ANALYSIS OF VOLTAGE DISTRIBUTION IN POWER TRANSFORMER WINDINGS DURING VERY FAST TRANSIENT OVER-VOLTAGES

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Submitted By

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CANDIDATE'S DECLARATION

I hereby declare that this thesis report entitled **ANALYSIS OF VOLTAGE DISTRIBUTION IN POWER TRANSFORMER WINDING DURING VERY FAST TRANSIENT OVER VOLTAGE**, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical Engineering with specialization in power system engineering is an authentic record of the work carried out by me during the period June 2015 through May 2016, under the supervision of **Dr. G. KUMBHAR, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.** The matter presented in this thesis report has not been submitted by me for the award of any other degree of this institute or any other institutes.

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CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

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ABSTRACT

In this work, the non-linear voltage distribution in transformer winding is investigated that occurs due to switching and lightning. The major factors that contribute to premature insulation failure are lightning/line surges, switching over voltages and internal over voltages. It is imperative to determine the voltage behavior across winding during such transient switching voltages. So requirement is to develop a suitable model which can describe accurately the voltage distribution. Various model has been proposed to determine the driving point impedance and voltage characters. As the frequency varies the model requirement also changes at low frequencies lumped or general model can be followed but as frequencies goes higher the model has to be distributed where the complete capacitive, inductive and resistive effect of each small section need to take into consideration. In this report first three models have been discussed. First ladder type model, then multi conductor transmission line model and then combination of both, hybrid model is discussed and differentiated. However relevant study describes MTL model which gives highly precise results when the frequencies reach up to various MHz ranges. In the present work, first winding parameters are calculated which is based on the geometrical structure of the winding, then work is done on the multi conductor transmission line model with the help of which voltage distribution in the winding is estimated. the modeling of the winding is done in the frequency domain.Also in the thesis work, the comparison between the continuous and interleaved winding is performed, various parameter for interleaved winding is also calculated and then voltage distribution is estimated.Comparison of voltage pattern across both winding is carried out at different frequency. Once the model accuracy is checked it can be applied to estimate the partial discharge or any insulation failure of the winding during transients.

Acknowledgements

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Chapter 1

INTRODUCTION

There are various factors which do affect condition and the time of life of the insulation in a winding of the transformer. There are numerous factors which are responsible for the before time insulation failure which are lightning Surges,over voltages caused due to switching and developed internal over voltages. Because of these fast transients, problem of resonance can be occurred or generally arise. when a surge wave passes through a winding the phenomenon of resonances occurs at certain frequency which causes very high transients over voltages. Other kind of problem related to very Fast Transient Over voltages (VFTOs) those generated because of switching operations. Such over voltage which are of short duration can cause heavy damage to the transformer. They can also cause deforming or non-linear voltage distribution across transformer windings. In certain cases, voltages of some inter turns may reach to above the basic insulation level . These problems may either break down the insulation or may initiate the partial discharge which degrades the insulation quality and soon if process continues for a long time proper breakdown may occur to transformer insulation. Such happening of over voltages that occur in the winding which are cumbersome to detect and measure. So it is require to use proper high frequency model which is necessary for the transformer savior purpose. Because there is inclusion of high frequency electromagnetic transient so modeling of for such purpose require typical high frequency analysis.At high frequency various parameter like inductances(self and mutual) ,capacitance (between turns, between turn to ground) and resistances affect highly. It is imperative to determine them as per the geometrical and frequency dependencies. So its indispensable to find the behavior of these parameter with the help of winding geometry and obtain the accurate distributed parameters. As high frequency operation is considered the skin effect and proximity concept will have to take into consideration as their effect is highly noticeable.

1.1 Problem statement

Life of transformer especially the insulation is heavily affected from the various reasons that include major factors like over voltages due to switching, surges produced due to lightning and internal over voltages.During such instances very high frequency transients produces abnormal voltages , nonlinear voltages which tends to affect the transformer windings and insulation. Pre evaluation and determination of abnormalities that occur during such circumstances is of prime importance hence the required insulation can be suggested. So we can be able to overcome such situations like partial discharge and various other deformities that occur due to very high and nonlinear voltages.With the help of which fast transformer aging can be arrested and hence the transformer can be guarded from such high voltages. In case the transformer is subjected to such incidents then through the proper modeling the defect location can be find out and corresponding remedies can be taken hence forth. Generally at high frequency the inter turn capacitances and turn to turn capacitances play a major role as capacitive impedance becomes very low as compared to the inductances and resistive impedance so the most current passes through the capacitance leading to the large voltage drop in the very start of the winding.This leads to very large voltage difference between very few turns. So the problem of related insulation failure occurs which has to be restricted by proper modeling and experiments related to various winding structures.

1.2 Objectives of Dissertation Work

The objectives of this dissertation work includes to develop a model for high frequency and very high frequency transients those are resemble to transients that occur during lighting and switching of GIS etc. First the model is developed for the checking and simulate the exact behavior of non-linear voltages that occur during such transients. Then the required objective can be fulfilled like location of partial discharge.

1.3 Organisation of Report

This report is organized as follows: Chapter 2 describes literature survey done for the project work. Chapter 3 describes and classify various over voltages those may hamper the insulation. They are fully described and their origins are studied.Chapter 4 is dealing with various model and their comparison especially the multi conductor transmission line model is throughly used in the project. However, the comparison is also done with other models. Chapter 5 deals with all the parameter calculations of transformer windings.Chapter 6 discusses all the results that obtained from the MTL model. Conclusions and scope for future work are stated in Chapter 7.

Chapter 2

LITERATURE REVIEW

In the fine span of recent years various transformer unusual failures were reported. It has been noticed, that in various countries different categories include both dry and oil-filled type of transformers were investigated and it was clearly found, that they are exposed to various over voltages. Through inquiry was done but, no such clear faults regarding design or manufacturers was found out, at least publically. After lot of studies, it was getting the doubt that the , internal resonances may be the most common cause of such circumstances [2]. K.U. Leauven in 2006 investigated and found the internal resonance behavior or phenomenon in practical winding of various low and medium voltage transformers.He got that the occurrence of such faults are these resonances which produces due to combinations of such impedances, the various type of Switching transients arise because of multiple re-strikes, internal resonance those occurs in the transformer winding. This abnormalities causes material declension by biased discharges. When a circuit breaker chops the highly inductive currents which produces a voltage rise after which the sudden release of huge magnetic energy that is stored in the inductive component. Manifold re-ignitions which are produced in the circuit breaker can create continual pulses with a sweeping frequency spectrum, and which may excite the self-generated frequencies of the transformer. For many years so many people have studied internal faults related to transformer resonances. These various studies are related to high insulation failure rate in high voltage transformers at that time. However after throughly work on resonance, Mr K.U Luaeve made some conclusions regarding the behavior out of them, these are also valid for various distribution transformers, as follows

- Resonance frequency which cause the problems were found between 40 Khz and 8 Mhz, they are considered to be origin from fast transients
- over voltage which are produced because of these resonances cannot be measure at the terminals as they appear inside the winding.
- In order to make the required measurement at multiple points inside the winding, their is requirement of some special prototypes of transformer
- Various protective and defensive devices used for arresting the lighting and other surges at the terminal are not able to protect against resonance [2]

.

As the insulation problem is of very much concern when it comes to transformer and rotating machines because they are dealing with huge voltages. These huge voltages generally comes from outside or inside .These self generated internal heavy voltages have much importance because they produces resonance in the winding and also have huge effect of insulation failure. These over voltages will not cause sudden and immediate breakdown, but will generally only cause a partial discharge, due to which winding insulation aging gets faster[1, 3]. In all around the world various transformer insulation failure case have been found and reported in spite of being properly tested and complied to all the industry based test also passed quality based requirements. In order to understand the effects of the various electromagnetic transients which are initiated either by lighting or causes of switching based for different equipment wide range is required in frequency representation of various machines like transformers, reactors, rotating machines. During the design phase of these heavy voltage machines, it is required to have proper cognition about the voltage stress across winding sections. So proper and economical usage of insulation material can be made. When reference is taken to the high voltages (HV) and extra high voltage(EHV) based networks, the requirement is to have a knowledge and prediction of voltage stress across winding and hence finding the critical points in a winding which is a dire need of manufacturing such huge apparatus. Also the knowledge of possible voltage stresses at critical points is necessary for better and efficient insulation coordination and protection across winding. From past ten to fifteen years around thousand of many publications have been published and analysis made on the variety of surge performance in the various case of high voltage transformers and multi rotating machines. In the commencement, mainly analytical methods people were using to made the model the transformer windings under transients. There after in the years, people have used numerical methods that were introduced to get much more accurate results.The geometry of the various later models is nearly resembling that of the the actual transformer. Lumped parameter, single and multi conductor transmission line models are some more popular and mostly used type of models categorized for numerical methods. Broadly, it is assumptive that winding spatiality, various material constants and other related constructional details are known. However, in some of the special cases which are related to the huge power system transients,acted on transformers, reactors winding and the rotating part of machines when these are considered as a system components and because of it generally there is not proper or insufficient information and parameter available regarding internal structure of the transformer and related huge apparatus. Various studies those are actually dealing with the very high and high frequency modeling of the related power system equipment those are based on some external measurements they have been published. such outside measurements based on the geometry can either be performed in the frequency domain or in the time domain [16]. When many transient oscillations those are having a steep front enter from one and other system into a transformer, in the starting time it generally reacts as a system or group of capacitances. The values of various resistance, inductances and capacitances undergo vast temporary changes if we compare them from their normal conditioned values due to dependency of them on the frequency as all vary significantly at high frequency. The transformer winding is used to be considered as a huge inductance. For such high and very high frequency transients, stray capacitances and turn to turn and interdisk capacitances of the windings, which very much depend on the various type of winding coils and the other winding arrangement type, which mainly check the transformers transitory response. At normal condition and operating frequencies, the capacitance effect between turns and various winding layers of different individual coils is minimal. The winding used to be said inductive or considered as inductances which used to produce and give linearly distributed voltage across winding. In contrast to linear voltage distribution, when the transformer winding is subjected to differently high or very high frequency based steep-fronted waves, in order to determine the initial voltage distribution the capacitance effect is used to be more prominent. It is because of the reason that at such huge frequency the capacitive impedance generally tend to go short circuit or go to very low values, much of the current passes through the capacitive way. In addition,when we take into account the resonance frequencies condition the voltage generally rises at certain points across the winding because of the many combinations is fulfilled for inductances and capacitances [5]. At lower frequencies capacitance can be ignored and so the same current is flowing through all turns which results in the same voltage drop. In contrast, at higher frequencies, the capacitances and leakage inductances draw currents which results in a variation in currents for each turn. The result of which will be different voltage drops across each winding segment and a nonlinear voltage distribution can be seen. The common flux which will induce the same voltage drop in every turn influences this effect to some extent. The difference will be due to the presence of the leakage capacitances and inductances. The voltage drop caused by the current in a single turn is still lower as compared to the magnetizing inductance. At the resonance, currents to some extent, cancel the magnetic field due to differences in phase in the currents [16].

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Chapter 3

CLASSIFICATION OF OVER VOLTAGES

In the different categories of voltages, over voltages have various categories. According to the origin these voltages can be divided or classified as the internal and external generated over voltages. Internally generated over voltages are those which are the results of various switching operations and different types of faults. External type of over voltages are the one which are generated by lightning strike to the power system. In the similar way such over voltages can also be categorized and classified according to their varying characteristics. These characteristics are like frequency range, signal duration, signal peak voltage amplitude and its shape. According to International Electro Technical Commission (IEC), transients are those disturbances that may occur like for a very close duration may be less than one cycle , and the electrical circuit is quickly restored to original operation provided no damage has occurred due to the transient. Now the description of such over voltages depending on their characteristics[16]

- Temporary type of over voltages: These certain types of high voltage which are little damped and have power-frequency of relatively durable duration (from several milliseconds to some seconds), mostly created by faults, resonance conditions, load rejection , or a combination of these.

- Slow-front type over voltages: These some types are of the highly damped transient over voltages of relatively short-duration (varies from a few milliseconds to a few power frequency cycles). They have a special charcterstics of being either oscillatory or unidirectional, and also their range of frequency may varies between 2 to 20 kHz. These are usually caused and generated by the faults or various switching operations.
- Fast-front type over voltages: These transient over voltages are considered of very short duration, time interval generally (less than 1 ms). They are usually highly damped and also generally unidirectional. They generally cause and creates by the means of lightning strikes or may be from switching operations.
- Very fast-front type over voltages: These are the type of transient over voltages are kind of very short duration generally (less than 1 msec). They can either be oscillatory or may be unidirectional, and their generating frequency range can vary between 100 KHz to 50MHz. The most common frequent origin, of such over voltages is because of various faults and various switching operations. [7]

Other types also includes sub cycle transients which occur randomly depending on environment and are difficult to detect due to their short duration. Conventional meters are not able to measure due to their limited frequency response. For example, if a transient occurs for 2 msec and is characterized by a frequency content of 20 kHz, the measuring instrument must have a frequency response or sampling rate of atleast 10 times 20 kHz, or 200 kHz, in order to fairly describe the characteristics of the transient. For faster type of transients, higher sampling rates or values are necessary. [1] An electrical transient which generally occur is a cause-and-effect phenomenon. If we talk of cause of such electrical transient, one can take the following effects:

- Atmospheric phenomena (lightning, solar flares, geomagnetic disturbances)
- Switching loads on or off
- Interruption of fault currents

- Switching of power lines
- Switching of capacitor banks

3.1 Characteristics of the transient voltage waveform:

The most common transient is the "oscillatory transient. This can be seen in Figure 3.1. It is sometimes described as a "ringing transient". This type of transients is characterized by swings above and below the normal line voltage.

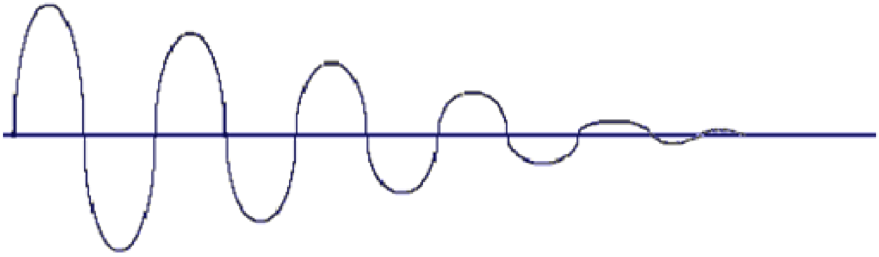


FIGURE 3.1: Oscillatory transient [16]

The other type (impulse) transient is more easily explained as a "one-shot" type of event, and it is characterized by having more than 77 percent of pulse above the line voltage. A lightning strike can be composed of multiple transients of this type. Even these type of transients can be divided up into different other

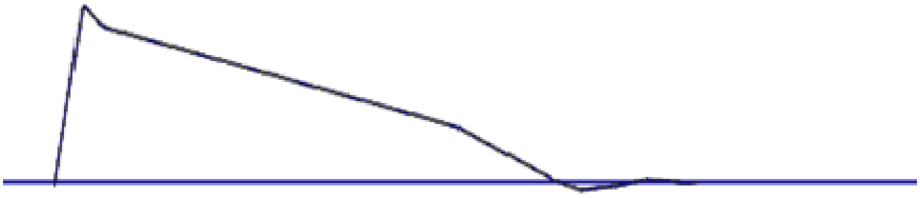


FIGURE 3.2: Impulse transient [16]

categories which are identified by their frequency. Electromagnetic transients generally appear having wide ranges of frequencies that vary from several Hz to hundreds of MHz Differentiation is usually made between slow electromagnetic transients and faster electromagnetic transients. The latter type of transients may occur for a shorter duration that is ranging from some microseconds to various cycles. Frequency ranges can be generally classified into different groups that is because of the ease they provide for developing models case and they are accurate enough due to frequency dependent behavior of power components. An accurate mathematical representation of each power component can generally be developed for a specific frequency range (CIGRE, 1990). One of the reason of generated VFTOs is re-strikes and pre-strikes during opening or closing of switching devices. Very Fast Transients (VFT),and so its also known as Very Fast Front Transients,which belongs to the very high frequency range of those transients in power systems. According to the classification proposed by the CIGRE Working Group 3302, VFT may vary from 100 kHz and up to 50 MHz. According to IEC 711, the shape of these very fast front over voltage is usually unidirectional with time to peak<0.1 ms, total duration< 3 ms, and with superimposed oscillations at frequency 30 kHz <f<100 MHz. In practice, the term VFT is restricted to transients with frequencies above 1 MHz [8]

3.2 Power transformer under VFT

Generally at such very high value of frequencies, the winding of a power transformer mainly behaves like a capacitive based network which are consisting of various series capacitances between turns and coils, and various shunt capacitances that exist between turns and also in between coils with respect to grounded core, transformer tank; the saturation of the magnetic core can be neglected. Interwinding capacitances and secondary capacitance-to-ground must also be represented while voltage transfer has to be calculated, otherwise an accurate representation can be obtained by developing a circuit that matches the frequency response of the transformer at its terminals. [8] Due to various VFT steep fronted wave impulses, which are extremely nonlinear type of voltage distribution that may appear across

the high-voltage windings with some high resonant based voltages due to these transient oscillations that might be generated. Transformers can still generally can withstand against these stresses, however, in critical cases, it may be required to install varistor based protection to protect such tap changers. In case of huge reactor, it will also experience the same such nonlinearity (if we consider voltage distribution across the winding) as well as resonance [1] These such type of very fast transients based over voltages that cause these damage because of internal resonance in the winding. These resonant over voltages were generated by resonance phenomena between the incoming surge wave through the transformer and the natural frequency based characteristics of the transformers windings.
There is very much importance of such internal winding resonances that should be given worth while deciding insulation but is very often underestimated: these resonance generally will not necessarily direct result into immediate such breakdown, but will lead to very often develop such partial discharges, which are causing accelerated aging of the winding insulation [1-4]. Also for a longer period of time the effect will not be seen influence of such resonance silently killing the performance also the resonances will not be visible, and in the case of a failure, the resonance phenomenon will most probably not be recognized .[1]

Very Fast type of Transient Over voltages (VFTOs) are generated by such switching operations which are breakneck for the transformer insulating material because such voltages have always very short rise time, due to which it may cause voltage distribution very non linear within transformer windings. Under some special cases, the turn-to-turn voltage can arise near to the transformer basic insulation level. These problems can either lead to direct break down or initiation of partial discharge which deteriorate the insulation and with the passage of time resulting into total breakdown.

Chapter 4

COMPARISON OF VARIOUS TRANSFORMER MODELS

The transient oscillation and very fast type of transient oscillation are the basic and main causes of such transformer outages. In order to predetermine the over voltages during the design stage of various type of detailed transformer model can be considered. Using one of these models depending upon the need of the accuracy, the proper requirement of the insulation can be proposed and designed for the winding. Transformer modeling methods [6]can be divided into two types that is Gray Box and Black Box models. The Gray Box models can be used by designers to study the resonance behavior of transformer winding and the distribution of electrical stresses along the transformer windings. The Black Box models are [6] necessary for the insulation coordination of power system and can be employed to evaluate the current and voltage wave shapes at the terminals of the transformer. The category of the Black Box models which is normally based on the results of measurements in time or frequency domains [11] [12]. Thus, it would be possible to develop this kind of model after its design and construction. As a result, we can say that during the various designing plan and other stages gray box model have more privileges and usage as compared to the Black Box model. The Gray Box models then can be further categorized as follows: RLC Ladder Network Model and MTL Model.

The proposed scheme is simulated in MATLAB ® programming environment with the help of geometrical analysis of the transformer winding and thereafter implemented using MTL model. Simulation results and experimental results to validate the proposed schemes are discussed in this section.

4.1 Ladder network based model

For transient studies, the lumped linear model of a transformer winding is one of the best representations. The disk-to-disk model of the winding is shown in Fig. 1. The basic element of this model is a double disk. In this basic element for representation of each double disk in the Ladder Network model, three parallel branches are employed with a capacitance

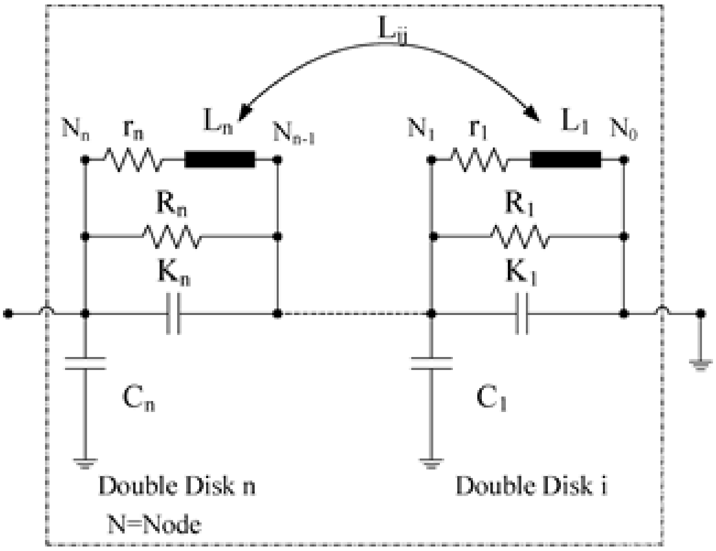


FIGURE 4.1: RLC ladder model for transformer winding[6]

Branch(Cn) is connected to the ground system. The system resistance and the inductance of thei_{th} double disk have been presented by r_i and L_{ii} , respectively. The ith double disk series capacitance has been named by K_i and double disk resistance or dielectric losses can be presented by R_i. The mutual term inductance which is present between the i_{th} double disks with every other double disk those are present in the winding has to be considered and modeled by L_{ij} .

This ladder type model can be written and represented by these following equations:[6]

$$\begin{bmatrix} I_s \end{bmatrix} = \begin{bmatrix} Y_s \end{bmatrix} \begin{bmatrix} U_s \end{bmatrix} \tag{4.1}$$

where

$$Y_s = (1/s) * (\begin{bmatrix} H_s \end{bmatrix} + \begin{bmatrix} G_s \end{bmatrix} * s + \begin{bmatrix} C_s \end{bmatrix} * s^2) \tag{4.2}$$

and these terms H, G, C are the inverse nodal inductances, nodal conductances and such nodal capacitances matrices, Respectively and these other parameter $[Y_s] and [U_s]$ are the current and node voltage vectors, respectively when the surge input is applied to the node n , then as a result nonzero element which is only of [I(S)] , would be the only last rows elements. Solving (equ.4.1) for the voltages that will results in [6]

$$\alpha_j(s) = \frac{1}{Z_{in}(s)}.[Y(s)_{j,n}]^-1 \tag{4.3}$$

for j=1,2,3,4...n in the equation Zin(s) is the required input impedance of the winding . This valid equation for j = n represents Zin(s), which is the required Black Box model of the winding. The zeros of impedance Zin(s) determine the behavior of black box model resonances. [6]

4.2 Multi conductor transmission line model(MTL model)

The fundamental elements of the particular Ladder based Network model are these lumped values of R, L, and C elements. The frequency is limited for the validity of this type of model that is in the range of a hundred kilohertz. If order to extend this particular range of few kilohertz to a few megahertz, it is require and necessary to use different model like that of turn-to-turn modeling procedure instead of considering lump parameter in disk-to-disk modeling. however this operation will result into a large scale system,[7] after which to simulate such a system is really difficult task to and also to analyze such a sophisticated system. To overcome and remove this particular problem of huge computation a method method of MTL theory is utilized which is widespread present to solve voltage distribution in power transformer winding which is based on the MTL theory. Using this multi conductor transmission based theory, the total number of equations and method computation decreased much.However, the size of the matrix are huge so calculation time are bit more as compared to ladder model but with respect to other multi turn methods its better in every aspect also time that is required in the calculation of transient responses decreased significantly. In addition, a transient model can be developed which is valid for FTO and VFTO studies. [7] In MTLM, complete transformer winding is generally divided into no of turns like n conductors (sections) and each winding conductor is used to modeled as a long transmission line because it is working at very high frequency. So the complete winding can be represented by a large group of interconnected and coupled transmission lines as shown in Fig.4.2. Following boundary are valid for the required transmission line model and will be used for the solving 2n equations[7]

$V_R(i) = V_S(i+1)$
$I_R(i) = I_S(i+1)$ both equations for i=1 to i=n-1

$$\begin{bmatrix} I_s \\ I_R \end{bmatrix} = \begin{bmatrix} (Y_0)coth[P]l & -1*(Y_0)cosech[P]l \\ -1*(Y_0)cosech[P]l & (Y_0)coth[P]l \end{bmatrix} \begin{bmatrix} V_s \\ V_R \end{bmatrix} \tag{4.4}$$

where$[P]^2 = [Z][Y], [Y_0] = [Z] - [I], [P] = [Y] * [P]^-1$

$[Z] = R.[I] + j.2\pi.f.[L] and [Y] = [G] + j.2\pi.f.[C]$

[Z] and [Y] are impedance and admittance matrices of the model, respectively, that consist of resistance, inductance, capacitance and conductance matrices, f is the frequency and l is the average length of the line. To calculate coth([P]l) and cosech([P]l) in above equation [P] must be diagonalized using modal transform.

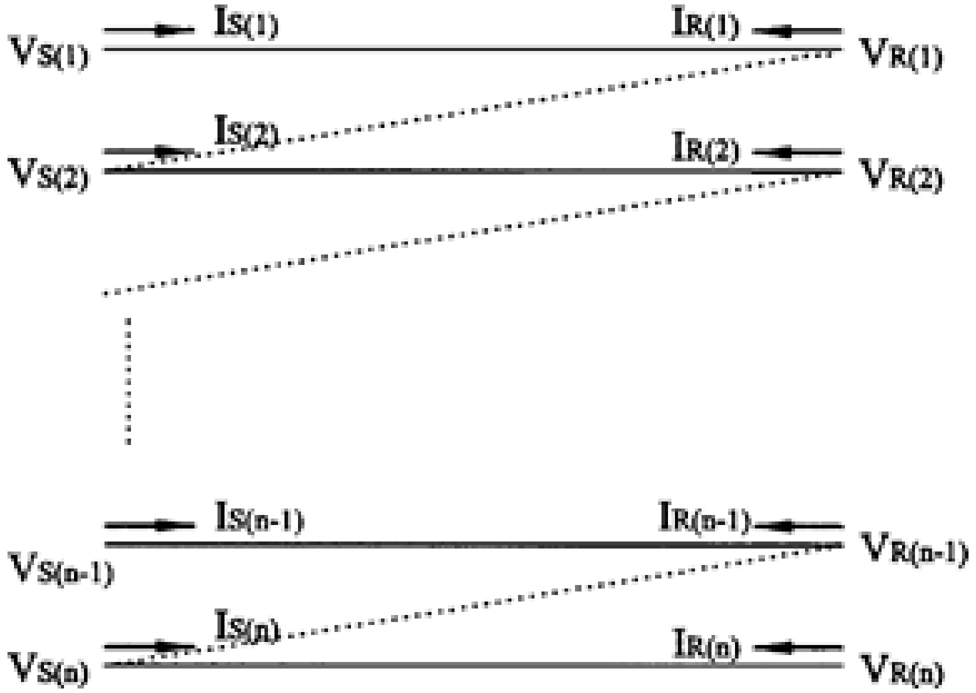


FIGURE 4.2: Multi conductor transmission line model [7]

For this, if [γ] is a diagonal matrix including eigenvalues of [P] and [Q] is the eigenvectors matrix of [P], can be written as [7]

$$\begin{bmatrix} I_s \\ I_R \end{bmatrix} = \begin{bmatrix} (A & -B \\ -B & A \end{bmatrix} \begin{bmatrix} V_s \\ V_R \end{bmatrix} \tag{4.5}$$

where $A = [Y][Q][\gamma]^{-}1.coth([\gamma].l).[Q]^{-}1$ and $B = [Y][Q][\gamma]^{-}1.cosech([\gamma].l).[Q]^{-}1$ in which A and B having the dimensions of N*N after this step of equation of 4.5 and further two stages of simplifications and matrix inversion we have:

$$\begin{bmatrix} V_s(1) \\ V_s(2) \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ V_s(n) \end{bmatrix} = \begin{bmatrix} [T]_{(n+1,n+1)} \end{bmatrix} \begin{bmatrix} I_s(1) \\ I_s(2) \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ I_s(n) \end{bmatrix} \tag{4.6}$$

where the vectors V and I have N+1 vectors If the neutral-end of the winding is grounded via a resistor Re, then, $V_R(n) = ReI_R(n)$. Substituting this terminal condition in (4.6) and expanding the first and last rows: [15]

$$I_s(1) = V_s(1)/[T(1,1) - (T(1,n+1), T(n+1,1))/R_e + T(n+1,n+1)] \tag{4.7}$$

$$I_R(n) = -\frac{T(n+1,1).I_s(1)}{R_e + T(n+1,n+1)} \tag{4.8}$$

once we calculated the value all current vectors then multiplication with T matrix will give the voltage vector across complete winding turns

4.3 Hybrid model

Hybrid model consists of both above discussed models i.e the lumped parameter model and MTL based model so that the model has a capability of finding voltage solution for wide area of frequency. That is from few KHz to few MHz. However, in the present work we are dealing with very fast transients where they vary in Mhz ranges. So in this range of frequency distributed parameter model will give more accurate details hence only MTL model will be used and discussed to do the frequency response analysis.

Chapter 5

CALCULATIONS OF VARIOUS PARAMETER OF TRANSFORMER WINDING

For the simulation purpose following model has been used to obtain the results.

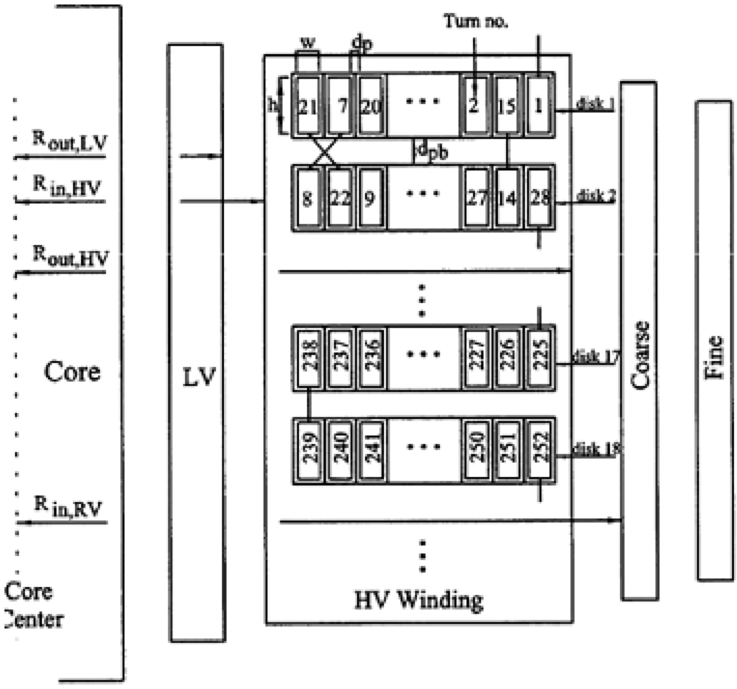
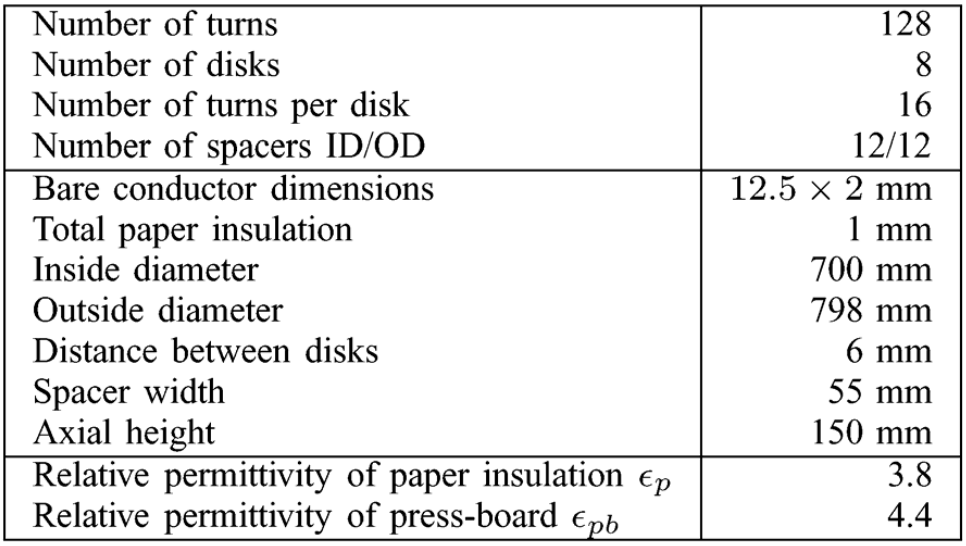


Figure 5.1: Transformer model used for simulation purpose[7]



Number of turns	128
Number of disks	8
Number of turns per disk	16
Number of spacers ID/OD	12/12
Bare conductor dimensions	12.5×2 mm
Total paper insulation	1 mm
Inside diameter	700 mm
Outside diameter	798 mm
Distance between disks	6 mm
Spacer width	55 mm
Axial height	150 mm
Relative permittivity of paper insulation ϵ_p	3.8
Relative permittivity of press-board ϵ_{pb}	4.4

FIGURE 5.2: Transformer model specification [4]

5.1 Calculation of capacitance matrix

5.1.1 Initial Voltage Distribution

Whenever a series or sudden step voltage impinges on the transformer winding terminals, the initial distribution in the winding depends on the capacitances between turns, between windings, and those between windings and ground. [1]The winding inductances have no effect on the initial voltage distribution since the magnetic field requires a finite time to build up (current in an inductance cannot be established instantaneously). Thus, the inductances those practically do not take or carry any current in the starting and so the voltage distribution in the winding is mainly decided by the capacitances in the network, and such problem can be seen as totally electrostatic based without too appreciable error. In some other words, the presence of these series capacitances between winding sections usually causes the transformer winding to respond to the abrupt impulses as a network of capacitances for all frequencies above its lower natural frequencies of oscillations. When such applied voltage is maintained for a sufficient time (50 to 100 microseconds),appreciable currents will begin to flow in the various inductances present eventually and will lead to the more uniform voltage distribution. Since there is much difference between the initial and final voltage distributions, as shown in figure 5.1.[1]A transient phenomenon takes place during which the voltage distribution across winding readjusts itself right from the initial to final value. During this transient period, there is continual interchange of energy between electric and magnetic fields

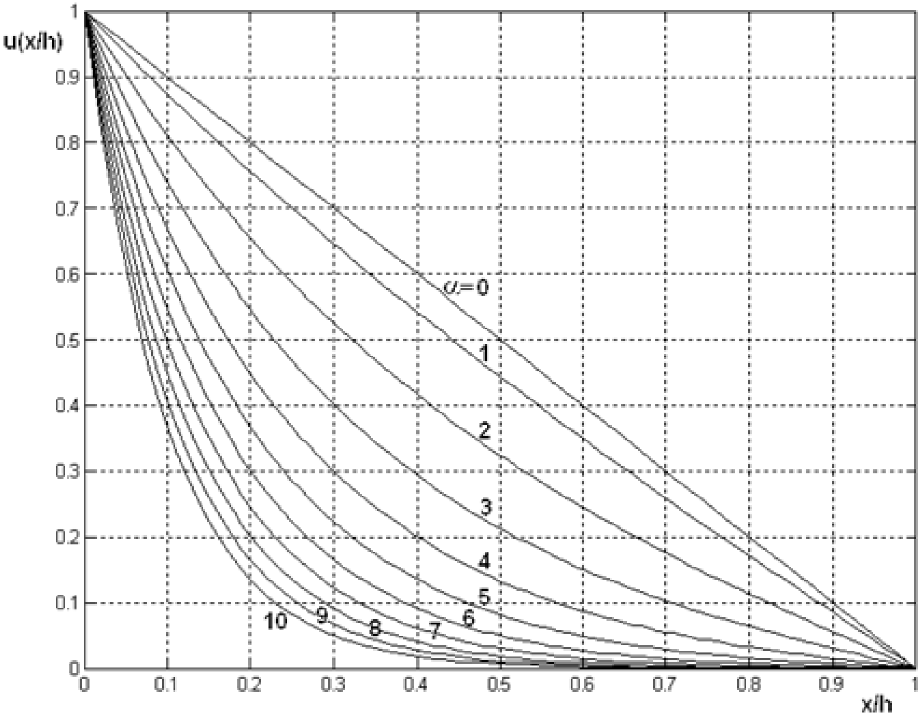


FIGURE 5.3: Voltage distribution on changing values of α[1]

The differential equation that is governing the initial voltage distribution u0=u(x,0),

$$\frac{d_2 u_o}{dx^2} - \frac{c_g}{c_s}.u_o = 0 \tag{5.1}$$

c_g is called the ground capacitance present in the winding c_s is called the series capacitance present in the winding where this ratio of c_g and c_s is called α

There are various capacitances between different conductors. The capacitance between two adjacent turns in a disk can be calculated by assuming parallel plate capacitor approximation as [7]:

capacitance calculation between adjacent turns in the disks:[7]

$$C_t = \frac{2\pi\epsilon_o\epsilon_p R_{ave}(h + 2.d_p)}{d_p} \tag{5.2}$$

where Rave is the average radius of a disk coil, p the relative permittivity of paper and $\epsilon_0 = 8.85 * 10^{-12}$f/m. Other dimensions have been shown in Fig. 5.2 The capacitance between two face-to-face turns of two adjacent disks can be obtained as :[7]

$$C_D = \frac{\pi\epsilon_o\epsilon_{d,eq}(R^2_{out,hv} - R^2_{in,hv)}}{N_t.(d_p + d_{pb})} \tag{5.3}$$

where d,eq is the required equivalent relative permittivity of the compound insulation that is present between two disks and Nt is the total number of present turns in a disk. The insulation between two disks consists of paper, oil and key spacers made of pressboard. Having total width of key spacers and oil channels, d,eq can be calculated by means of the simplified model proposed in Ref. [7]. For the above-mentioned transformer, there are 20 key spacers between adjacent disks and width of each spacer is 35 mm. The capacitance between each bordered turn of HV winding to LV winding can be calculated by cylindrical capacitance [7]

$$C_g = \frac{2\pi\epsilon_o\epsilon_{1,eq}.h}{Ln\frac{R_{in,hv}}{R_{out,lv}}} \tag{5.4}$$

where l,eq is the equivalent relative permittivity of the present compound insulation that exist between HV and LV winding that consist of oil and cylindrical pressboard barriers supported by pressboard spacers and can be calculated by means of the simplified model presented in Ref. [16]. The capacitance between each bordered turn of HV winding to voltage regulating winding (Cr) can be calculated similarly.

The total series capacitance of the winding is given by [1]

$$C_s = \frac{(\frac{2C_D tanh 2\alpha}{\alpha})(\frac{\sqrt{2}C_D tanh\sqrt{2}\alpha}{\alpha})}{\frac{4C_D tanh 2\alpha}{\alpha} + (N_{DW} - 2)\frac{\sqrt{2}C_D tanh\sqrt{2}\alpha}{\alpha}} \tag{5.5}$$

After calculating all the parameters like capacitance between turns and capacitance between disks and capacitance between inner conductor and ground we can formulate the capacitance matrix of winding. Size of the matrix will depend on the no of turns in the winding like the one in this project having 128 turns.If each turn of the winding is modeled as a transmission line, capacitance matrix can be formed according to the following procedure:

- Cii elements are equal to the summation of all capacitances connected to ith conductor
- Cij elements are minus of the capacitance between ith and jth conductors

If each s turns of the winding is modeled as a transmission line, the values of $C_T and C_G$ do not change. But the capacitance between two face-to-face conductors of two adjacent disks is assumed to be s times of the C_d calculated using equation 5.3

there are multiple ways to increase the value of α either by electrostatic shielding or by the introducing the interleaving windings in which the series capacitive reactance of the winding increase appreciably

for the continous winding the value net series capacitance obtained is as follows: [1]

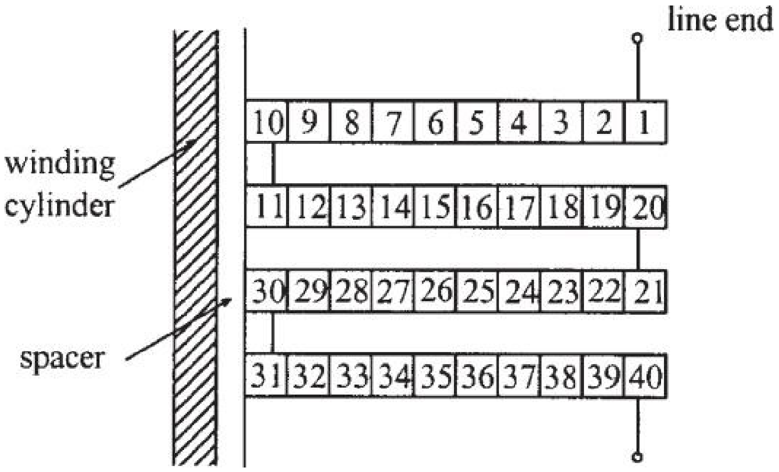
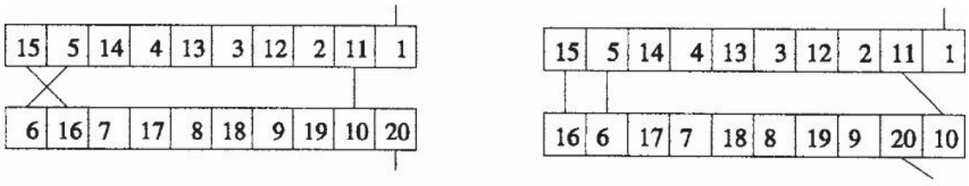


Figure 5.4: Continuous winding structure[4]

$$C_{se} = (\frac{C_T}{2N_D^2})(N_D - 1) + \frac{C_{DU}R}{3} \tag{5.6}$$

where CT is capacitance between turns N_D is total no of turns present in one disc $C_{DU}$is per unit distributed capacitance R is aradial depth of each turn similarly for the interleaved winding the total series capacitance obtained as calculated based on the energy conservation theorem as obtained in the reference[1]



(a) Stern winding (b) Nuys winding

FIGURE 5.5: Interleaved winding structure[4]

$$C_{se} = \frac{C_T}{2}(N_D - 1) \tag{5.7}$$

5.2 Calculation of Inductance parameters and matrix

At high frequencies, it can be assumed that the penetration of magnetic flux into the laminated iron core of transformer is neglected, so the winding can be regarded as a conductor in free space surrounded by insulation. Nt Nt inductance matrix is formed by self and mutual inductances between different turns of the winding. To calculate mutual inductances between two turns of the winding, they are represented as two circular filaments wound concentrically on the core as shown in Fig. 6. The mutual inductance between two turns can be calculated by [7]:

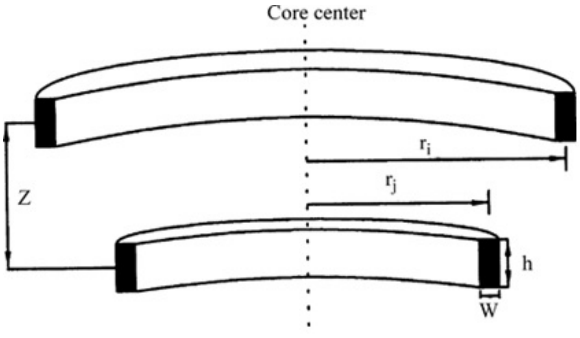


FIGURE 5.6: Two circular filament wound on a core

$$L_{ij} = \mu\sqrt{(r_i r_j)}(\frac{2}{k} - k)K(k) - \frac{2}{k}.E(k) \tag{5.8}$$

$$K^2 = \frac{4r_i r_j}{(r_i + r_j)^2 + z^2} \tag{5.9}$$

where ri, rj and z these term have been shown in the figure 5.6 K(k) and E(k) are complete elliptic type of integrals of some first and second kinds which can be easily calculated by using present MATLAB codes. For calculation of the various self inductances, it is usually recommended that in Ref. [7] to put z = 0.0035(h + w) in (5.4). This additional term is the nothing but the geometrical mean radius (GMR) of the rectangular conductor.

5.3 Calculation of Resistance parameter and matrix

The resistance measured in per unit length of the conductor can be obtained by:

$$R = R_{dc} + \frac{1}{2(h+w)}\sqrt{\frac{\pi * f\mu}{\sigma}} \tag{5.10}$$

where $R_{dc} = \frac{1}{\sigma\omega t}$ and t is thick ness of conductor w is width and σ is conductivity

where rest pf the terms have been defined before. The actual turn-base resistance matrix that can be figured by multiplying R into a nt*nt unit matrix. If group of s turns are being modeled by a MTL, value of resistance should be multiplied by s.

.

5.4 Calculation of parallel conductance and matrix

Parallel conductance are due to dielectric losses and can be obtained by: [G] = 2πf [C] tanδ

Where [C] is the required Capacitance matrix that already calculated above and $\tan\delta$ gives the loss tangent

Chapter 6

RESULTS AND COMPARISONS

In this result and discussion, includes various capacitance like between turns ,between disks, between turn and ground, inductance matrix and resistance measurement of the conductor, also the driving point input impedance is calculated in the frequency domain. Over the complete frequency range the impedance is calculated and plotted .

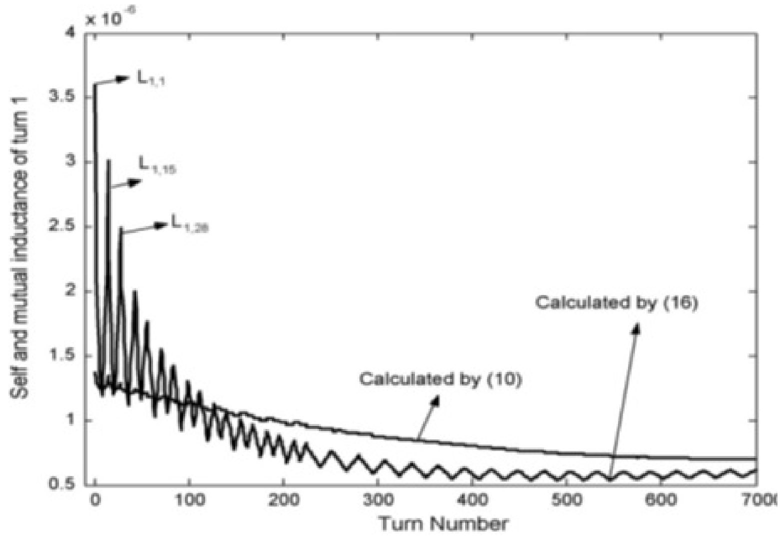


Figure 6.1: Inductance behavior of turn 1(as obtained in refrence paper [7]

following are the results obtained for the continuous winding and the nuys interleaved windings

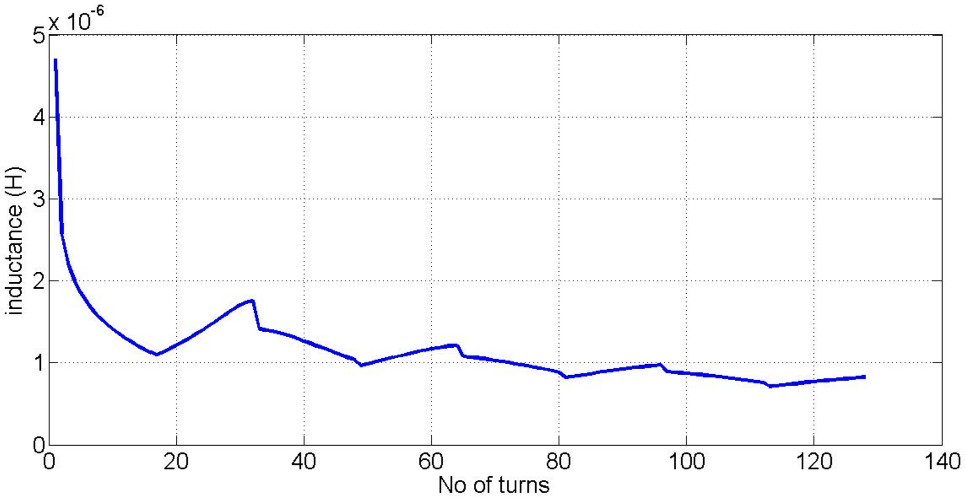


FIGURE 6.2: Inductance behavior for continuous winding(as obtained by simulation)

In the given two figure describe the various inductance of turn 1. Fig.6.1 shows the behavior which was obtained in the reference paper [7] and Fig 6.2 represent the behavior which obtained through present matlab simulation. On comparison we find that first peak shows self inductance of turns so it is L(1,1) second and other peaks shows the mutual inductance of turn 1 with rest of the other turns,as we can see from interleaved winding inductance simulation results are matching with that of the reference. Inductance matrix would be consisting of Nt*Nt where Nt is no of total turns.

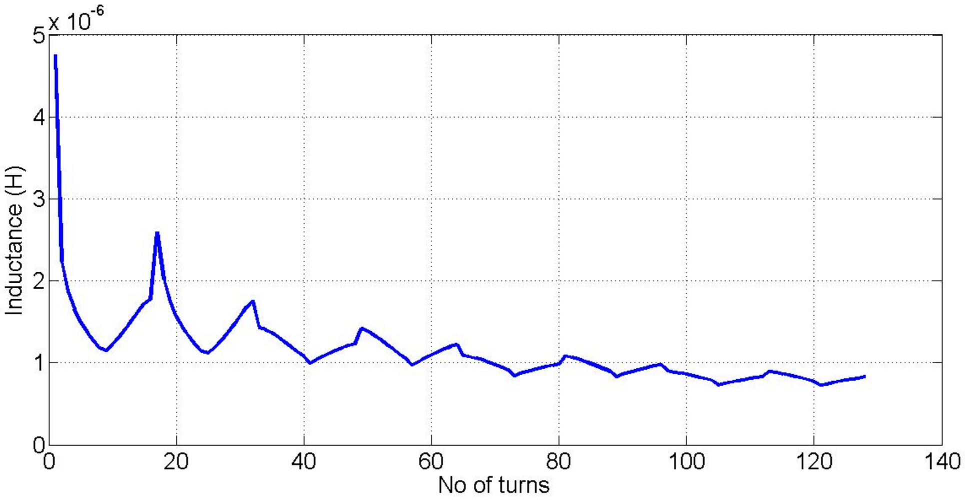


FIGURE 6.3: Inductance behavior for interleaved nuys winding(as obtained by simulation)

6.1 Computation of Capacitance matrix

Calculation of capacitance: Capacitance calculation is done by equations (5.1),(5.2) and (5.3) various capacitance values are given here by:

1.) Turn to turn capacitance :1700pf/m

2.) Disc to disc adjacent turns:888.8pf/m

3.) HV to LV or ground: 100pf/m As we can see inter turn capacitance would be highest as the distance is least then followed by face to face turn of adjacent discs and then by the HV winding to the LV or ground. All the capacitance would be calculated on the basis of the geometry of the transformer and is given in figure 5.1 and hence the complete matrix is consist of Nt*Nt where Nt is the no of total turns. After calculating various parameter according to the geometry of the winding we can code in program to include various capacitances to generate the required capacitance matrix.

6.2 Computation of impedance transfer function

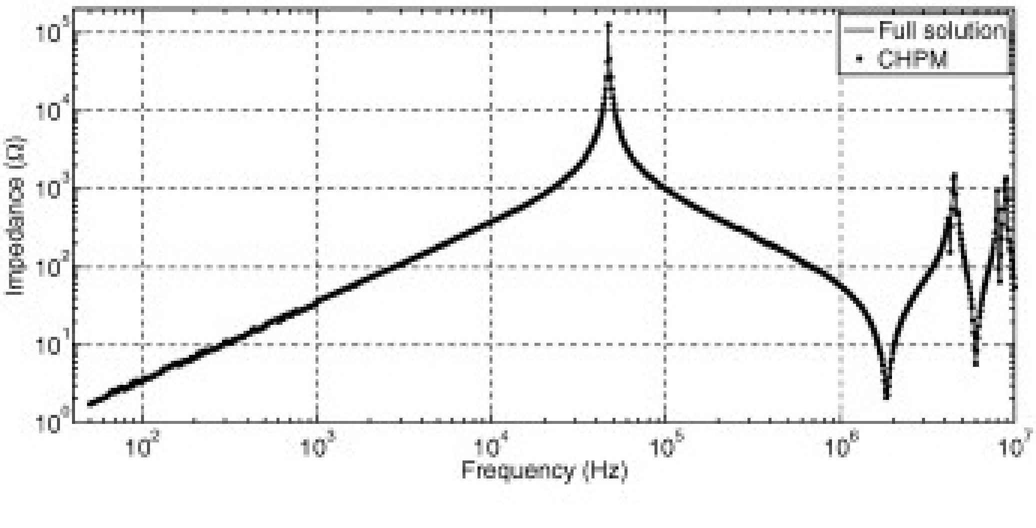


FIGURE 6.4: Driving input impedance (as obtained in reference paper)[4]

Similarly, in the given two figure 6.4 and figure 6.5 description of the transfer function is given. In figure 6.5 results obtained in reference paper is given. On y axis magnitude in p.u is there and on X axis frequency is given. In figure 6.5 actual transfer function is computed both the figures describes that impedance behavior. Peak are clearly visible at those frequencies where the incident frequency is matching with the resonant frequency of the transformer. Such frequency are in Mhz ranges as we earlier discussed.

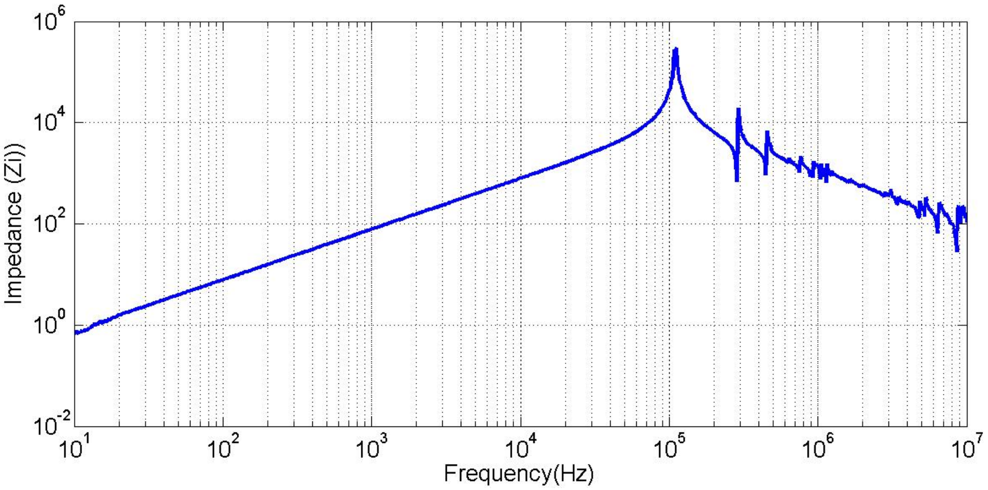


FIGURE 6.5: Driving input impedance of continuous winding (as obtained in simulation)

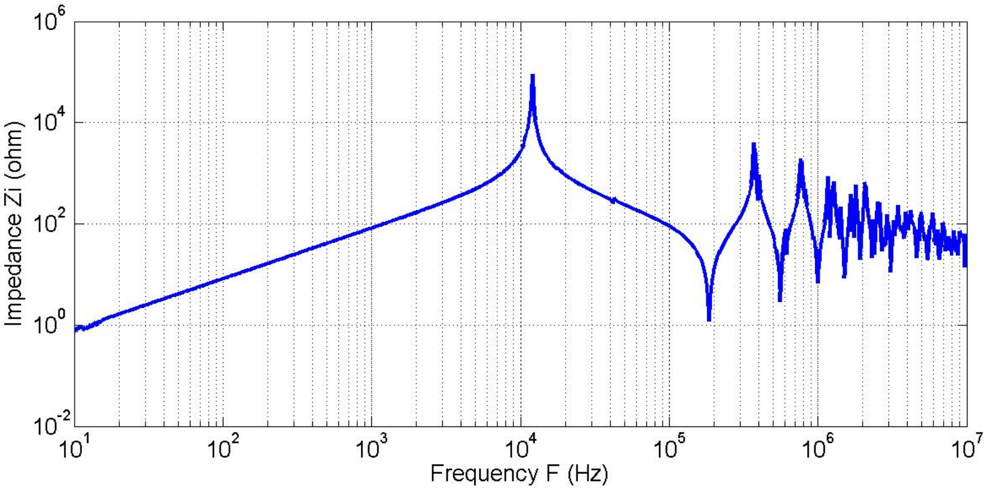


FIGURE 6.6: Driving input impedance of nuys interleaved (as obtained in simulation)

6.3 Computation of Voltage distribution across transformer winding

For continuous winding for interleaved winding voltage measurement at high frequency tends to make the distribution very much non linear for the continuous winding while its getting improves with interleaving. Following results shows the respective behavior at very high frequency including resonances and non resonant frequency.

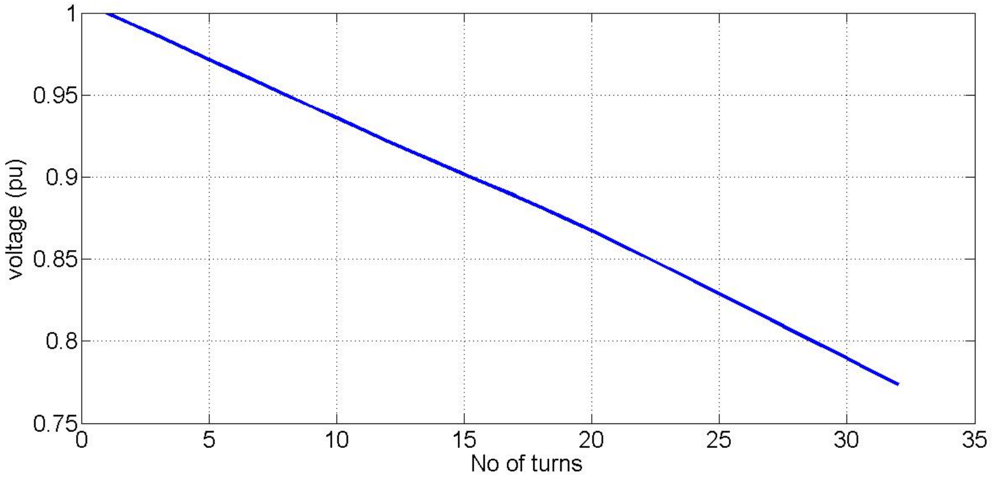


Figure 6.7: Voltage distribution at 50 Hz for continuous winding pair of disc)

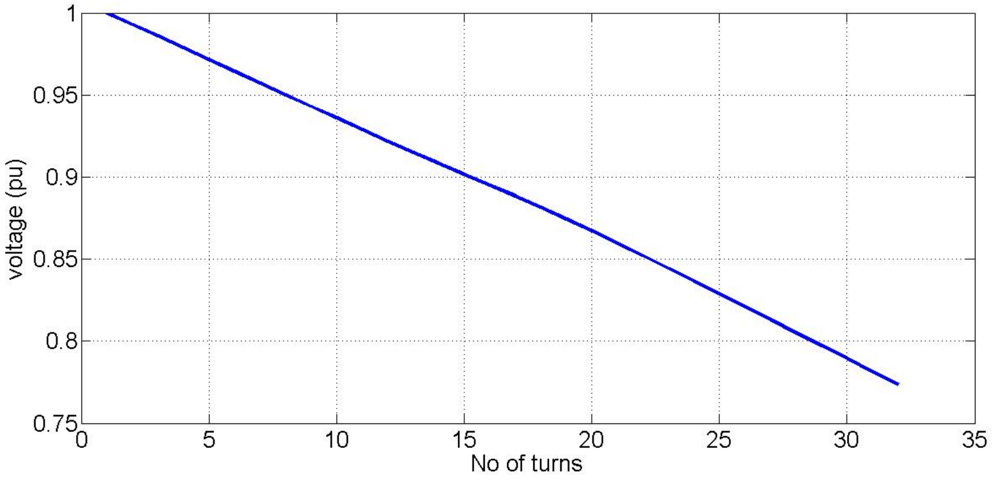


Figure 6.8: voltage distribution at 50 Hz for interleaved winding pair of disc

As we can see(for continuous winding) from the figure 6.9 and 6.11 that the voltage difference in starting turns. It can be observe that when 0.8 Mhz frequency is

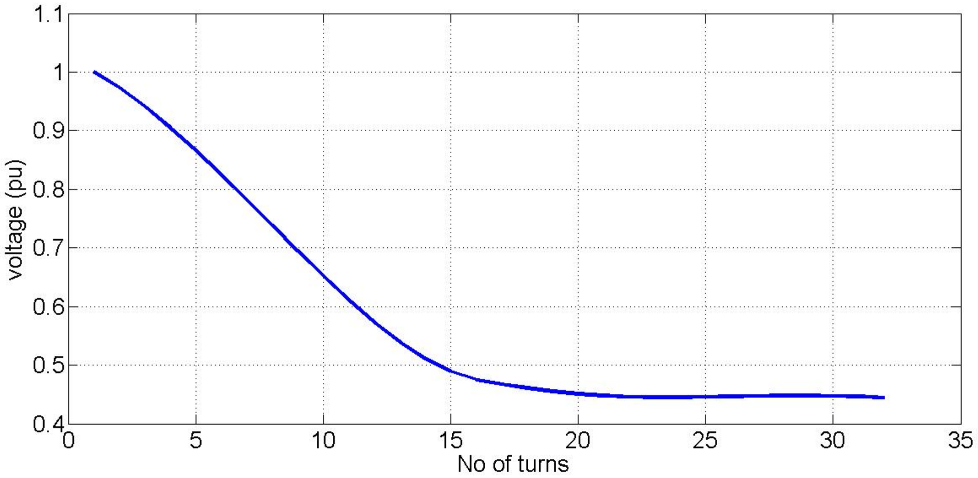


Figure 6.9: Voltage distribution at 0.8 MHz for continuous winding pair of disc

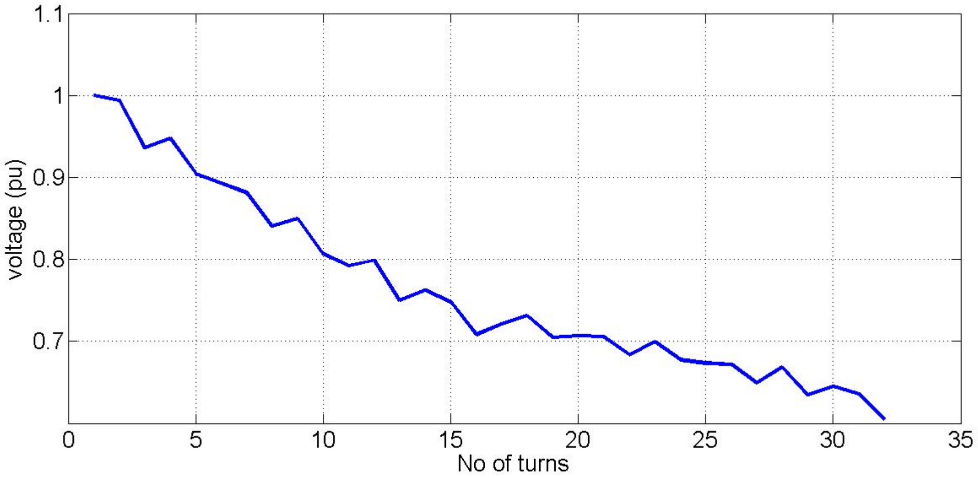


Figure 6.10: Voltage distribution at 0.8 MHz for interleaved winding pair of disc

applying to a continuous winding up to 15th turn voltage difference is too much which leads to more stresses in the starting turns similarly in the fig 11 at 1.2 Mhz we can see he initial voltage drop drastically up to 10_{th} turn voltage reduces by 1/8.

In contrast to when we observe the voltage at 1.2 Mhz and 0.8 Mhz in figure 6.10 and figure 6.12, we see that the voltage distribution across the winding tend to becomes more linear across turns. since more voltage getting same at some points so that the voltage gradient becomes less and in the figure 6.12 it can also be observed that the voltage distribution getting better or normal as compared to the continuous winding. So interleaving of such type help to stop the unwanted stress in the winding.

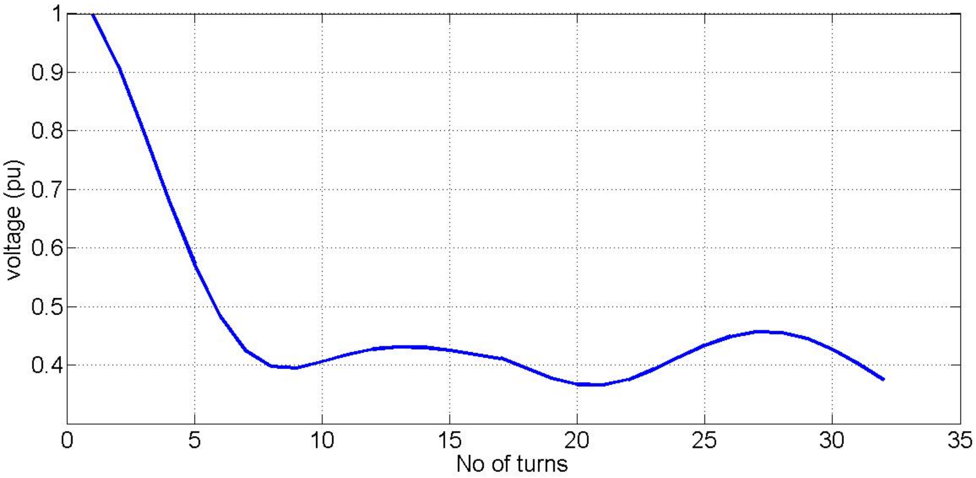


FIGURE 6.11: Voltage distribution at 1.2 MHz frequency for continuous winding pair of disc(as obtained in simulation)

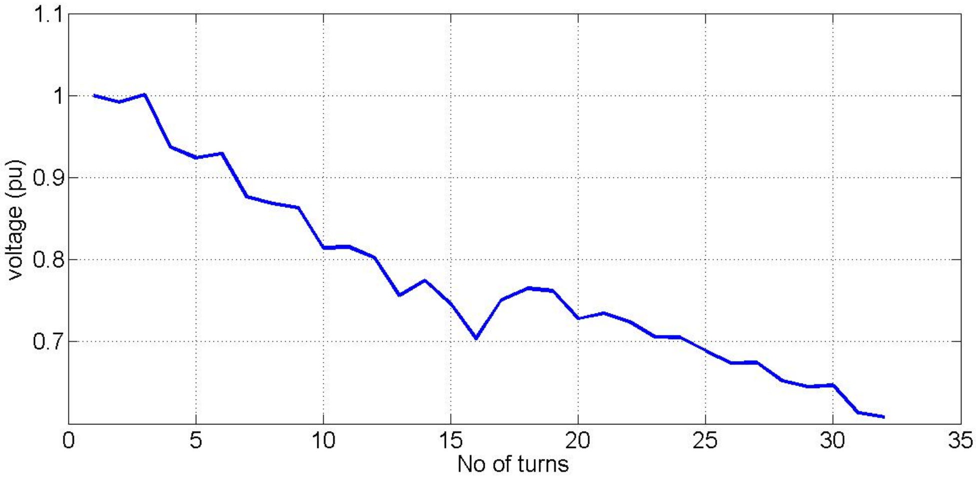


FIGURE 6.12: Voltage distribution at 1.2 MHz frequency for nuys type interleaved winding pair of disc(as obtained in simulation)

In the figure 6.13 we can see that the voltage level going above 1 pu in some part of winding. It means some part of winding must be in resonance which is causing the voltage to rise above 1 pu. The results in reference paper reflects that during the resonance phenomenon the voltage across winding raises abruptly. So these are some factors which helps in decide the insulation level across the winding.

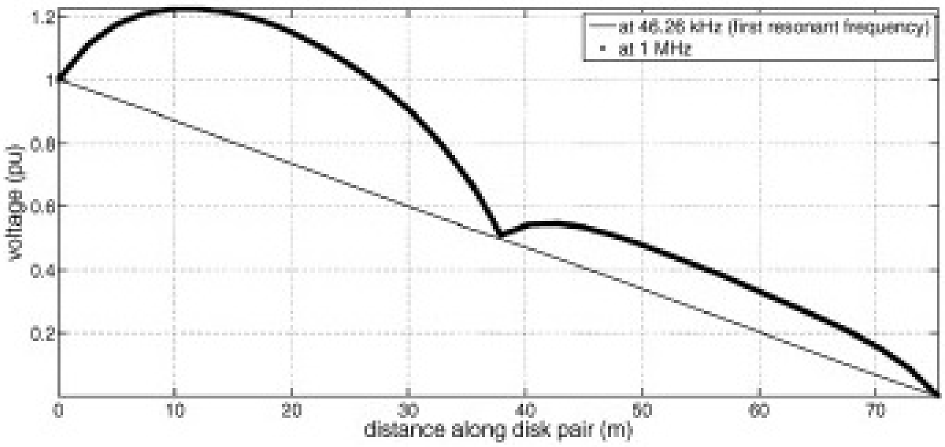


FIGURE 6.13: Voltage distribution at 46.6KHz resonance frequency for nuys type interleaved winding pair of disc(as obtained in refrence paper)[4]

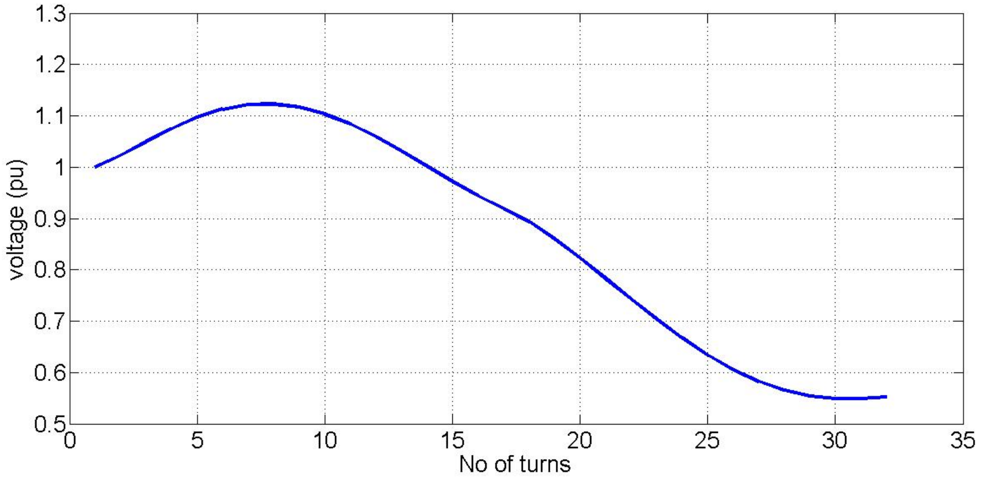


FIGURE 6.14: Voltage distribution at 47 KHz resonance frequency for nuys type(as obtained in simulation)

Chapter 7

CONCLUSION AND SCOPE OF WORK

7.1 Conclusion

In the thesis work, voltage distribution across transformer winding i.e continuous and interleaved type of windings are analyzed. At start we studied complete transformer winding and calculated the various parameter that is inductance,capacitances and resistances.As the project work is prominently based on the high frequency signal effects. So for the required purpose , MTL model is developed and utilized to calculate the voltage behavior in winding. In the process we have analyzed two types of winding continuous and interleaved to study voltage pattern. It can be concluded that voltage pattern in the interleaved windings are much better and causing less stress to the winding turns.

7.2 Scope of work

The present work is only done in the frequency domain. This work can be extended to the time domain analysis of voltage behavior across the winding which can give a more clear perception regarding the voltage pattern. It can be seen that the voltage behaviors in the interleaved winding are better than that of the continuous winding at high frequency. But we know that the interleaved winding have high cost in manufacture and we analyses that the voltage across starting turns having more voltage gradient so the work can be extended to the combination of interleaved and continuous winding. In the beginning interleaved winding can be used then after certain distance the continuous winding can be used in order to curb the high cost.

Bibliography

[1] S. V. Kulkarni and S. A. Khaparde, *Transformer Engineering: Design, Technology and Diagnostics*, 2nd ed. Boca Raton, FL: CRC, Sep. 2012.

[2] M. Popov, L. van der Sluis, R. P. P. Smeets and J. Lopez Roldan, "Analysis of Very Fast Transients in Layer-Type Transformer Windings," in *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 238-247, Jan. 2007. d .

[3] J. Weed and Murray, Abnormal voltages in transformers, *Trans. AIEE, vol.* XXXIV, pp. 21972236, 1915.

[4] M. M. Kane and S. V. Kulkarni, "MTL-Based Analysis to Distinguish High-Frequency Behavior of Interleaved Windings in Power Transformers," *in IEEE Transactions on Power Delivery*, vol. 28, no. 4, pp. 2291-2299, Oct. 2013.

[5] Y. Yu and W. ZanJi, Wide band modeling of large power transformer windings for very fast transient overvoltage (VFTO) analysis, *Sci. China Ser. E: Technol. Sci.*, vol. 52, pp. 25972604, 2009.

[6] S. M. H. Hosseini, M. Vakilian, and G. B. Gharehpetian, Comparison of transformer detailed models for fast and very fast transient studies, *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 733741, Apr. 2008.

[7] A. M. Jafari and A. Akbari, Partial discharge localization in trans- former windings using multi-conductor transmission line model, *Elect. Power Syst. Res.* , vol. 78, no. 6, pp. 10281037, 2008.

[8] Z. Zhongyuan, G. Shuguo, L. Fangcheng, and L. Yunpeng, The calcu- lation of the voltage distribution in transformer windings under VFTO based on FDTD method, *in Proc. IEEE Asia Pacic Conf. Circuits Syst.*, Dec. 2006, pp. 856859

[9] E. Agheb, E. Hashemi, A. Mousavi, and H. K. Hoidalen, Study of very fast transient overvoltages and electric eld stresses in air-cored pulsed transformers based on FDTD, *in Proc. 3rd Int. Adv. Res. Workshop Transformers*, Oct. 2010, pp. 303308.

[10] M. Popov, R. Smeets, L. van der Sluis, H. de Herdt, and J. Declercq, Experimental and theoretical analysis of vacuum circuit breaker pre- strike effect on a transformer, *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 12661274, Jul. 2009

[11] A. Chadwick, J. Ferguson, D. Ryder, and G. Stearn, Design of power transformers to withstand surges due to lightning, with special refer- ence to a new type of winding, *Proc. Inst. Elect. Eng., Power Eng.*, vol. 97, no. 60, pp. 737744, Dec. 1950. .

[12] C. R. Paul, *Analysis of Multiconductor Transmission Lines.* Hoboken, NJ: Wiley, 1994.

[13] T. Teranishi, M. Ikeda, M. Honda, and T. Yanari, Local voltage oscil- lation in interleaved transformer windings, *IEEE Trans. Power App. Syst.*, vol. PAS-100, no. 2, pp. 873881, Feb. 1981.

[14] P. McLaren and H. Oraee, Multiconductor transmission-line model for the line-end coil of large ac machines, *Proc. Inst. Elect. Eng., Elect. Power Appl.*, vol. 132, no. 3, pp. 149156, May 1985.

[15] T. R. B. Mohammad, S. Naderi, M. S. Naderi, R. Ghaemmaghami, and A. Nasiri, Determination of partial discharge propagation and location in transformer windings using a hybrid transformer model, *J. Elect. Power Compon. Syst.*, vol. 35, pp. 607623, 2007.

[16] K. Cornick, B. Filliat, C. Kiney, and W. Muller, *Distribution of very fast transient overvoltages in transformer windings,* in CIGRE Study Committee, 1992, vol. 12-204

[17] R. Rudenberg, *Electrical Shock Waves in Power Systems: Traveling Waves in Lumped and Distributed Circuit Elements.* Cambridge, MA: Harvard University Press, 1968.

[18] S. A. Ryder, Diagnosing transformer faults using frequency response analysis, *IEEE Elect. Insul. Mag.*, vol. 19, no. 2, pp. 1622, 2003.

[19] M. Florkowski and J. Furgal, Detection of transformer winding deformations based on the transfer function- measurements and simulations, *Measur. Sci. and Technol.,* vol. 14, no. 11, pp. 19861992, 2003.

[20] A. Shintemirov and Q. H. Wu, Transfer function of transformer winding for frequency response analysis based on traveling wave theory, *in Proc. Int. Control Conf.* (ICC 2006), Glasgow, Scotland, Aug. 2006, p. 6.

[21] Abeywickrama, K.G.N.B.; Serdyuk, Y.V.; Gubanski, S.M., ”Exploring possibilities for characterization of power transformer insulation by frequency response analysis (FRA),” *in Power Delivery, IEEE Transactions on*, vol.21, no.3, pp.1375-1382, July 2006