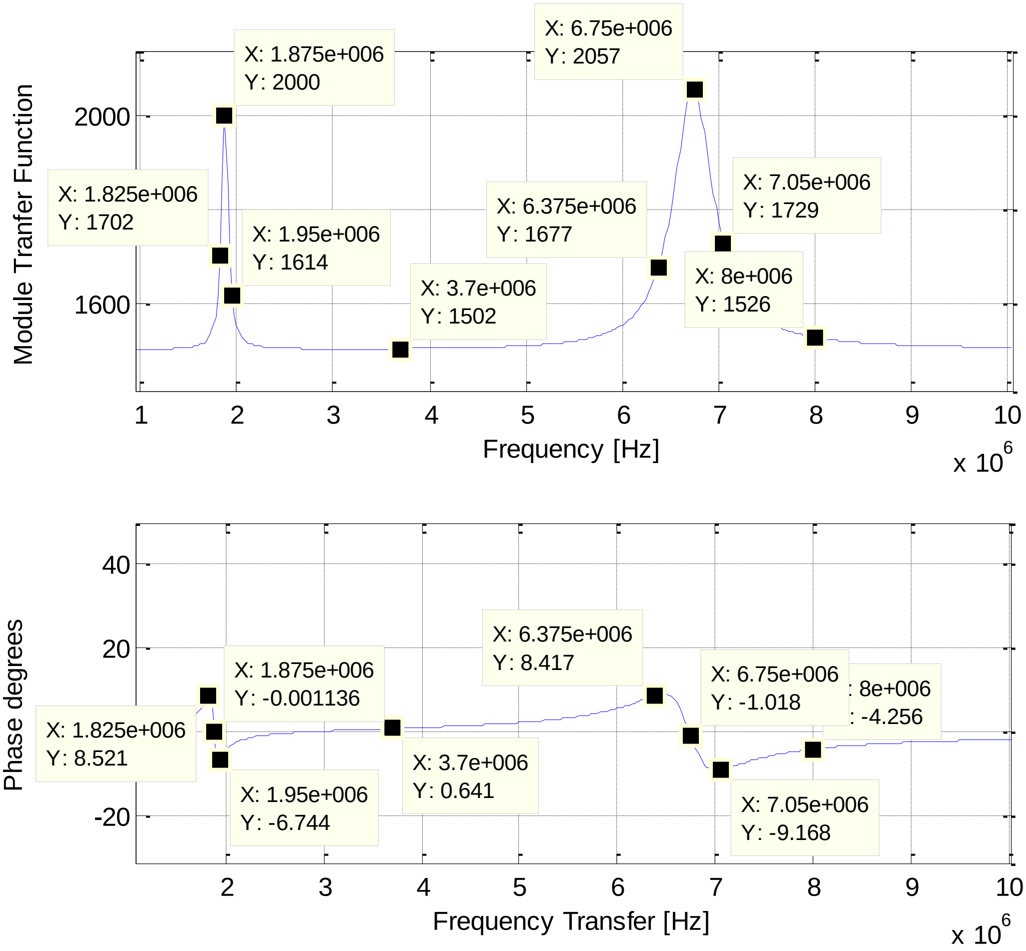


Figure 3-9 Selected random frequencies of magnetizing impedance magnitude and phase angle

<u>Step 4</u> Determination of the transformer parameters at all selected frequencies.

$$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0} \qquad Z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

$$Z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \qquad Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

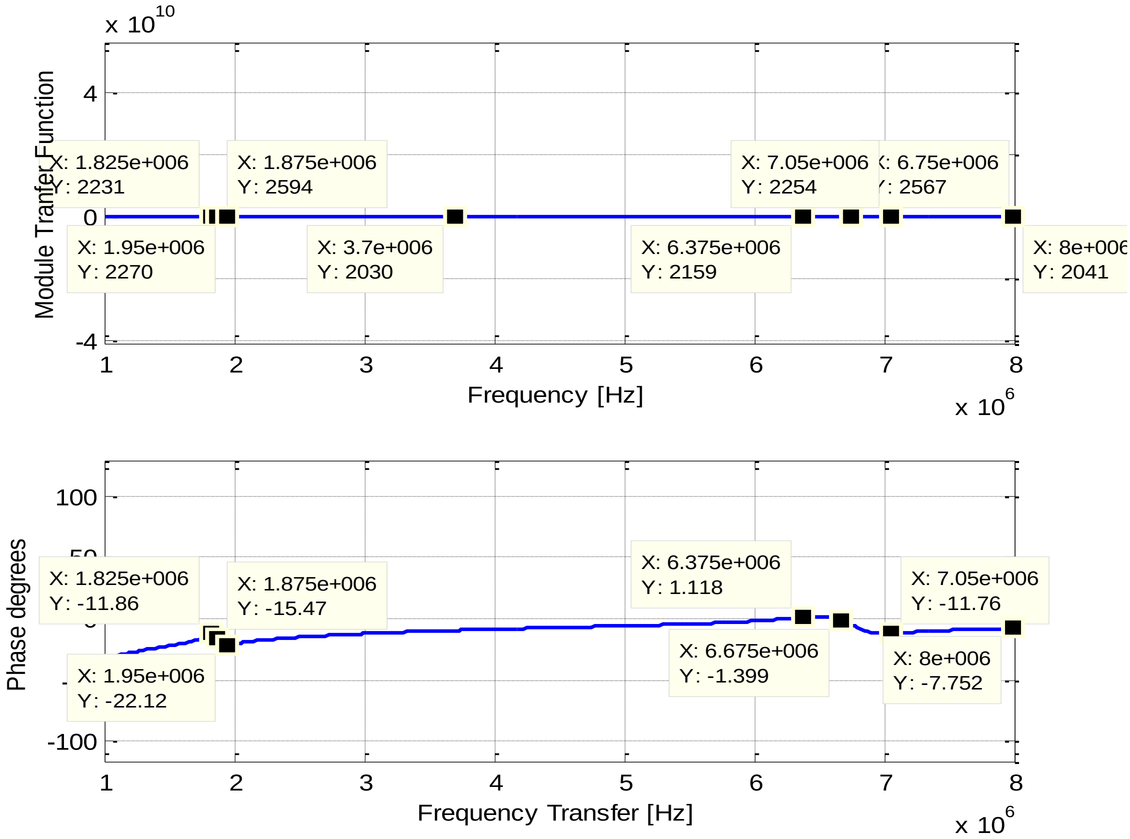


Figure 3-10 Selected random frequencies of primary impedance (magnitude and phase angle)

The selected frequencies indicate that these are the actual frequencies at which the transients are occurring, because at these frequencies the parameters of the transformer, i.e. primary side, secondary side and magnetizing side are responding similarly as described in table 3-3below.

Step 5 Now, the impulse is applied to the secondary side with the primary side open-circuited. The determination of the remaining two parameters at all selected frequencies is conducted using the same procedure as mentioned above.

$$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0} \qquad Z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

$$Z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \qquad Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

<u>Step 6</u>The impedance values are placed in a table for all the considered frequencies.

Table 3-1 Magnitude and phase of primary, secondary, and magnetizing side of the transformer at all selected frequencies.

Frequency / Impedance	f1	f2	f3	f4	f5
Z11	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$
Z12	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$
Z21	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$
Z22	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$

<u>Step 7</u>In this step, convert all the impedances into T- model.

Table 3-2 T- model formation at all selected frequencies

Frequency / Impedance parameters	f1	f2	f3	f4	f5
Z11-Z12	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$
Z22-Z12	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$
Z21=Z12	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$	$\lvert Z\rvert\angle\emptyset$

Step 8 Selection of the values of those frequencies from table 3-2 which satisfy the condition given in the table 3-3 below. Consider an impedance of parallel RLC elements, if the frequency of observation (f) is before the first resonance frequency (fr_1), then its response must be inductive. At the resonance point, (f=fr) when the inductive and capacitive reactance's are equal, the response must be resistive. When the frequency of observation is after the first resonance, its response must be capacitive.

The theoretical table 3-3 is explained in figure 3-12&figure 3-13.

Table 3-3 Frequency vs. impedance behavior with surge

Frequency / Impedances	f<fr_1	f=fr_1	fr_2<f>fr_1	f=fr_2	f>fr_2
Z12=Z21	R+L	R	R+L+C	R	R+C
Z22-Z12	R+C	R+C	R+C	R+L	Fluctuating
Z11-Z12	R+C	R+C	R+C	R+L	Fluctuating

f = Frequency of observation (at which the parameter is calculated).

fr_1 = Frequency at which the first resonance is occurring.

fr_2 = Frequency at which the second resonance is occurring.

The figure 3-12 shows that the magnitude at the selected frequency, i.e. **f<fr_1**, is at an angle of 8.521^{o}, which represents the resistive plus inductive response (R+L).

Step 9 As The circled values of the impedances meet the requirements that are given in table 3-3, then, the transformer parameters are valid for these frequencies (F_1 and F_5).

Use the actual values of the transformer primary and secondary side parameters as shown in the model below.

Frequency / Impedance parameters	f1	f2	f3	f4	f5
Z11-Z12	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø
Z22-Z12	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø
Z21=Z12	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø	|Z|∟Ø

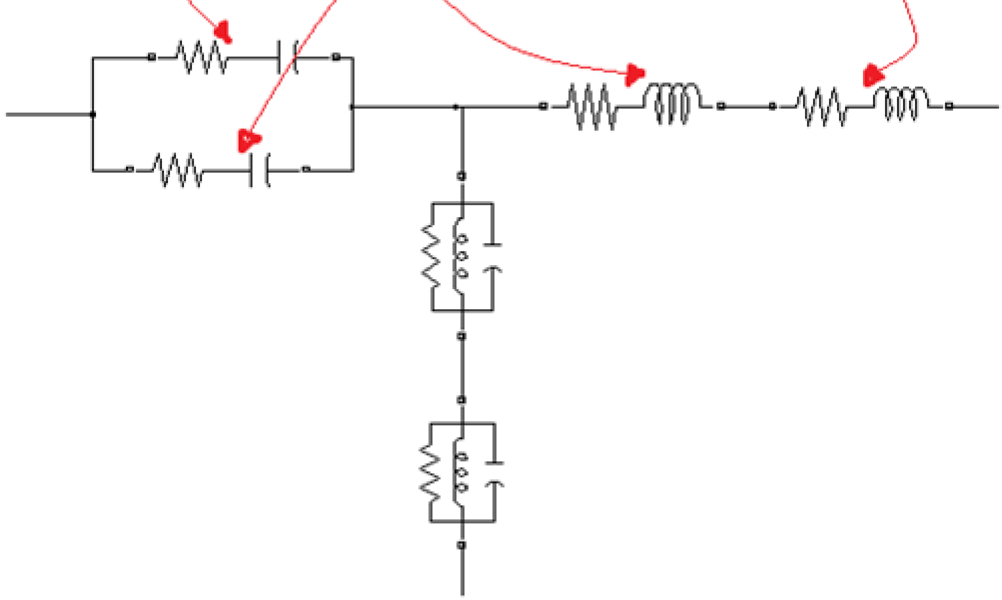


Figure 3-11Final model on selected parameters of the transformer

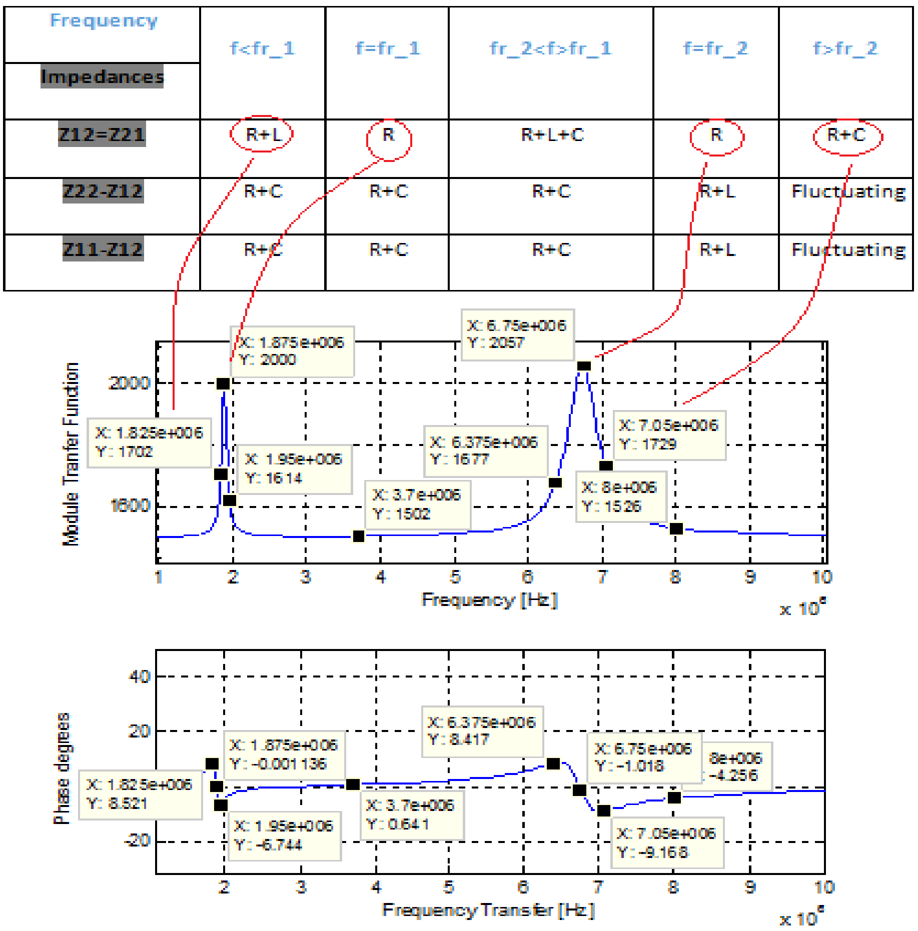
Step 10 In order to obtain the magnetization impedance (Z21 or Z12) parameters, the following formula is used.

$$f_r = {}^{1}\!/_{2\pi\sqrt{LC}} \tag{3-5}$$

In equation (3-5), use the particular value of the impedance at the selected frequency (F1and F5). At these frequencies the imaginary part of the impedances provides only the inductance or capacitance. As at those frequencies the impedance is not resonating, but it is very close to resonate. as example see figure 4-4, where the angle is not zero (0.004681°). In order to create a pure resonating effect, use the known value of the imaginary part of the impedance using equation 3-5 and the missing value of the imaginary part tuned in such a way that it produces the resonance at that particular frequency (F1 or

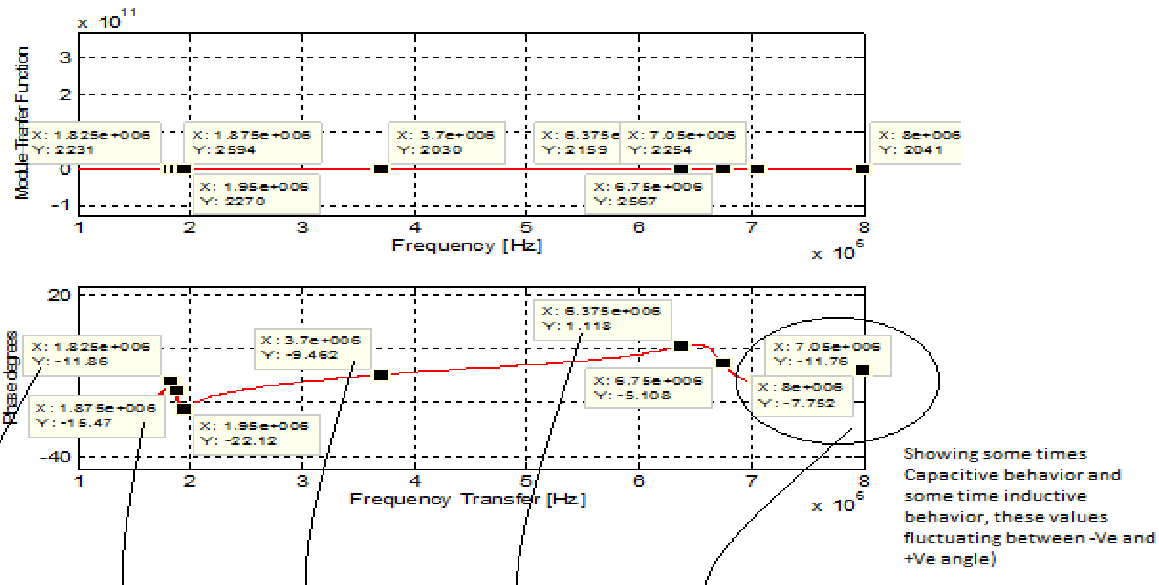
F5). The obtained value of the reactance with known values of reactance used to produce the resonance frequency, same process use for the second resonance. These forced frequencies of resonances are actually providing the correct parameters of the transformer (theoretical conditions shown in table 3-3),i.e. at the primary side and secondary side. Therefore, it is required to force the magnetizing part of the transformer to resonate at these frequencies.

Now, the theoretical values for all the parameters of the model presented in table 3-3 are obtained using figures 3-12 and 3-13.



Frequency / Impedances	f<fr_1	f=fr_1	fr_2<f>fr_1	f=fr_2	f>fr_2
Z12=Z21	R+L	R	R+L+C	R	R+C
Z22-Z12	R+C	R+C	R+C	R+L	Fluctuating
Z11-Z12	R+C	R+C	R+C	R+L	Fluctuating

Figure 3-12Theoretical behavior of the magnetizing impedance under surge voltage



Impedances	f<fr_1	f=fr_1	fr_2<f>fr_1	f=fr_2	f>fr_2
Z12	R+L	R	R+L+C	R	R+C
Z22-Z12	R+C	R+C	R+C	R+L	Fluctuating
Z11-Z12	R+C	R+C	R+C	R+L	Fluctuating

Figure 3-13Theoretical behavior of primary impedance under surge voltage

3.5. Drawbacks of the reference model

The review of the existing models in chapter 2 has shown that those models are only suitable for one resonance (Piantini, [26]) and two resonances (Sabiha, [28]). In this section, a discussion of the application of the parameters obtained in section 3.4.1 to the model proposed by [28] is presented.

The method proposed in [28] for the determination the parameters of the T model are the following:

- In [28], referring to Table 3-3 Z22-Z12 is not reflecting the inductive behavior at that particular frequency. The transformer with nominal voltage at industrial frequency shall behave as inductive.
- The resonance occurs at f=374.20 kHz in [28], but by calculations, actually at that point an RC response exists.

- Higher frequencies from primary to secondary transformer should exhibit an inductive behavior but the response is fluctuating; compare from the table at that point mathematically inductive response is dominating, i.e. in [28] the results of two tested transformers at high frequency fluctuating between inductive and capacitive.

The highlighted points in the Sabiha model indicate that the used method for the parameter calculation was not correct. Therefore, another method for the parameter calculation is presented in this thesis which is validating the theoretical concepts with practical analysis.

Table 3-3 describes the conditions of the model under surge, and the behavior of the transformer will be determined by applying the transfer function method, i.e. the surge voltage is the output and the primary current is the input, the transfer impedance must be with RC or C elements (as described in the theoretical analysis). The transfer impedance must also satisfy the experimental data of the transformer. In other words, the reference model is not validating the results of experimental data with the proposed model results, i.e. the primary side parameters are not actually fully capacitive, but the model represents its behavior as capacitive. All observations given are below:

3.6 Improvements in the proposed model in this thesis

The proposed model is designed at high frequency, normally the two resonance frequency models dominating on two different frequencies, i.e. one at kHz and the second at MHz, which can increase the response time of the model at these two resonances. In the proposed model, the two frequencies are 1.65 MHz and 9.99 MHz, which indicates that both frequencies are selected to respond in a short time.

The bandwidth of the transient frequencies was modified in order to counter the lightning transients of very high frequencies which strike the primary winding of the transformer for a very short interval of time.

Chapter FOUR

FIRST PROPOSED MODEL FOR HIGH FREQUENCY RESPONSE OF A POWER TRANSFORMER USING FREQUENCY RESPONSE ANALYSIS

Lightning surges consequently induce high frequency overvoltages to power transformers. Therefore, it is alluring to study the transfer voltage of lightning surges from the primary to the secondary side of transformers. The high frequency response of a SIEMENS power transformer of rating 25 kVA, 11kV/400V is examined. In this chapter a modified high frequency transformer model is presented. The suggested model is modified from [28], which is based on black box two-port, four-terminal network theory. For the no-load condition, the transformer parameters are calculated at two resonance frequencies of 1.65 MHz and 9.99 MHz using the Fast Fourier Transform. The impedance parameters of the transformer are tested in the time and frequency domains to validate the accuracy of the model. Agreement between experimental and calculated results confirms the precision of the proposed model when an impulse of 1.2/50μs is applied to the terminals.

The modified model of power transformer at two resonance frequencies is presented in this chapter. The transformer parameters at high frequencies are calculated using FFT analysis based on the transfer function method. In the proposed model, the transformer is considered a black box two-port network. The experimental data on 25 kVA transformers is used to estimate its parameters using the method of parameters calculation described in section 3-4.1.

4.1Experimental setup

The experiment was performed in the high voltage laboratory of the Electrical Engineering Department of the Universitat Politècnica de Catalunya (UPC) at ESEIAAT School. The rating of the tested transformer is25 kVA, 25 kV/400V DYn5 (Delta start connected with earth neutral). Shown in figure 4-1

Figure.4-1Experimental setup for transformer testing

Impulses of 4 kV were applied to the primary side of the transformer while the secondary side remained open-circuited. The primary current (Ip), primary voltage (Vp) and secondary voltage (Vs) were measured by means of a four channel oscilloscope as shown in Figure 4.2.

The experimental procedure is the same as presented before in figure 3.3 (a) & (b) of chapter 3.

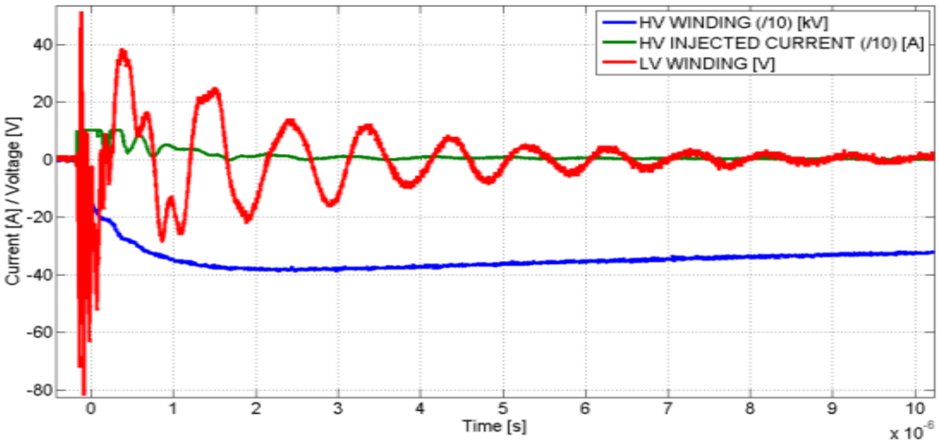


Figure 4-2Impulse voltage, current and secondary voltage on HV side

After taking the values of Vp, Ip, and Vs, from these waveforms the following transfer functions in table 4-1are calculated:

Table 4-1 Definition of transfer function for each impedance

Impedance	Transfer function of parameters
Z12 (magnetizing impedance)	T(s)2=Z12=Vp/Is
Z21(magnetizing impedance)	T(s)1=Z21=Vs/Ip
Z11(primary impedance)	T(s)1=Z11=Vp/Ip
Z22(secondary impedance)	T(s)2=Z22=Vs/Is

From $T(s)_1$, two resonance frequencies at 1.65MHz and 9.99 MHz are found for which Z_{11}presents capacitive behavior.

Similarly, when the impulse is applied on the secondary side of the test transformer and the primary side is kept open-circuited, the values of V_s, I_s, and V_p are measured. The transfer function $T(s)_2$ for the secondary side is calculated. From this $T(s)_2$, the two resonance frequencies are found out, for which Z_{21}hasan inductive behavior. Bothe, $T(s)_1$ and $T(s)_2$resonateatthe same frequency as shown in figures4-4 & 4-5.

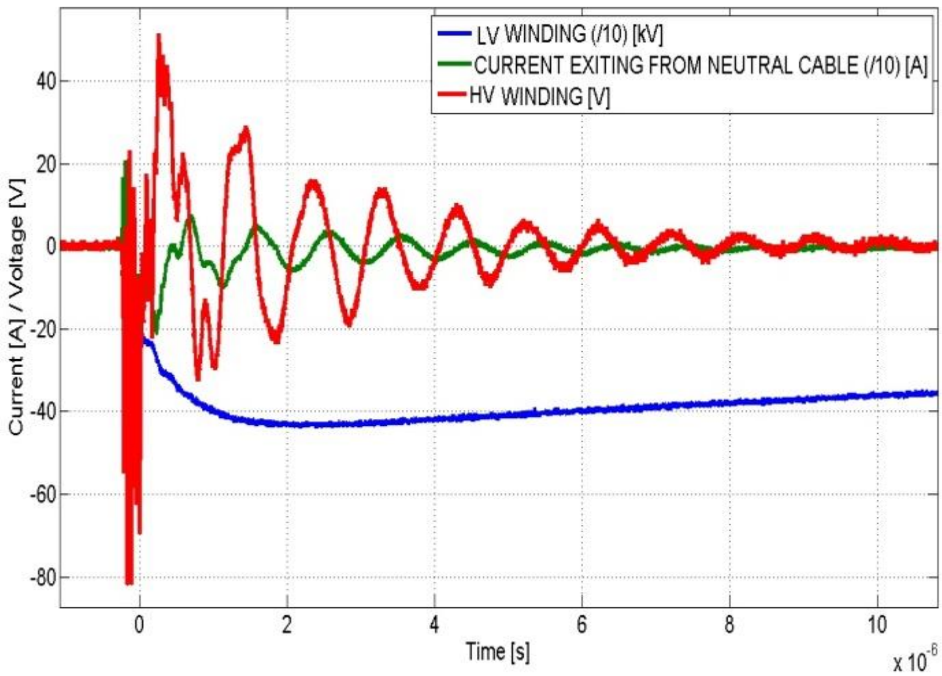


Figure 4-3Impulse voltage, current and primary voltage on LV side

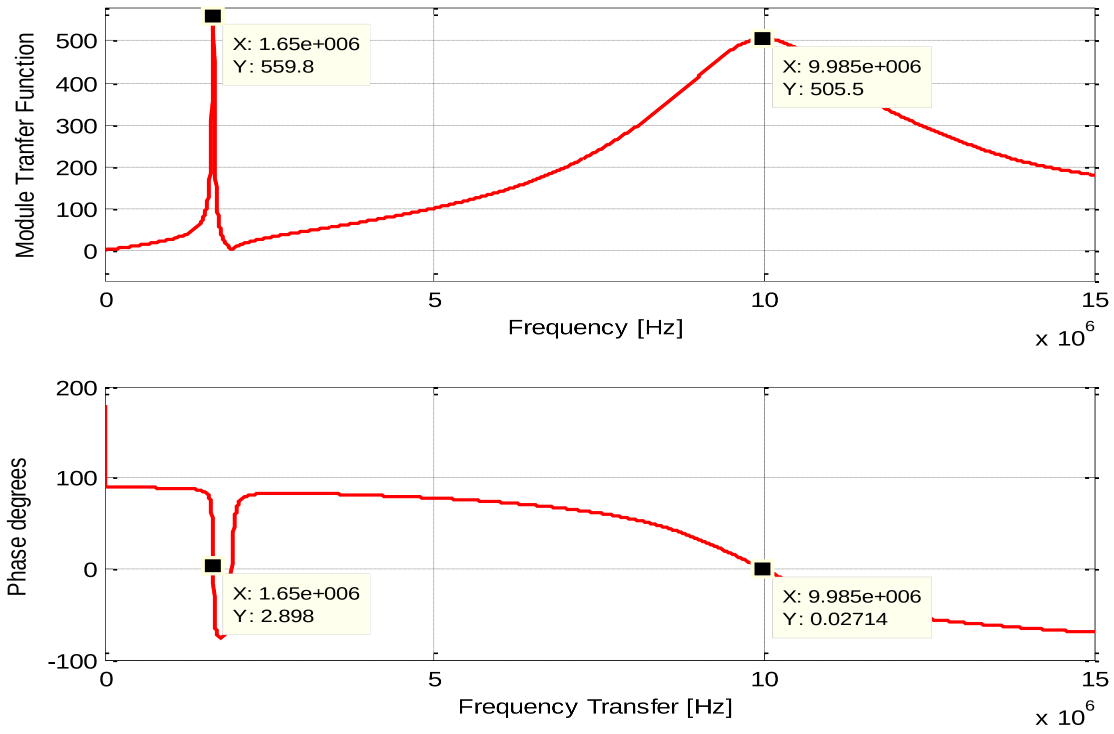


Figure 4-4 Magnitude and phase angle for transfer function T(s)1 and T(s)2 for Z12

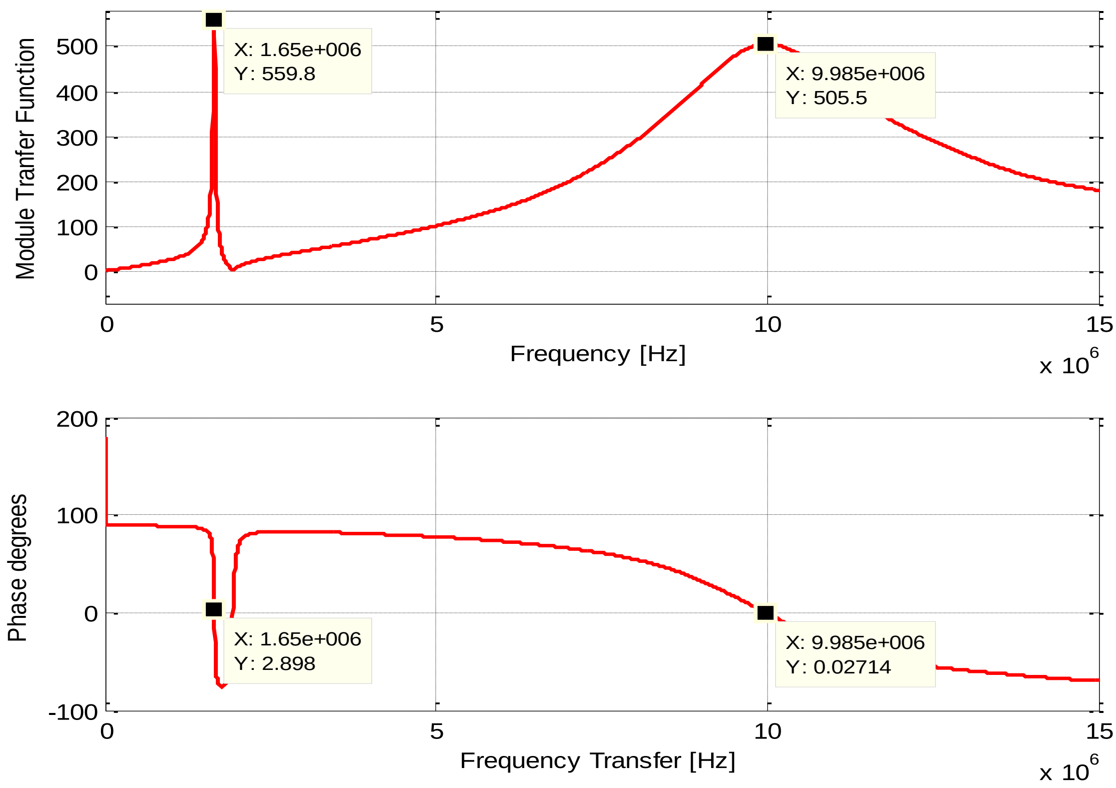


Figure 4-5Magnitude and phase angle for transfer function T(S) 1 & T(S) 2 for Z21

The current and voltage waveforms are first discrete-time provided from the test and then the Fast Fourier Transform is applied. Using the transfer function method (see section 3-4.1), the parametric values for the proposed model of the transformer are obtained. Figure 4-6 describes the amplitude and phase angle of Z11-Z12.

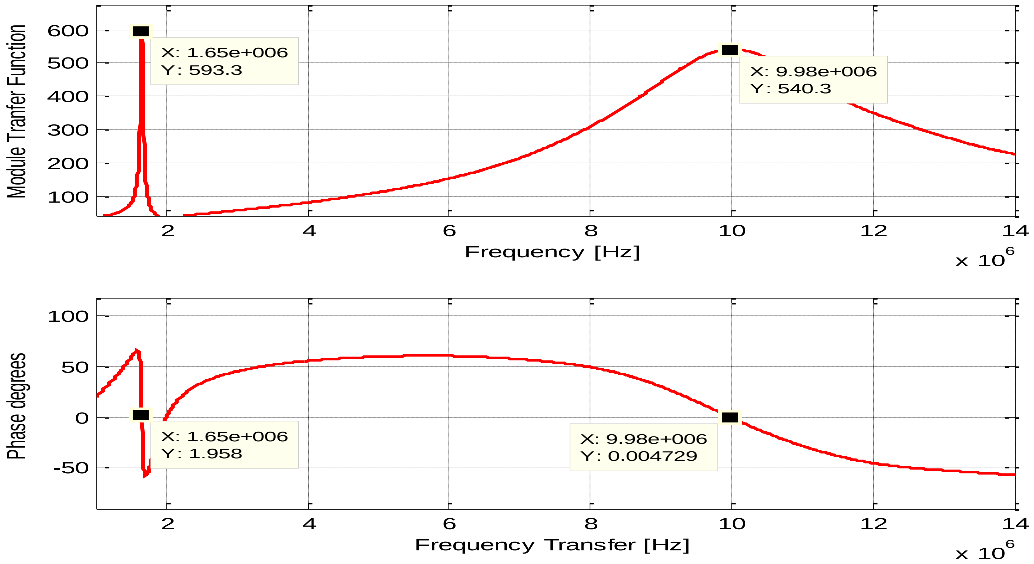


Figure 4-6Magnitude and phase angle for Z11-Z12

The negative value of the imaginary part of Z11-Z12 indicates a capacitive behavior of the transformer in the primary side.

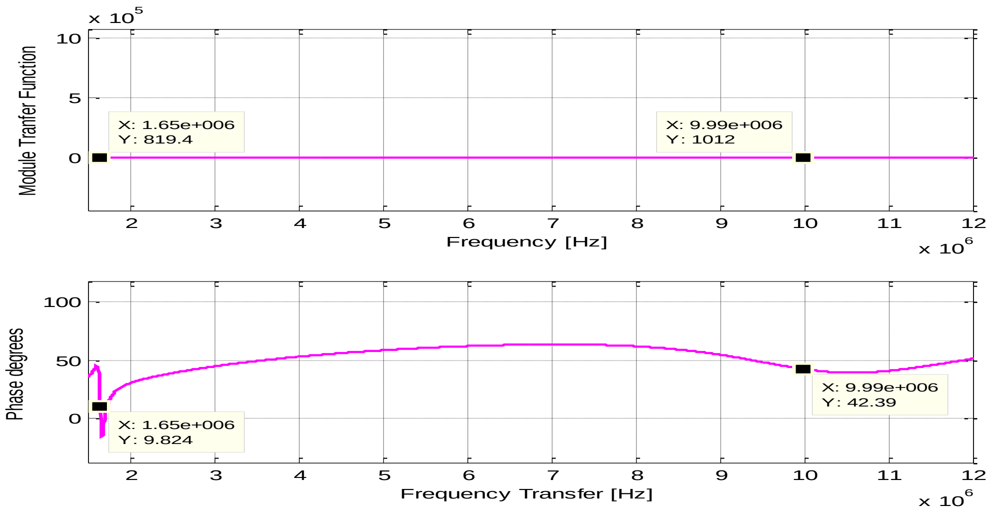


Figure 4-7Magnitude and Phase angle for Z22-Z12

The positive value of Z22-Z21 shows the inductive behavior in the secondary side of the transformer shown in figure 4-7.

From the two-port method presented in section 3-4.1, the transformer resistance R, inductance L and capacitance C are determined. The parametric element resistance (R), capacitance (C) and inductance (L) of the proposed transformer are given in table 4-2;

Table 4-2: RLC elements of proposed transformer model

Elements	**Values**	**Impedance**
R1	337.293Ω	
C1	14.404e-6F	Z11-Z12
R2	37.62Ω	
C2	0.0095069e-6F	
R3	558.5405Ω	
L3	0.0009786e-3H	
C3	0.0095069e-6F	Z12
R4	500 Ω	
L4	0.00253654e-3H	
C4	0.00009966e-6F	
R5	85.809Ω	
L5	8.277e-6H	Z21-Z22
R6	161.546Ω	
L6	2.568e-6H	

4.2 Proposed model

In the proposed model, a simple approach is used to determine the parameters of the transformer. The conventional method of parameter estimation is based on experimental results only; in other words, the proposed approach is very useful to design the transformer model for any specified or desired resonance frequency, the proposed model is also tested for the unloaded condition (no load).

The proposed T-model of the power transformer is shown in figure4-8. In the model, each Z11-Z12, Z12 and Z22-Z12 contains two branches, one is for 1.65MHz and the other is for 9.99MHz.

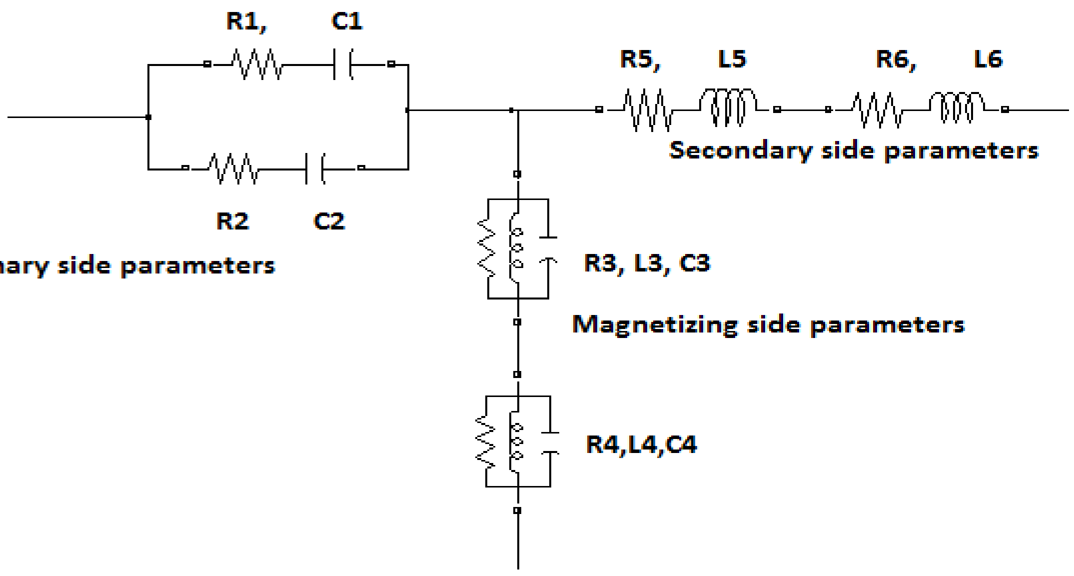


Figure4-8 Proposed T-model for transformer

4.3 Results of transfer voltages

The transfer function of the proposed model in terms of the transfer voltage is calculated by solving the impedance parameters. Table 4-3 presents the impedances at two different frequencies.

Table 4-1 Comparison table at two frequencies

Impedance	Frequency (1.65MHz)	Frequency (9.95MHz)
z_a(Magnetizing side)	$558.54\angle-0.087$	$347.466\angle-51.53$
z_b(Magnetizing side)	$104.953\angle-77.88$	$62.231\angle-82.85$
z_c(Secondary side)	$26.680\angle61.96$	$37.483\angle70.45$
z_d(Secondary side)	$88.408\angle52.99$	$118.519\angle63.32$
z_e(Primary side)	$8.272\angle-68.64$	$5.954\angle-59.60$
z_f(Primary side)	$0.624\angle2.13$	$0.624\angle3.20$

The following impedances are equal:

$$Z12 = Za \text{ and } Zb \qquad (4\text{-}1)$$

$$Z34 = Zc \text{ and } Zd \qquad (4\text{-}2)$$

$$Z56 = Ze \text{ and } Zf \qquad (4\text{-}3)$$

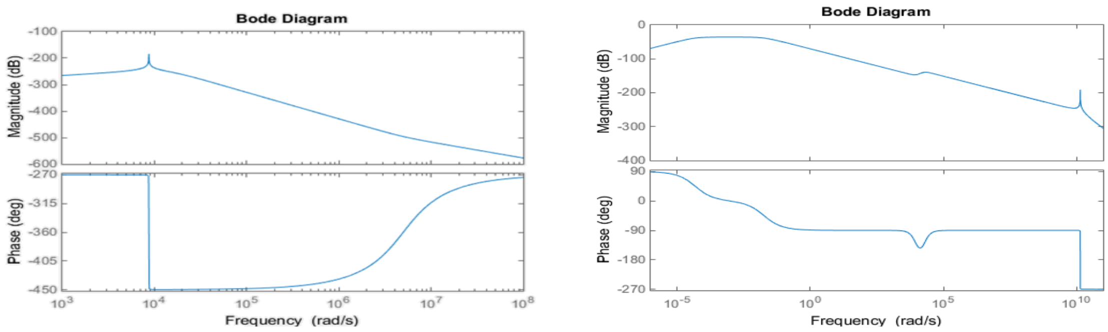
Equations 4-4 and 4-5(described in Appendix B) correspond to the transfer function of the transfer voltages. The transfer function TF1 corresponds to the input voltage to the primary and output to the secondary side:

$$TF1(s) = \frac{V_{out}}{V_{in}} = \frac{z_{12}}{z_{12}+z_{34}} \qquad (4\text{-}4)$$

The transfer function TF2 corresponds to the input voltage to the secondary and output voltage to the primary side is:

$$TF2(s) = \frac{V_{out}}{V_{in}} = \frac{z_{12}}{z_{12}+z_{56}} \qquad (4\text{-}5)$$

The bode plots of the transfer voltages are obtained using equations 4-4 and 4-5 shown in figure 4-9.



(a) (b)

Figure 4-9Transfer voltage from (a) primary to secondary side (b) secondary to primary side

The secondary transfer voltage of the proposed model for the unloaded condition with impulse is shown in Figure 4-10. Impulsive transients vanish in negligible time because of the proposed parameters. The response time increased in all two resonance frequencies.

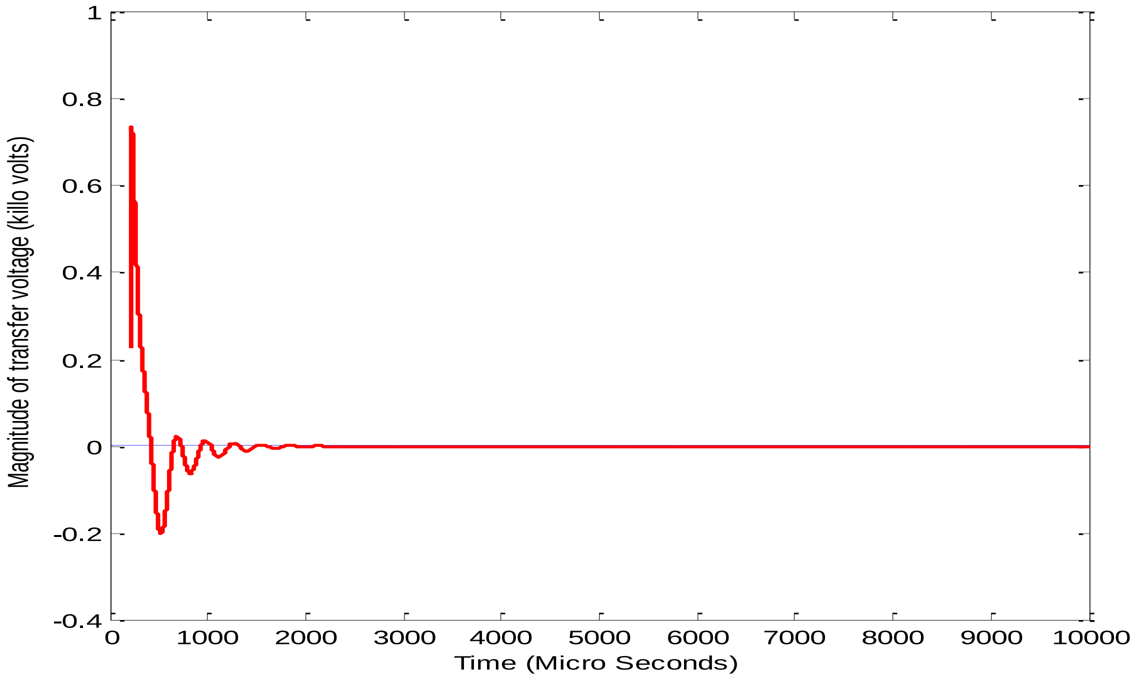


Figure 4-10Transfer voltage from primary to secondary side

The transfer voltage from the high voltage side to the low voltage side of the model shows that the proposed model is eliminating transients completely.

4.4 Conclusion

The modified model is tested and validated for no load protection, as this model is designed at two resonances. The present model discussed in this chapter, two higher resonance frequencies were selected for modeling and, therefore, it could be a more reliable model for lightning protection at higher frequencies. The model is designed based on actual real time values obtained from a test transformer. After the parameters of the model are calculated, the model is tested using the transfer function method in FFT algorithm given in appendix A. The resonance frequency for both magnetizing impedances (Z12 and Z21) is the same, validating the proposed model. The proposed technique can be used in the future for online conditional monitoring of transformers.

Chapter FIVE

SECOND MODEL FOR UN-LOADING AND LOADING CONDITIONS. VALIDATION AND CALCULATION OF THE OVERVOLTAGE TRANSFER FUNCTIONS

This chapter deals with the high frequency model of a transformer as the transformer design using RLC elements in such a way that it responds in two resonances as well as a single resonance, by tuning the switching resistance. The proposed model is able to analyze the transformer under the effect of transients using the transfer function method for comparison with the reference models [26] & [28].When lightning occurs, which actually contains high frequencies, a model that is not able to represent the behavior at these frequencies is not suitable for the design of lightning protection. Therefore, it would be convenient in the design of transformers to consider their high frequency response in order to mitigate the transfer overvoltages. The term protection of a transformer or costumer side means the high frequency modeling will help to design the transformer model for protection from transients.

5.1 Proposed model

In this section, a modified high frequency model is proposed. This model allows the analysis of a single resonance frequency as well as a dual resonance frequency. In [27], for the development of a model for two resonances, a series branch was added. In this model, one series branch is removed aiming for the duality function of the model. The proposed model is shown in figure 5-1 and its elements are shown in Table 5-1. In the proposed model, the only emphasis is on the development of the magnetizing side impedance of the transformer for single and dual resonance frequencies using the resonance frequency formula described in section 3.4.1, step-10 for the development of the high frequency model described in chapter 4.

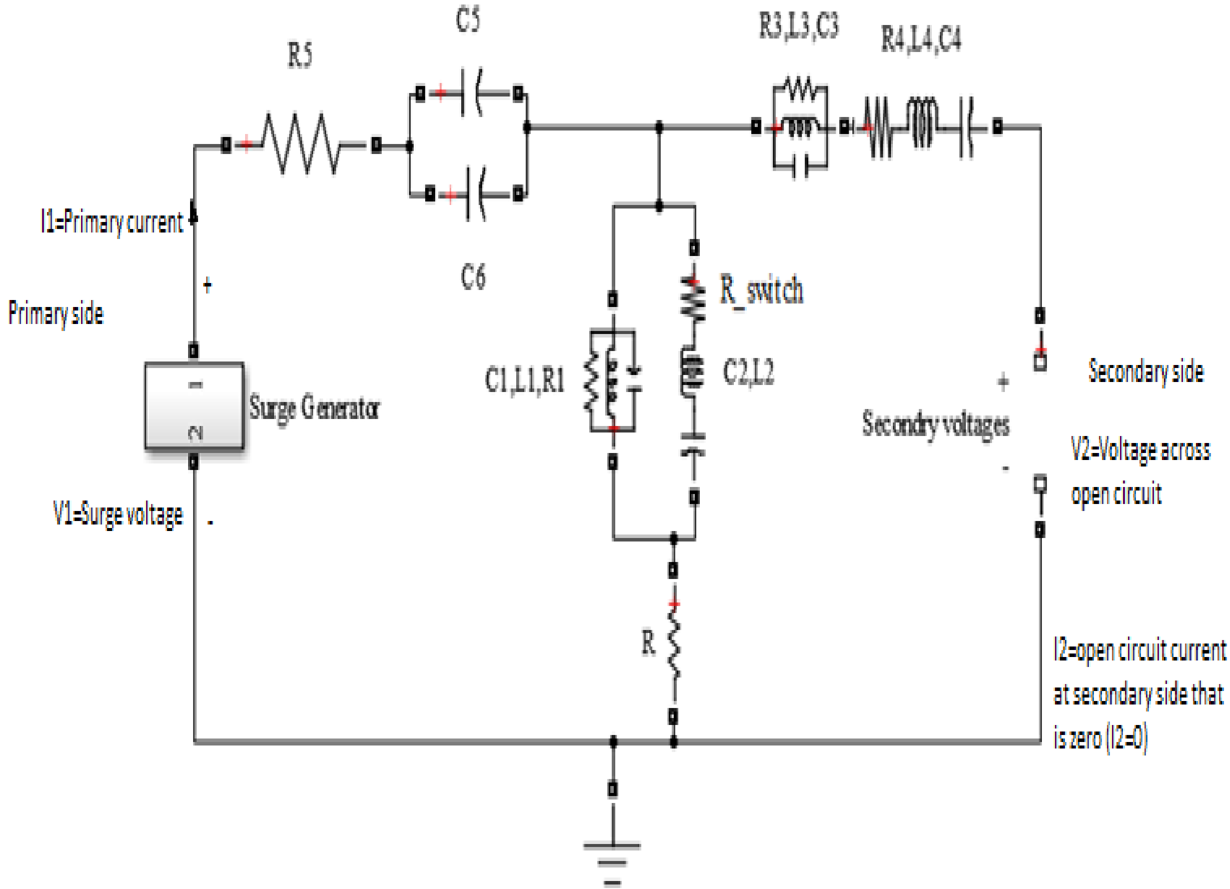


Figure 5-1High frequency T model of a distribution transformer

The transformer model parameters of the primary and the secondary sides are obtained from the reference model presented in [28]. The magnetizing side parameter is computed using the two- port network theory described in section 3.4.1 of chapter 3.

The same procedure is adopted for the magnetizing impedance, except the resistance (R_switch) is selected from the single and dual resonance frequency models presented in [26] and [28]. The graphical value of the R_switch (a variable resistor) allows turning the model behavior from single resonance frequency to dual resonance frequency.

Table 5-2: Elements values of proposed model

Elements	Values
C1	0.021063 pF
C2	0.021063pF
C3	0.00512 μF
C4	0.00022167 μF
C5	0.0004221 μF
C6	0.00019152 μF
L1	0.00856 mH
L2	0.00856 mH
L3	0.036897 mH
L4	0.048296 mH
R1	500 Ω
R_switch	5kΩ
R3	1kΩ
R4	1 μ Ω
R5	50 Ω
R	1500Ω

5.2 Test setup

In order to obtain the correct results of experimental data from the reference model [28], a surge voltage of 450V0.8μs/50μs (same configuration of rise and fall time adjusted with the reference model) [28] is used for simulations by the following steps:

1) Application of a surge on the HV side;

2)V_1,V_2 determined for examination of the effective transfer voltage in time domain/frequency domain (by FFT algorithms).Described in figure5-9 and figure 5-10.

To determine the characteristics of the transformer, the following test is used:

1) Low voltage side to high voltage side test (LV-HV when 1_p=0). In this test, the transformer primary side is kept open. Figure5-2 shows the configuration.

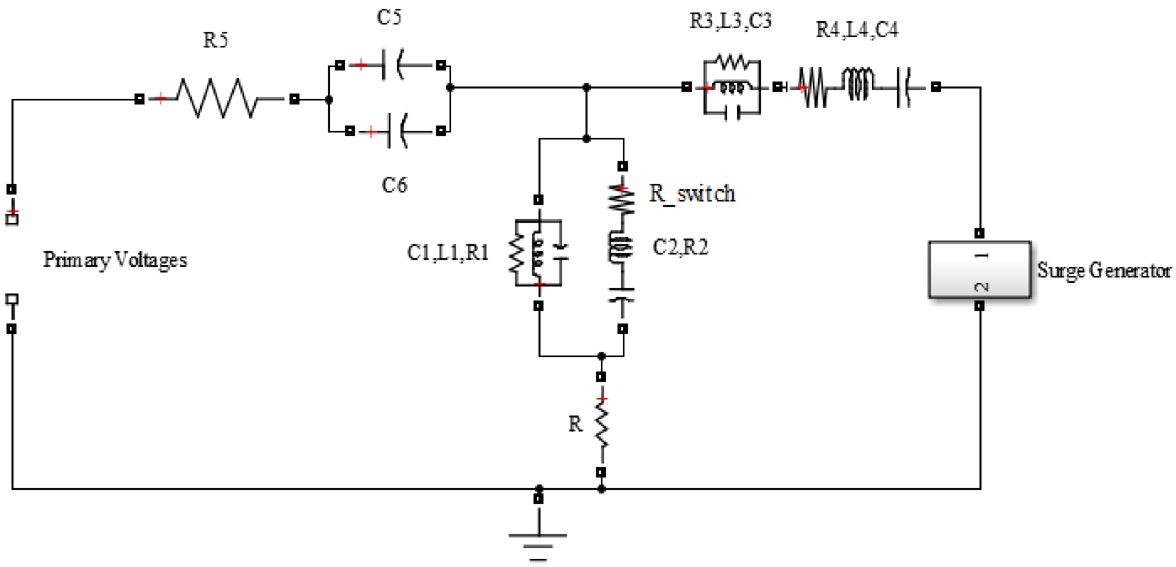


Figure 5-2Secondary to primary open circuit test.

2) High voltage side to low voltage side test (HV-LV when 1_s=0); the configuration of the test is given below in figure 5-3.

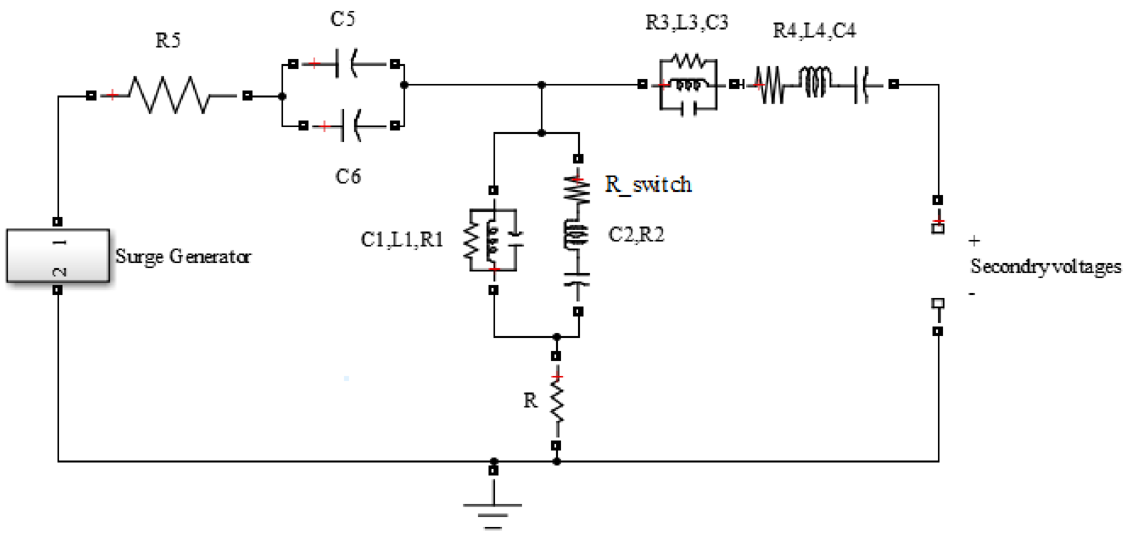


Figure 5-3 Primary to secondary open circuit test.

3) Transformer loading (resistive/parallel resistive and capacitive) tests;

In this test, two different types of transformer loading effects are tested for validation of the model under load, i.e. resistive load (50 Ω) and non-resistive load as a resistor with a parallel 1200µF capacitor. Its configuration is described in figure 5-4 below.

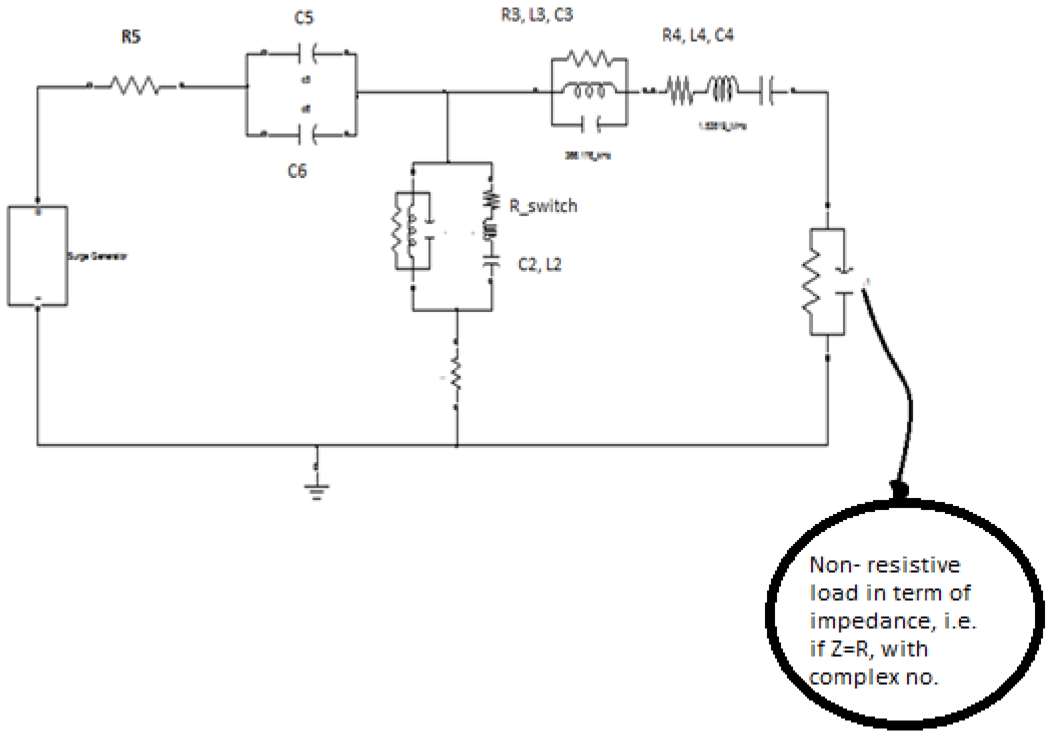


Figure 5-4 Transformer model with resistive and parallel capacitive load

5.3 Single resonance test

The test is conducted as proposed by Piantini in [26]. This model provides the flexibility for single and dual resonance testing. For the single-resonance test, the resistance shown in figure 5-5of the series branch will be high enough so that current (see figure 5-5) through this branch will be low. The high magnitude current will flow through the parallel RLC branch that will produce a single resonance frequency as shown in figure 5-6.

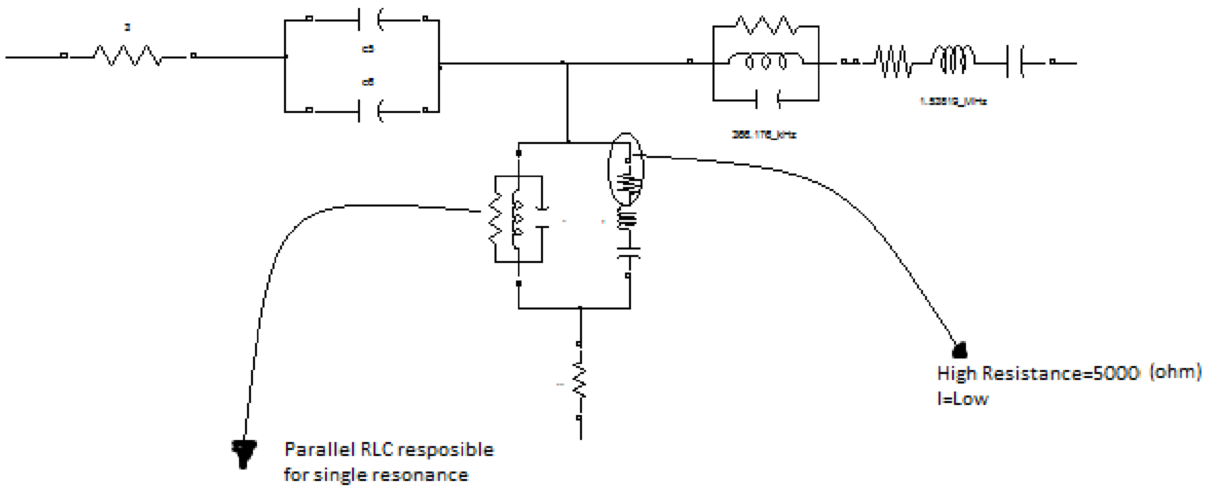


Figure 5-5 Transformer model with single resonance behavior

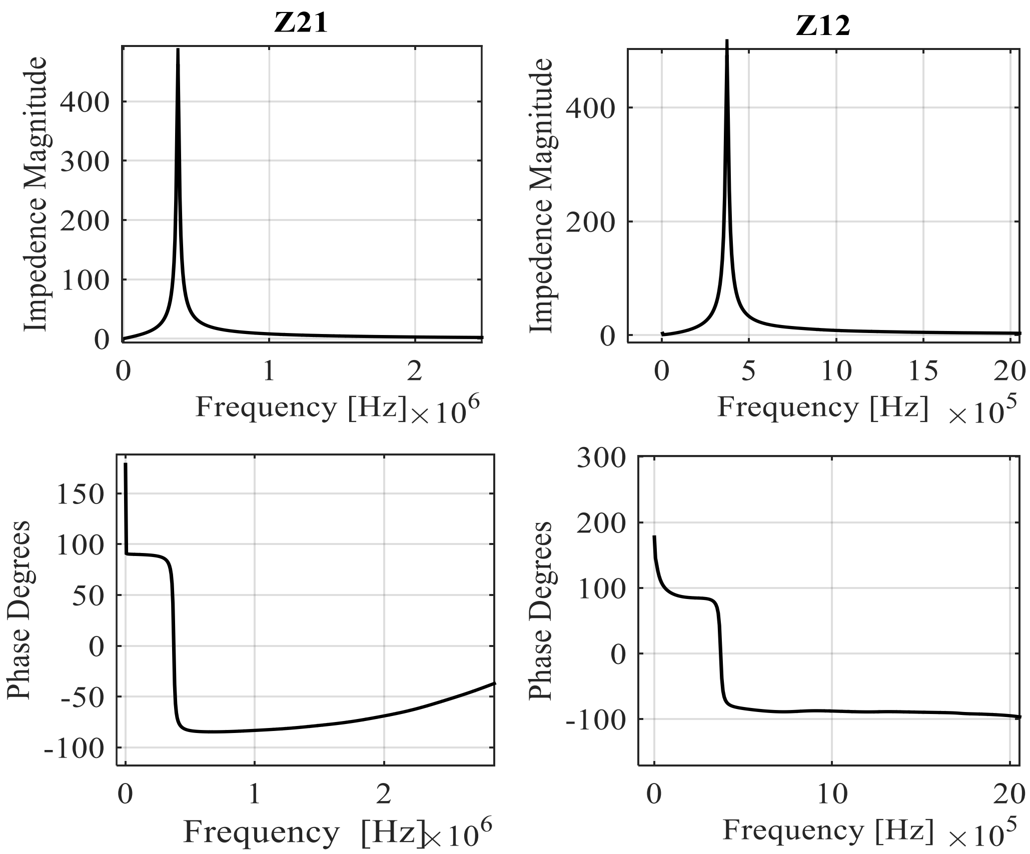


Figure 5-6 Frequency domain response of model for transferred impedances Z12, Z21 for one resonance frequency

Figure 5-6 shows the behavior of the transformer reflecting its single resonance frequency with magnitude and angle for both cases. The magnetizing impedance from the high voltage side to the low voltage side and from the low voltage side to the high voltage side show similar responses (see figure 5-6).

5.4 Dual resonance test

When the *R_switch* is tuned towards a low resistance, the series branch's effect is no longer negligible and it causes the signal to exhibit 2 resonant frequencies. After certain bandwidth of tuning complete second resonance frequency start resonating the magnetization at second frequency (see figure 5-7).

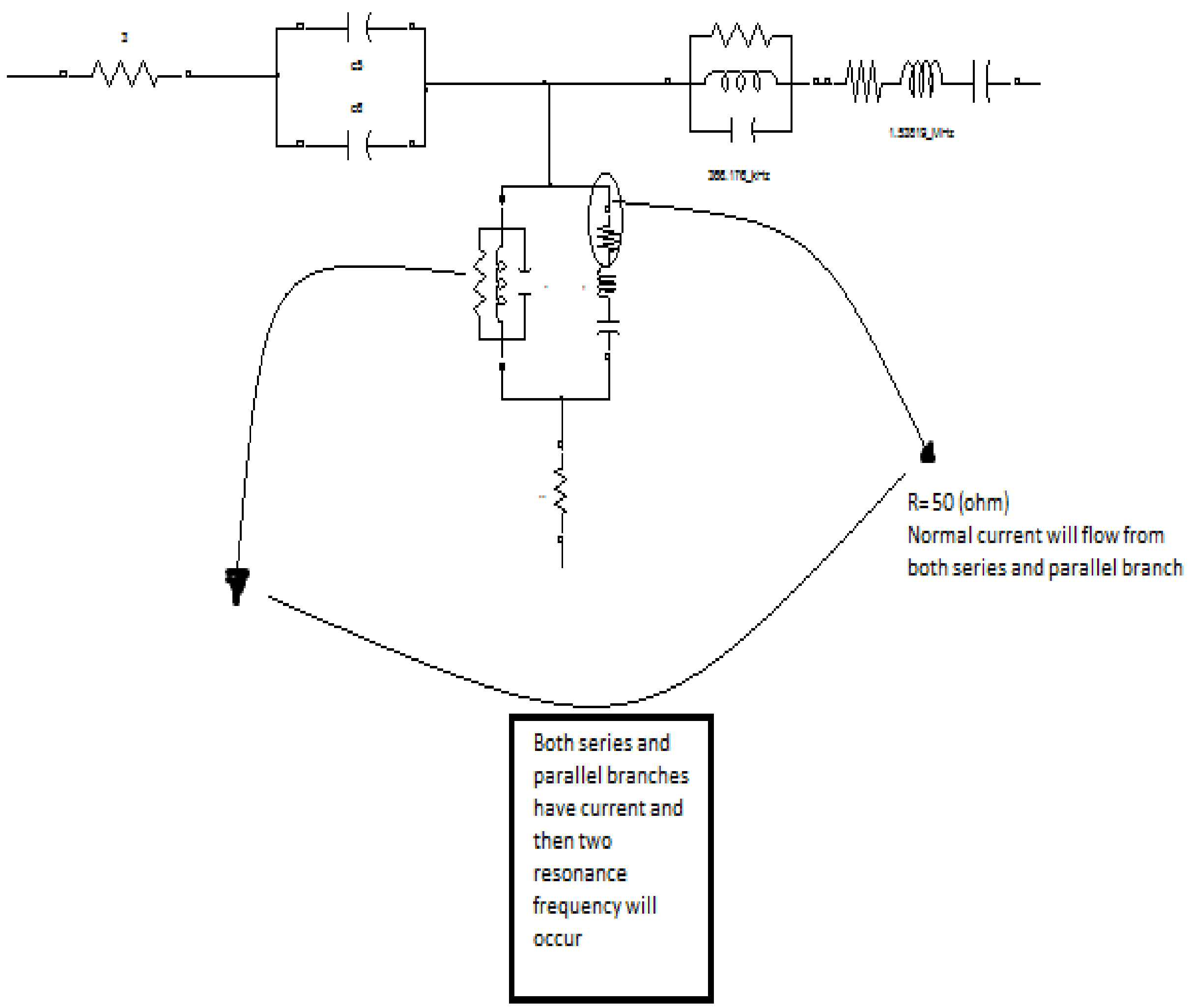


Figure 5-7 Transformer model with single resonance behavior

The response of the magnetizing parameter at two resonance frequencies is shown in figure 5-8.

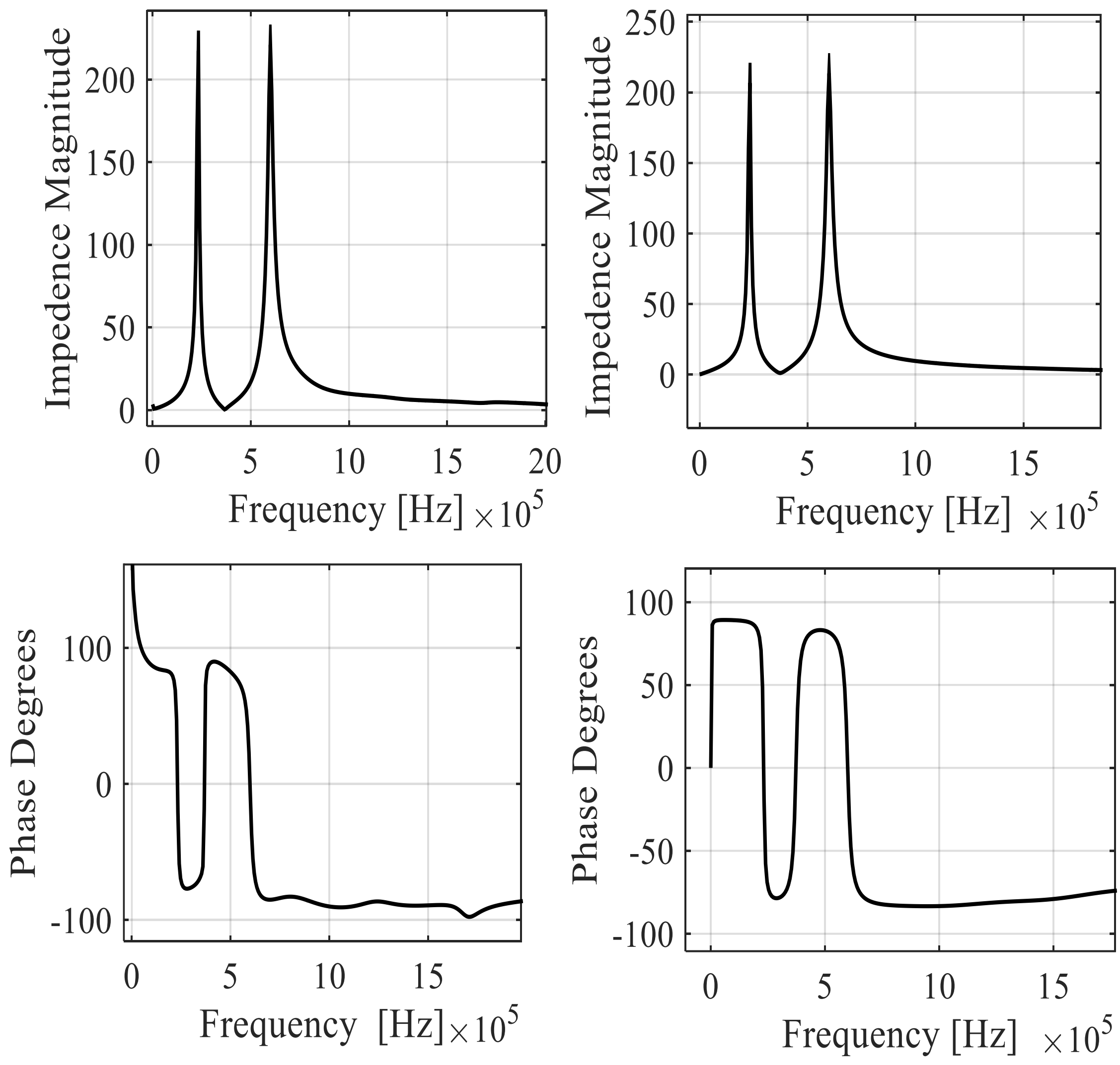


Figure 5-8Frequency domain response of model for transferred impedances Z12, Z21 for dual resonance frequency

According to the two-port theory for T modeling discussed in chapter 3,the magnetizing impedance from HV-LV must be equal to the magnetizing impedance from LV-HV (in magnitude and phase angle).Figure 5-8 validates this condition.

5.5 Adjustment of frequencies and bandwidth

The resonant frequencies can be adjusted by setting the values of L1, L2 and C1,C2. By decreasing the values of both L1 and L2, the frequencies will move forward and, hence, the bandwidth will increase.

To set the bandwidth corresponding to the practical resonances, both values of C1, C2 must be increased. It will result in a narrow bandwidth, which ultimately affects the location of the resonant frequencies.

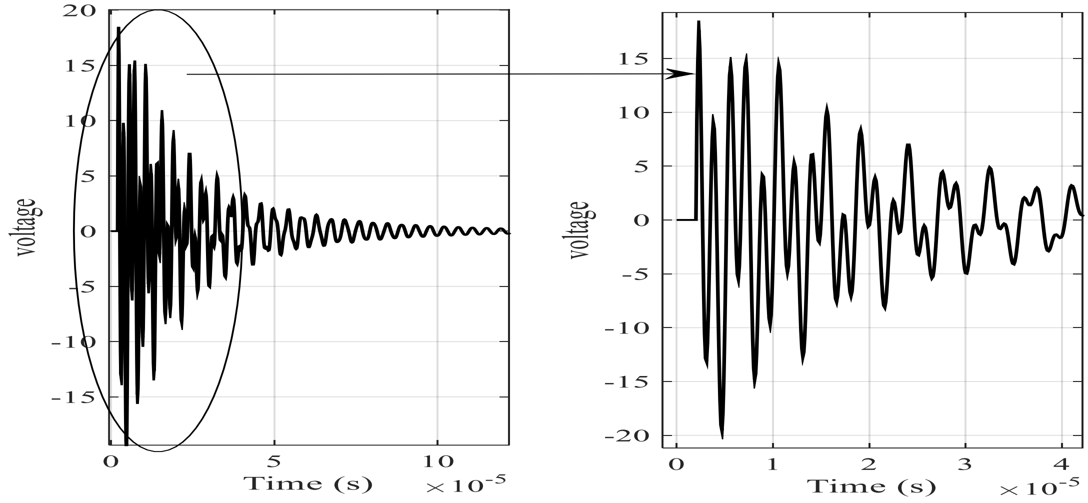
Optimizations are required to increase the capacitances and decrease the inductances. The transients reflect the increase in terminal voltage due to sudden overvoltage or lightning that is belonging to the raise of capacitive behavior over inductive.

5.6 Model validations

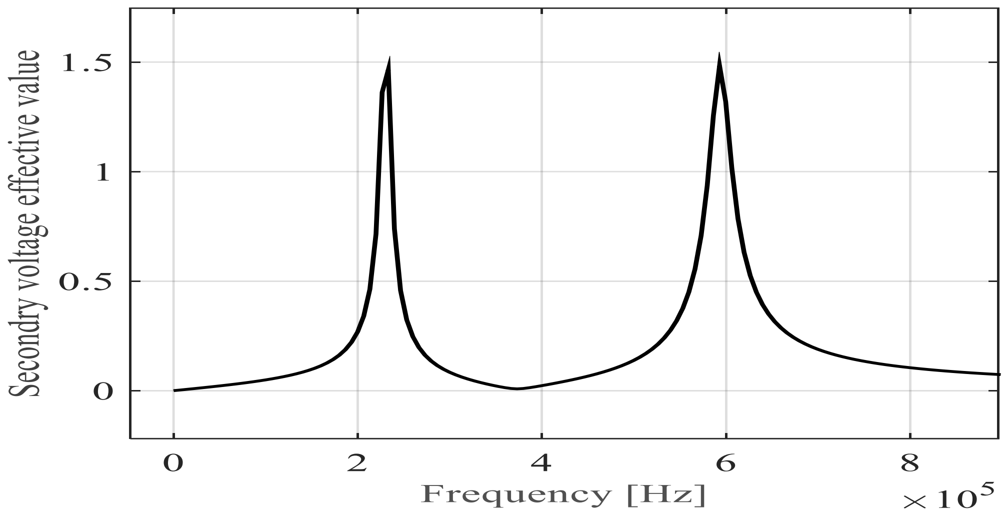
To validate the proposed model, the transfer function method is used. The effective secondary voltage in time/frequency domain and transformer loading (resistive/non-resistive) in frequency domain are tested.

5.6.1 Effective transferred voltage

In this section, the effective voltages on the secondary side of a transformer (in time and frequency domain) are taken into account under single and dual resonance frequencies.



(a)

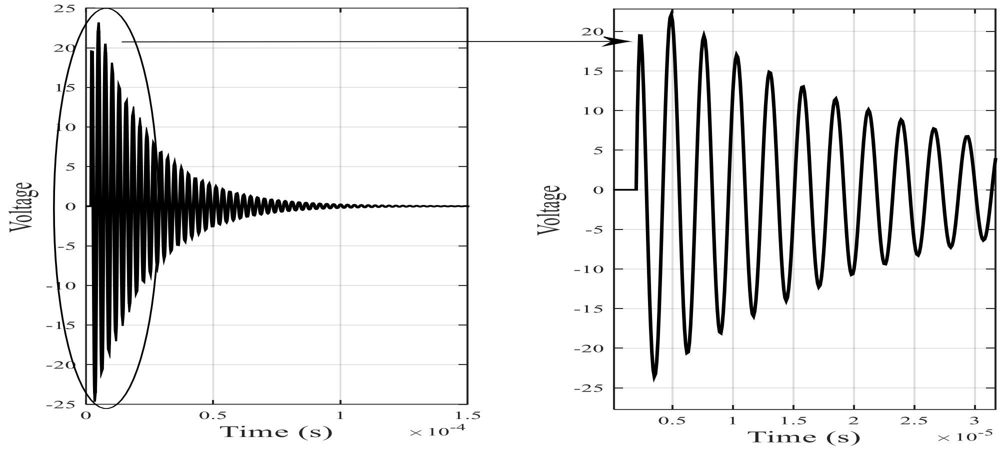


(b)

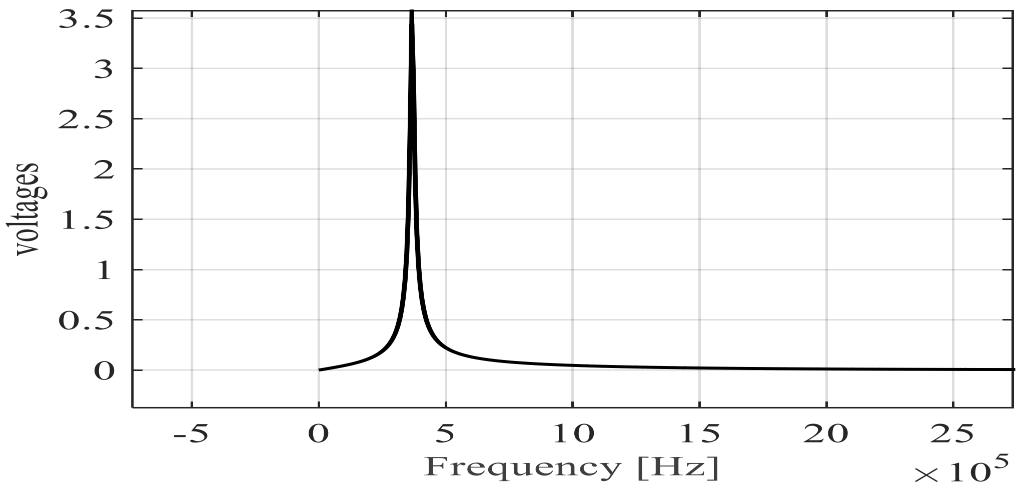
Figure 5-9 Effective secondary voltages for dual resonance frequencies (HV-LV lines) (a) Time domain response (b) frequency domain response

The effective value of the secondary voltage in time domain represents the RMS value of the voltage that is transferring from the primary to the secondary side. Its significance for testing is that connected loads on the distribution side use the RMS values of the voltage.

Figure 5-9 represents the effective value of the voltage in the frequency and time domains, as its response in both cases, validating the fact that it has a dual resonance effect. The results in figure 5-9 agree with the result presented by [28] in its figure 6.



(a)



(b)

Figure 5-10 Effective secondary voltages for single resonance frequencies (HV-LV lines) (a) Time domain response (b) frequency domain response

The difference between dual and single resonance frequency behavior is that the transformer under the transient's effect with dual resonance frequency will be more protected than that of a single resonance frequency. In other words, the dual resonance frequency model will check the transformer in two specified time periods, whereas the single resonance frequency model will check it once at a specified resonance frequency.

The results of figure 5-10 (a) & (b) agree with the results presented by [26] in its figure 6.As both resonating on one resonance frequency measured in time domain.

5.6.2. Transformer loading

Transformer loading is applied on the secondary of the transformer to see the behavior of the transformer under loads. Two types of loads are used as in the 100kVA transformer in [28]:

(1) 50 ohm resistive load at secondary side

(2) 50 ohm in parallel of 1200µF capacitor

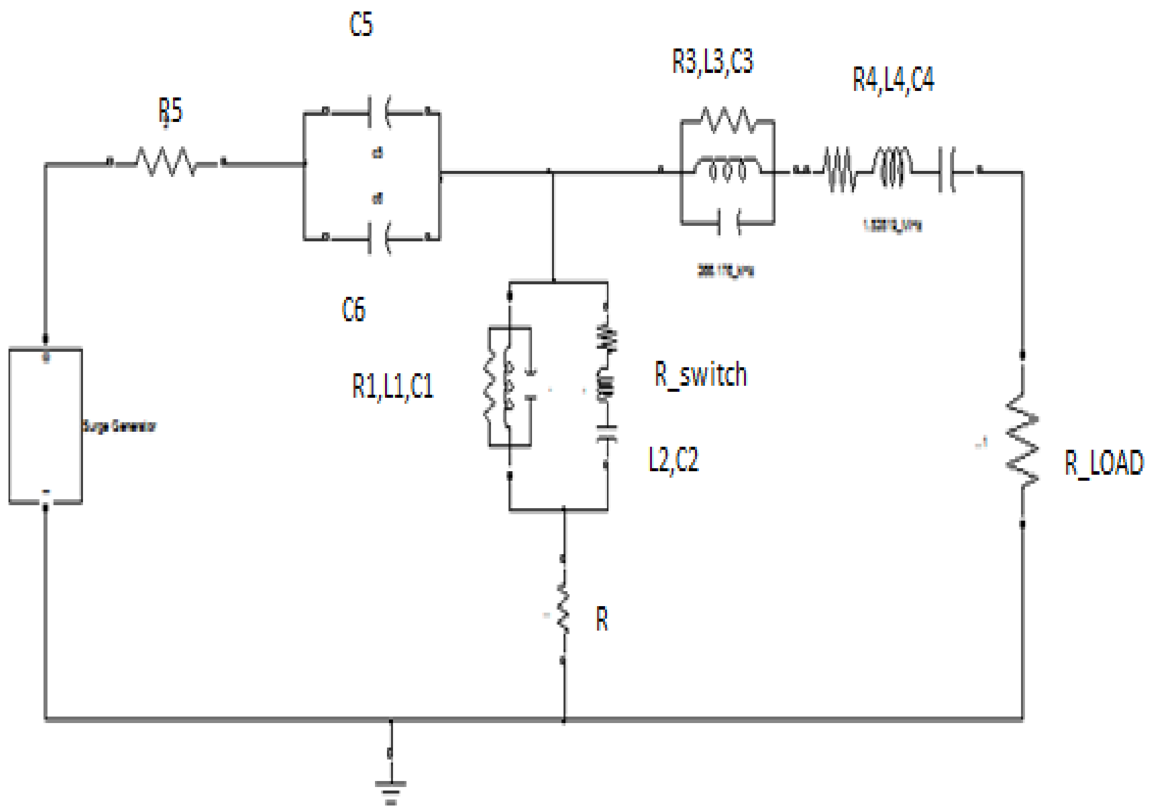


Figure 5-11 transformer model with resistive load (resistive load)

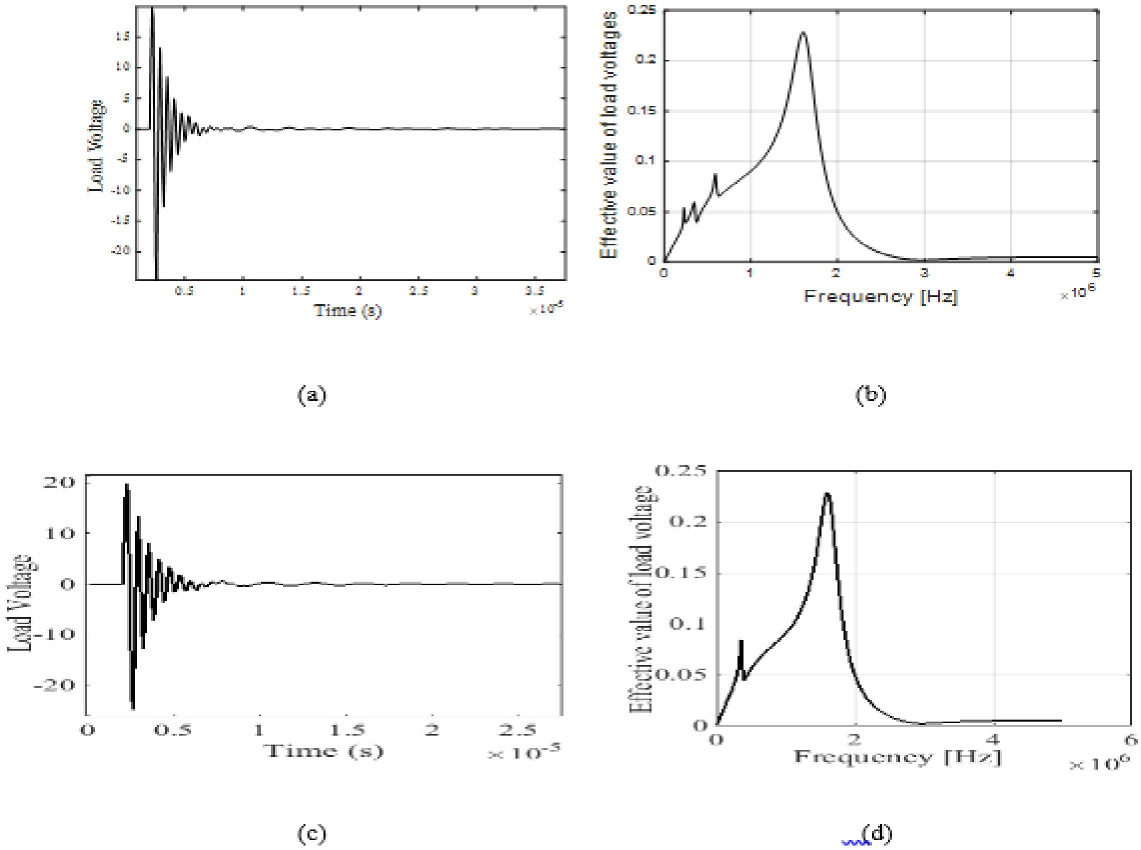


Figure 5-12 50Ω load (for dual resonance) (a) time domain response (b) frequency response (for single resonance) (c) time domain response (d) frequency response

Figure 5-12 represents the model validation with a resistive load. The single and dual resonance frequency of the model appearing correctly indicate that the model is valid for the design of a resistive load protection.

The results of figure 5-12 (a) & (b) agree with the results presented by [28] in its figure 9.

Similarly, the transformer model was also tested for a non-resistive load.

The good agreement between the single and dual resonance frequency obtained is shown in figure 5-13.

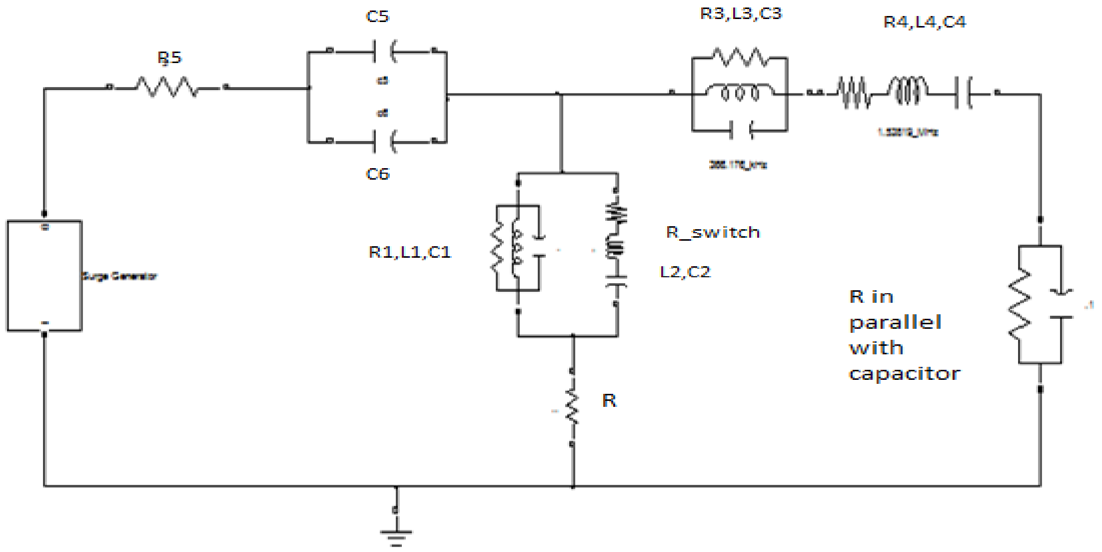


Figure 5-13 Transformer model with resistive in parallel with capacitive load (non-resistive load)

The results of figure 5-13 (a) & (b) agree with the results presented by [28] in its figure 10.

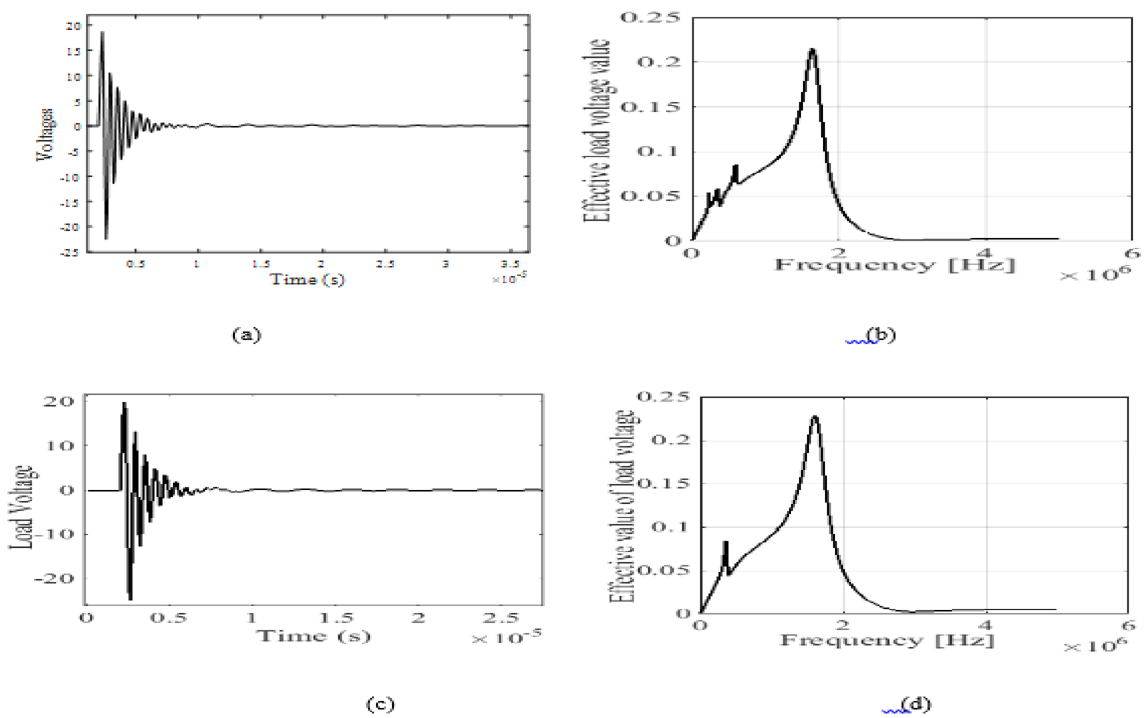


Figure 5-14 *50Ω in parallel with 1200µf load at secondary (for dual resonance) (a) time domain response (b) frequency response (for single resonance) (c) time domain response (d) frequency response*

To observe the behavior of the transformer, different types of loads are applied at the secondary, i.e., resistive, capacitive etc. to see the behavior of the frequencies.

First, a resistive load is applied and we see the single and dual resonance occurrence behavior. After that, we applied a resistive in parallel with a capacitor to see the single and dual resonance frequencies.

It is observed that, under two resonances, the transformer model is capable to carry the load as well which is the agreement the verification of the model as in the response Sabiha[28].Also, the model agrees with the single resonance loading conditions of the model Piantini[26].

5.7 Mathematical expression of transfer function

The literature about the transfer function methodology provides information on its use in different applications such as to determine mechanical faults in power transformers, i.e. displacement and winding physical status, using frequency response analysis [53], [54], [55]. By means of the transfer function method, it is possible to detect faults, such as inter-turn, transient faults or over-voltages by analyzing the on-load and off-load. In [58], [59] the transfer function method is used to determine the faults in power transformers during different phases of manufacturing. The transfer function method is also used for insulation condition analysis of transformers as described in [60] [61]. Usually, the transformer model parameters are calculated using information about the transformer under examination. That was a complex method of mesh and nodal analysis described in [56], and also adopted in [57]. For the transfer function analysis, the RLC elements need to be found. In this regard, for lumped parameter analysis is used for modeling the transformer. The magnetic effects analysis with known geometrical configurations of transformer i.e. inter-turns voltages and currents. The calculation adopted using nodal and mesh analysis that was itself a complex method because a system was deform from series to parallel for completing single step and it is repeated for complete windings of “n” number of turns.

In this section, the simulated results of a transformer under transients are mathematically modeled using the transfer function method for transfer voltages calculation. The complete method of modeling (using the transfer function method) has been presented in section 3.4.1, chapter 3.

5.7.1 Impulse voltage analysis

The impulse voltage analysis consists of two basic tests: high voltage side to low voltage side, the purpose of which is to determine the transfer voltage g(s) and low voltage side to high voltage side, which is also used to determine the transfer voltage.

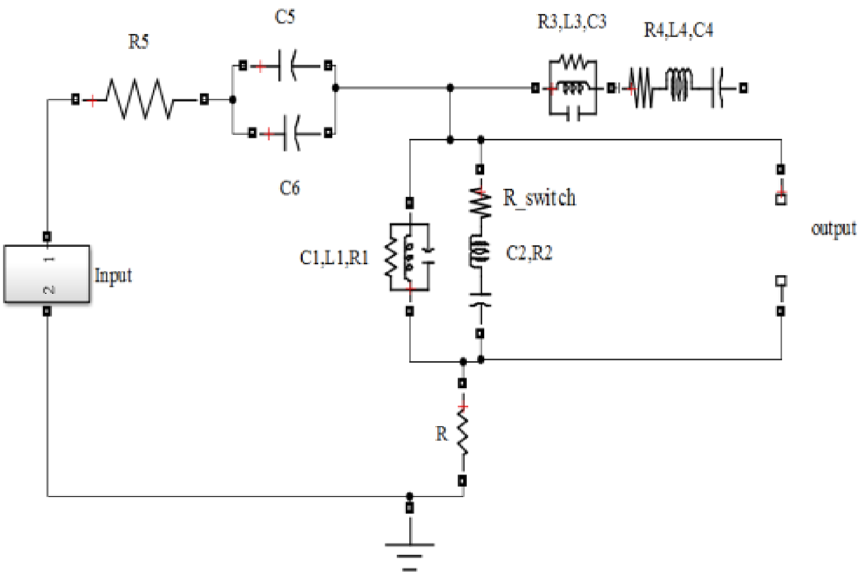


Figure 5-15 Modified model transfer function HV-LV

In the modified model is shown in figure 5-15. The output at the secondary side and the input at primary side (surge generator) are used to determine the transfer voltage. The Laplace domain representation of the transfer function is given below, where g(s) is the transfer voltage of the system.

$$Z1 = \frac{L_1 R_1 s}{s^2 C_1 L_1 + R_1 C_1 s + 1} \qquad (5\text{-}1)$$

$$Z2 = \frac{s^2 C_2 L_2 + R_{switch} C_2 s + 1}{C_2 s} \quad (5\text{-}2)$$

$$Za = \frac{1}{(C_6 + C_5)s} \quad (5\text{-}3)$$

$$g(s) = \frac{\frac{Z_a Z_1}{Z_a + Z_1}}{(\frac{Z_a Z_1}{Z_a + Z_1}) + R + Z_a + R_5} \quad (5\text{-}4)$$

Similarly, another transfer voltage expression is determined using the same procedure with the low voltage to high voltage test configuration.

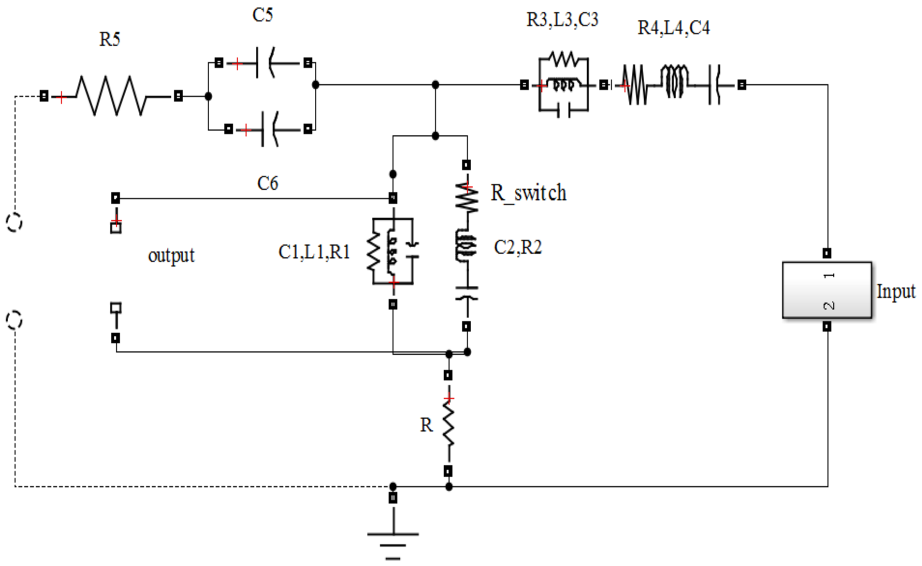


Figure 5-16 Modified model transfer function LV-HV

In the model shown in figure 5-16, the impulse generator is applied on the low voltage side whereas the transfer voltage is determined by the primary side output voltage and the input as the secondary side voltage. The mathematical calculations are given below.

$$Z1 = \frac{L_1 R_1 s}{s^2 C_1 L_1 + R_1 C_1 s + 1} \quad (5\text{-}5)$$

$$Z2 = \frac{s^2 C_2 L_2 + R_{switch} C_2 s + 1}{C_2 s} \quad (5\text{-}6)$$

$$Zb = \frac{L_3 R_3 s}{s^2 C_3 L_3 + R_3 C_3 s + 1} \qquad (5\text{-}7)$$

$$Za = \frac{s^2 C_4 L_4 + R_4 C_4 s + 1}{C_4 s} \qquad (5\text{-}8)$$

$$g(s) = \frac{\frac{Z_1 Z_2}{Z_1 + Z_2}}{(\frac{Z_1 Z_2}{Z_1 + Z_2}) + R + Z_a + Z_b} \qquad (5\text{-}9)$$

5.8 Conclusion

In this chapter, a high frequency model has been presented which has been tested at loading conditions for single and two resonant frequencies. The proposed single resonance model has been validated by two models found in the literature: the Piantini's model at a single resonance frequency presented in [26] and the Sabiha's model, at two resonance frequencies presented in [28].These are verified by two-port network theory, unloaded transfer under time domain and frequency domain analysis(see figure 5-9 and 5-10),and transformer loading under two (resistive/non-resistive) loads using the transfer function method (see figure 5-11 to 5-14). The accountability of simplicity has been taken into account. The results of figures 5-9 and 5-10 are validated by results presented by [26] & [28] in figure 6 in both.

The presented model is an option for any model of a distribution transformer in order to design an overvoltage protection scheme because it provides flexibility to adjust resonance frequencies as required. It has been observed from experimental results of researches that output transfer overvoltages cannot exceed by two resonances. The proposed model is capable to carry at most dual resonance frequencies. Also, this model is capable to carry single resonance loading as well the modification proposed by Piantini.

The mathematical results of the transfer voltages g(s) have been also computed.

CONCLUSIONS OF THESIS

The high frequency transformer model presented by Sabiha at two resonance frequencies under both, loaded and unloaded output was used as a reference model for modification and further enhancement. A transformer with 25kVA capacity was tested at the High Voltage Lab in the UPC, Terrassa, Spain, under the effect of impulse voltage and the recorded digital data were stored via oscilloscope in a computer. An algorithm was developed to estimate the transformer parameters by the transfer function method using Fast Fourier Transform analysis. In this scheme, the two-port network theory concept was taken for a black box analysis of the transformer. The series of transient frequencies of experimental digital data were noted. The transformer parameters, such as Z11, Z12, Z21, and Z22, were calculated a tall these frequencies in order to generate a narrow band of correct frequencies at which the transients were developed experimentally and therefore it has to be developed on that specific frequencies. Earlier, the transfer function method was used for the mechanical deformation analysis in the transformer. Now, a similar method of modeling is used to estimate the parameters of the transformer and to propose an accurate transformer model for two resonance frequencies only and the parameter estimation was based simply on placing RLC elements. The proposed model was also tested and validated for accuracy and reliability.

In the second phase of research, high frequency models of transformer for protection from the transients based on experimental data were presented, which were tested and validated for unloaded and loaded conditions and for single and dual resonant frequencies using the transfer function method. The proposed single resonance model leads to a further two models which are verified by the two-port network theory, unloaded transfer under time domain and frequency domain analysis, transformer loading under different loads and transfer function method. The accountability of simplicity have been taken into account.

The presented model is an option for any distribution transformer protection scheme because it provides flexibility to adjust resonance frequencies as required. It has been observed from experimental results of researches that output do not exceed two resonances; the proposed model is capable to carry at most dual resonance frequencies. Also, this model is capable to carry single resonance loading as well, which is a modification of the Piantini model.

The suggestion for future work is to use a different methodology of transformer life estimation using FFT analysis and the transformer's internal condition using the same approach can be adopted along with neural network, vector fitting techniques to define the transformer bandwidth operating region.

The literature of different models at higher frequencies can be divided into three categories: Single resonance frequency models, two resonance frequencies models and black box analysis models. Most of these models deal with the behavior of the transformer under transients in loadedand unloaded conditions. Another category of transformer modeling deals with the parameter estimation of transformers under transients using black box analysis.

The work methodology is described in chapter three. The novel idea of parameter estimation using the transfer function method and its complete procedure are described to understand the modeling procedure of the transformer under transients. Conventional internal faults or the transformer's mechanical deformation is formulated using the transfer function method. In this proposed modeling approach, the transformer transfer function method is used to estimate the parameters of the transformer using the two-port network theory analysis. In chapter four, a transformer model at high frequencies is proposed. The proposed model is validated and tested for unloaded conditions. The novelty of the proposed model is the simplicity of its parameter estimation using the transfer function method. The transformer modeling is carried out from experimental data. The primary and secondary side parameters are calculated from experimental data using the transfer function method. The magnetizing side parameters are selected and validated using tuning effects in which the magnetizing side from HV-LV and LV-HV is equal.

In chapter five, a second model of transformer is presented which is validated for the single and dual resonance frequencies presented by Piantini and Sabiha in their research. The proposed model is also tested for loaded and un-loaded conditions. The magnetizing side impedance for single and two resonance frequencies is obtained graphically using FFT analysis. The mathematical expressions for the transfer function are also calculated for the proposed model. The bode diagram of the proposed model for both, i.e. HV to LV and LV to HV, is also calculated.

Appendix A

```
% FUNCTION FOR THE CALCULATION OF THE FFT WITHOUT WINDOWING (ONLY VALID FOR
% SURGE VOLTAGES OR TRANSIENT ANALYSIS WITH NON PERIODICAL FUNCTIONS.

% THIS FUNCTION CALCULATES THE FFT OF THE INPUT AND OUTPUT DATA OF A
% SYSTEM

% ONCE BOTH FFT ARE CALCULATED THE FFTO OF THE TRANSFER FUNCTION
% OUTPUT/INPUT IS ALSO OBTAINED

function
[MAGNITUDEINPUT,PHASEINPUT,MAGNITUDEOUTPUT,PHASEOUTPUT,MAGNITUDETransFunct,PHASET
rasnFunct,FREQUENCIESINPUT,FREQUENCIESOUTPUT]=FFTtransfFunct(INPUT,OUTPUT,Tsample
)

%FFT of the INPUT
%Total time record is calculated
TrecordInput=length(INPUT)*Tsample;

%Frequency resolution is calculated
DeltafInput=1/TrecordInput;

% Since the FFT produces a dual results data must be multiplied by 2 and
% divided by the total length of the record

fftresultsInput=fft((INPUT)*2/length(INPUT));

% Calulation of the modules of the complex results
modulesInput=abs(fftresultsInput);

% First element is in the centre of the spectrum thus it does not need
% to be multiplied by 2. This is why it is now divided by 2 it is the DC
% component. If you want to have it you must write the following sentence:
% modules(1)=modules(1)/2; in our case it is filtered:

modulesInput(1)=0;

% Calculation of angles in radians

anglesradInput=angle(fftresultsInput);

%Calculation of angles in degrees
anglesInput=anglesradInput*(180/pi);

%Calculation of frequencies
fInput=(0:length(fftresultsInput)-1)'*DeltafInput;

%Only positive frequencies are needed. Therefore only 1/2 of the total date
%are taken

lengthmodulesInput=round((length(modulesInput)/2));
lengthanglesInput=round((length(anglesInput)/2));
lengthfrequenciesInput=round((length(fInput)/2));

MAGNITUDEINPUT=(modulesInput(1:lengthmodulesInput));
PHASEINPUT=(anglesInput(1:lengthanglesInput));
```

```
FREQUENCIESINPUT=(fInput(1:lengthfrequenciesInput));

figure(1);
subplot(2,1,1);plot(FREQUENCIESINPUT,MAGNITUDEINPUT);ylabel('Module
Input');xlabel('Frequency [Hz]');grid on;
subplot(2,1,2);plot(FREQUENCIESINPUT,PHASEINPUT);xlabel('Frequency Input [Hz]');
ylabel('Phase degrees');grid on;

%FFT of the OUTPUT

%Total time record is calculated
TrecordOutput=length(INPUT)*Tsample;

%Frequency resolution is calculated
DeltafOutput=1/TrecordOutput;

fftresultsOutput=fft((OUTPUT)*2/length(OUTPUT));

% Calulation of the modules of the complex results (results in dB)
modulesOutput=abs(fftresultsOutput);

% First element is in the centre of the spectrum thus it does not need
% to be multiplied by 2. This is why it is now divided by 2 it is the DC
% component. If you want to have it you must write the following sentence:
% modules(1)=modules(1)/2; in our case it is filtered:

modulesOutput(1)=0;

% Calculation of angles in radians

anglesradOutput=angle(fftresultsOutput);

%Calculation of angles in degrees
anglesOutput=anglesradOutput*(180/pi);

%Calculation of frequencies
fOutput=(0:length(fftresultsOutput)-1)'*DeltafOutput;

%Only positive frequencies are needed. Therefore only 1/2 of the total date
%are taken

lengthmodulesOutput=round((length(modulesOutput)/2));
lengthanglesOutput=round((length(anglesOutput)/2));
lengthfrequenciesOutput=round((length(fOutput)/2));

MAGNITUDEOUTPUT=(modulesOutput(1:lengthmodulesOutput));
PHASEOUTPUT=(anglesOutput(1:lengthanglesOutput));
FREQUENCIESOUTPUT=(fOutput(1:lengthfrequenciesOutput));

figure(2);
subplot(2,1,1);plot(FREQUENCIESOUTPUT,MAGNITUDEOUTPUT);ylabel('Module
Output');xlabel('Frequency [Hz]');grid on;
subplot(2,1,2);plot(FREQUENCIESOUTPUT,PHASEOUTPUT);xlabel('Frequency Output
[Hz]'); ylabel('Phase degrees');grid on;

%Calculation of the Transfer Function Output/Input
lines=length(FREQUENCIESOUTPUT)
```

```
for p=1:lines
    MAGNITUDETransFunct(p)=abs(fftresultsOutput(p)/fftresultsInput(p));
    PHASETrasnFunct(p)=angle(fftresultsOutput(p)/fftresultsInput(p))*180/pi;
end

figure(3);
subplot(2,1,1);plot(FREQUENCIESOUTPUT,MAGNITUDETransFunct);ylabel('Module Tranfer
Function');xlabel('Frequency [Hz]');grid on;
subplot(2,1,2);plot(FREQUENCIESOUTPUT,PHASETrasnFunct);xlabel('Frequency Transfer
[Hz]'); ylabel('Phase degrees');grid on;
```

Appendix B

Transfer function due to primary side

$$TF = \frac{V_{out}}{V_{in}} = \frac{z_{12}}{z_{12} + z_{56}}$$

$$z_{12=} \begin{matrix} s^5[L_1 + L_2]R_1R_2C_1C_2C_5L_1L_2 + s^4L_1L_2C_5\left[{R_1}^2R_2C_1C_2 + R_1L_1C_1 + {R_2}^2R_1C_1C_2 + R_2L_2C_2\right] + \\ s^3C_5\left[{R_1}^2C_1L_1L_2 + {L_1}^2R_1R_2C_1 + {R_2}^2C_2L_1L_2\right] + s^2R_1R_2C_5[R_1L_1C_1 + R_2L_2C_2] \end{matrix}$$

$$\begin{aligned}
z_{12} + z_{56} = {} & R_1R_2C_2L_1L_2^2 + R_1R_2^2C_1C_2^2L_1L_2 + R_1R_2L_1L_2^2C_1C_2 + L_1^2L_2^2] + [R_1^2R_2L_1L_2^2C_1^2C_2 \\
& + R_1R_2^2L_1^2L_2C_1C_2^2 + R_1L_1^2L_2^2C_1 + R_2L_1^2L_2^2C_2]\} \\
& + S^4\{(L_1L_2C_5[R_1^2R_2C_1C_2 + R_1L_1C_1 + R_2^2R_1C_1C_2 + R_2L_2C_2]) \\
& + L_6C_5(R_1^2R_2^2L_1C_1^2C_2 + R_1^2R_2^2C_1C_2^2L_2 + R_1R_2L_1L_2 + R_1^2C_1L_2^2 + R_1R_2L_1L_2C_2 \\
& + R_1R_2L_1L_2C_1 + L_1R_2C_2 + R_1R_2L_1L_2C_1C_2) \\
& + [(R_5 + R_6)C_5][R_1^2R_2L_1L_2C_1^2 + R_1R_2^2L_1^2C_1C_2 + R_1^2R_2L_1L_2C_1^2C_2 + R_1^2R_2C_1C_2L_2^2 \\
& + R_1R_2^2L_1L_2C_1C_2 + R_1L_1L_2^2 + R_1R_2^2L_1L_2C_1C_2^2 + R_2L_1^2L_2 + R_1C_1L_1L2_2^2 + R_2L_1^2L_2C_2] \\
& + [R_1^2R_2^2C_1^2C_2^2L_1L_2 + R_1R_2C_1L_1^2L_2 + R_1^2L_1L_2^2C_1^2 + R_1R_2L_1^2L_2C_1C_2 + R_1R_2C_2L_1L_2^2 \\
& + R_1R_2^2C_1C_2^2L_1L_2 + R_1R_2L_1L_2^2C_1C_2 + L_1^2L_2^2]\} \\
& + S^3\{(C^5[R_1^2C_1L_1L_2 + L_1^2R_1R_2C_1 + L_2^2R_1R_2C_2 + R_2^2C_2L_1L_2]) \\
& + (C_5L_6[R_1^2R_2C_1L_2 + R_1R_2^2L_1C_2 + R_1^2R_2C_1C_2L_2 + R_1R_2^2C_1C_2]) + \{(R_5 \\
& + R_6)C_5[R_1^2R_2^2L_1C_1^2C_2 + R_1^2R_2^2C_1C_2^2L_2 + R_1R_2L_1L_2 + R_1^2C_1L_2^2 + R_1R_2L_1L_2C_2 \\
& + R_1R_2L_1L_2C_1 + L_1R_2C_2 + R_1R_2L_1L_2C_1C_2]\} + [R_1^2R_2L_1L_2C_1^2 + R_1R_2^2L_1^2C_1C_2 \\
& + R_1^2R_2L_1L_2C_1^2C_2 + R_1^2R_2C_1C_2L_2^2 + R_1R_2^2L_1L_2C_1C_2 + R_1L_1L_2^2 + R_1R_2^2L_1L_2C_1C_2^2 \\
& + R_2L_1^2L_2 + R_1C_1L_1L_2^2 + R_2L_1^2L_2C_2]\} \\
& + S^2\{[R_1R_2C_5(R_1L_1C_1 + R_2L_2C_2)] + C_5L_6R_1^2R_2^2C_1C_2 \\
& + \{C_5(R_5 + R_6)\}\{R_1^2R_2C_1L_2 + R_1R_2^2L_1C_2 + R_1^2R_2C_1C_2L_2 + R_1R_2^2C_1C_2\} \\
& + (R_1^2 + R_2^2L_1C_1^2C_2 + R_1^2R_2^2C_1C_2L_2 + R_1R_2L_1L_2 + R_1^2C_1L_2^2 + R_1R_2L_1L_2C_2 \\
& + R_1R_2L_1L_2C_1 + L_1R_2C_2 + R_1R_2L_1L_2C_1C_2)\} \\
& + S^1\{[(R_5 + R_6)C_5(R_1^2R_2^2C_1C_2)] \\
& + [R_1^2R_2C_1C_2 + R_1R_2^2L_1C_2 + R_1^2R_2C_1C_2L_2 + R_1R_2^2C_1C_2]\} + S^0\{R_1^2R_2^2C_1C_2\}
\end{aligned}$$

Transfer function due to secondary side

$$z_{12}=\frac{s^4[L_1+L_2]R_1R_2C_1C_2L_1L_2+s^3L_1L_2\left[R_1{}^2R_2C_1C_2+R_1L_1C_1+R_2{}^2R_1C_1C_2+R_2L_2C_2\right]+}{s^2\left[R_1{}^2C_1L_1L_2+L_1{}^2R_1R_2C_1+R_2{}^2C_2L_1L_2\right]+sR_1R_2[R_1L_1C_1+R_2L_2C_2]}$$

$$\begin{aligned}
z_{12}+z_{34} = {} & s^7(L_3+L_4)\left(R_1R_2L_1{}^2L_2{}^2C_1C_2\right) \\
& + s^6\left[(L_3+L_4)\left(R_1{}^2R_2L_1L_2{}^2C_1{}^2C_2+R_1R_2{}^2L_1{}^2L_2C_1C_2{}^2+R_1L_1{}^2L_2{}^2C_1+R_2L_1{}^2L_2{}^2C_2\right)\right. \\
& \left. + (R_3+R_4)\left(R_1R_2L_1{}^2L_2{}^2C_1C_2\right)\right] \\
& + s^5\left[\left\{(R_3+R_4)\left(R_1{}^2R_2L_1L_2{}^2C_1{}^2C_2+R_1R_2{}^2L_1{}^2L_2C_1C_2{}^2+R_1L_1{}^2L_2{}^2C_1+R_1{}^2L_1L_2{}^2C_1{}^2\right.\right.\right. \\
& \left.\left. + R_1R_2L_1{}^2L_2C_1C_2+R_1R_2C_2L_1L_2{}^2+R_1R_2{}^2C_1C_2{}^2L_1L_2+R_1R_2L_1L_2{}^2C_1C_2+L_1{}^2L_2{}^2\right)\right\} \\
& + \left\{(L_3+L_4)R_1{}^2R_2{}^2C_1{}^2C_2{}^2L_1L_2+R_1R_2C_1L_1{}^2L_2+R_1{}^2L_1L_2{}^2C_1{}^2+R_1R_2L_1{}^2L_2C_1C_2+R_1R_2C_2L_1L_2{}^2\right. \\
& \left.\left. + R_1R_2{}^2C_1C_2{}^2L_2L_2+R_1R_2L_1L_2{}^2C_1C_2+L_1{}^2L_2{}^2\right\}\right] \\
& + s^4\left[(L_1+L_2)R_1R_2C_1C_2L_1L_2\right. \\
& + (R_3+R_4)\left(R_1{}^2R_2{}^2C_1{}^2C_2{}^2L_1L_2+R_1R_2C_1L_1{}^2L_2+R_1{}^2L_1L_2{}^2C_1{}^2+R_1R_2L_1{}^2L_2C_1C_2+R_1R_2C_2L_1L_2{}^2\right. \\
& \left. + R_1R_2{}^2C_1C_2{}^2L_2L_2+R_1R_2L_1L_2{}^2C_1C_2+L_1{}^2L_2{}^2\right) \\
& + (L_3+L_4)\left(R_1{}^2R_2L_1L_2C_1{}^2+R_1R_2{}^2L_1{}^2C_1C_2+R_1{}^2R_2L_1L_2C_1{}^2C_2+R_1{}^2R_2C_1C_2L_2{}^2+R_1R_2{}^2L_1L_2C_1C_2\right. \\
& \left.\left. + R_1L_1L_2{}^2+R_1R_2{}^2L_1L_2C_1C_2{}^2+R_2L_1{}^2L_2+R_1C_1L_1L_2{}^2+R_2L_1{}^2L_2C_2\right)\right] \\
& + s^3\left[\left\{L_1L_2\left(R_1{}^2R_2C_1C_2+R_1L_1C_1+R_2{}^2R_1C_1C_2+R_2L_2C_2\right)\right\}\right. \\
& + (R_3+R_4)\left(R_1{}^2R_2L_1L_2C_1{}^2+R_1R_2{}^2L_1{}^2C_1C_2+R_1{}^2R_2L_1L_2C_1{}^2C_2+R_1{}^2R_2C_1C_2L_2{}^2+R_1R_2{}^2L_1L_2C_1C_2\right. \\
& \left. + R_1L_1L_2{}^2+R_1R_2{}^2L_1L_2C_1C_2{}^2+R_2L_1{}^2L_2+R_1C_1L_1L_2{}^2+R_2L_1{}^2L_2C_2\right) \\
& + (L_3+L_4)\left(R_1{}^2R_2{}^2L_1C_1{}^2C_2+R_1{}^2R_2{}^2C_1C_2{}^2L_2+R_1R_2L_1L_2+R_1{}^2C_1L_2{}^2+R_1R_2L_1L_2C_2\right. \\
& \left.\left. + R_1R_2L_1L_2C_1+L_1R_2C_2+R_1R_2L_1L_2C_1C_2\right)\right] \\
& + s^2\left[\left\{R_1{}^2C_1L_1L_2+L_1{}^2R_1R_2C_1+R_2{}^2C_2L_1L_2+L_2{}^2R_1R_2C_2\right\}\right. \\
& + (R_3+R_4)\left(R_1{}^2R_2{}^2L_1C_1{}^2C_2+R_1{}^2R_2{}^2C_1C_2{}^2L_2+R_1R_2L_1L_2+R_1{}^2C_1L_2{}^2+R_1R_2L_1L_2C_2\right. \\
& \left. + R_1R_2L_1L_2C_1+L_1R_2C_2+R_1R_2L_1L_2C_1C_2\right) \\
& \left. + (L_3+L_4)\left(R_1{}^2R_2C_1L_2+R_1R_2{}^2L_1C_2+R_1{}^2R_2C_1C_2L_2+R_1R_2{}^2C_1C_2\right)\right] \\
& + s\left[\left\{R_1R_2\left(R_1L_1C_1+R_2L_2C_2\right)\right\}+(R_3+R_4)\left(R_1{}^2R_2C_1L_2+R_1R_2{}^2L_1C_2+R_1{}^2R_2C_1C_2L_2+R_1R_2{}^2C_1C_2\right)\right. \\
& \left. + (L_3+L_4)\left(R_1{}^2R_2{}^2C_1C_2\right)\right]+R_1{}^2R_2{}^2C_1C_2
\end{aligned}$$

$$TF=\frac{V_{out}}{V_{in}}=\frac{z_{12}}{z_{12}+z_{34}}$$

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