CHALMERS

VOLTAGE DISTRIBUTION ALONG REACTOR WINDING UNDER VERY FAST TRANSIENTS

Master of Science Thesis in the Master Degree Program, Electric Power Engineering

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ABSTRACT:

Electricity is a necessity of the modern life due to its everywhere usage. Its proper continuity depends on the reliability of the equipments used in power system. The transformer is one of the basic components which are commonly used in the power system, generation, transmission or distribution. Its high cost and difficult maintenance highlights its importance in power system. Proper protection is necessary to protect this costly equipment from any damage. Therefore, surge arresters are installed near to the transformer to protect from high voltages. However, during lightning and switching of circuit breakers, re-strikes and pre-strikes during opening and closing of a circuit breaker may lead to a broad band frequency spectrum of overvoltages. Such overvoltages may have an oscillating character and lower amplitude at the transformer terminals. In addition they may arrive at the transformer input without any changes in amplitude and waveform so the surge arrestor will not able to detect any overvoltages near the terminals as well as at the input sides. . If the oscillating frequency component of the external overvoltage is equal to the natural frequency of the windings, then the magnitude of the internal resonance overvoltage has its maximum value. Therefore, overvoltages generated in transients and switching stages in electrical power equipment may be dangerous for the insulating system despite the applied overvoltage protection.

The resonance frequencies for transformer winding have been experimentally determined. The frequency band taken into account was between 10Hz and 10MHz, in addition the band has been divided into lower frequency band (10 Hz-200 KHz) and higher frequency band (200 KHz-10 MHz). Then applying sinusoidal waves with the resonance frequencies, voltage stresses on different nodes along the winding have been located. From these voltages stressed nodes it was concluded that the stressed nodes are shifting from centre of the winding towards the upper part of the winding as from lower to higher resonance frequencies. After that the voltage distribution at different resonance frequencies was analyzed. At lower frequency band, the voltage stress between turn to ground in terms of standing wave was observed whereas at higher frequency band inter layer stress was the concluded result. Voltage stress on different nodes under wider frequency was also investigated where the same behavior was seen.

Step responses were also applied at the input to investigate the resonance frequencies and their voltage stressed along the length of the windings. Finally the results for sinusoidal wave and step response were compared.

CONTENTS

CHAPTER 1

INTRODUCTION

BACKGROUND

There are a number of factors which affect the life time of the insulation in a transformer winding. The major factors that contribute to premature insulation failure are lightning/line surges, switching over voltages and internal overvoltage [4]. These fast transients overvoltages can cause internal resonances in the winding. The resonance overvoltages are generated by a resonance phenomena initiated by an incoming surge wave passing through the transformer. Another problem are Very Fast Transient Over voltages (VFTOs) generated by switching operations. This type of overvoltages is dangerous for the transformer insulation due to a short rise time, which can cause non-linear voltage distribution along transformer windings. In some special cases, the turn-to-turn voltage can rise near the transformer basic insulation level [1]. These problems can either lead to direct break down or initiation of partial discharge which deteriorate the insulation. After a short time this can result in an insulation breakdown. These over voltages occur inside the winding and are difficult to measure and detect.

In this thesis work the voltage stresses under transients along the transformer windings due to the resonance frequencies will be experimentally presented. First the resonance frequencies of the windings will be find with the help of a network analyzer. Sinusoidal wave test will be performed to verify the resonance frequencies. During this test, voltage stress will be recorded for different resonant frequencies. Critical most voltage stressed point along the winding of the transformer will be presented. Voltage distribution along the length of the winding for different resonance frequencies will be plotted. Different node voltages at a wider range of frequencies will be shown. Then voltage step test will be performed to find resonance frequencies for different sections of the windings and finally the results for sinusoidal wave and step voltage results will be compared.

Modeling for high frequency transient analysis requires wide frequency range models due to the presence of a 50Hz signal and high frequency electromagnetic transients in range of tens of MHz. Electrical parameters like inductance and capacitance are important due to their frequency dependency. A proper calculation of Resistances, Inductances (self and mutual) and capacitances (capacitance between turns, between turn to ground) is necessary for accurate results. Finally it is important to find out the frequency dependent behavior of these distributed parameters for the study of the fast transients. Skin effect and proximity effects are also frequency dependent so these can affect results of simulations.

THESIS OUTLINE

Chapter 1 presents the background of the thesis. An overview of the previous literature is presented. Furthermore, the aim of this thesis work is defined.

Chapter 2 shows an overview of transient overvoltages (TOVs), their classification, generation and propagation through systems.

Chapter 3 describes measurements setup, measurement procedures and the voltage distribution along the terminals at a wider range of frequency.

Chapter 4 describes different techniques which can be used for proper modeling of transformer.

Chapter 5 presents conclusions of the thesis work and suggestions for the future work.

LITERATURE OVERVIEW

During recent years several unusual transformer failures were reported. It was noticed that both dry-type and oil-filled transformers were clearly exposed to specific overvoltages. Through investigation, no clear design or manufacturers fault has been established, at least publically. According to some studies, internal resonances are the most likely cause of such failures [3].

K.U. Lueven [3] during 2009 investigated the resonance phenomenon in medium and low voltage transformers and found that the cause was due to the series of combinations, the switching transients due to multiple re-strikes, internal resonance in the transformer winding and material deterioration by partial discharges.

Chopping of inductive currents by a powerful circuit breaker causes a voltage rise due to the release of magnetic energy stored in the inductive element. Multiple re-ignitions produced in the circuit breaker can generate repetitive pulses with a wide frequency spectrum, exciting the natural frequencies of the transformer.

There have been a lot of studies on internal transformer resonances. These studies are related to high voltage transformers due to their high insulation failure rate at that time. However, after investigating resonance, K.U Lueve made some conclusions which are valid for distribution transformers, as follows.

- Resonance frequencies were examined between 40kHz and 8MHz, which are initiated by fast transients
- Overvoltages generated by internal resonances cannot be measured at the terminals of the transformers, as their appearance inside the windings.
- The required measurements at different points inside the winding can only be made on special prototype transformers, as a result of which, a few detailed measurements can be found.
- Protective devices, arresters at the transformer terminals cannot protect against resonance [3].

The importance of internal winding resonances is very high since the internal overvoltages often cause insulation failure. Internal overvoltages will not cause immediate breakdown, but will often only cause a partial discharge, resulting in an accelerated ageing of the winding insulation [4, 5]. Transformer insulation failures have been reported, caused by VFT, while all these transformers had passed all the standard tests and compiled to all quality requirements.

A wide frequency range representation of transformers, reactors and rotating machines is necessary to study the effects of the electromagnetic transients initiated either by switching type disturbances or lightning. During the design stage of the high voltage apparatus it is necessary to have proper knowledge about the voltage stress on winding sections for economical use of insulation material. When talking about high voltage (HV) and extra high voltage (EHV) networks, the proper prediction of possible voltage stresses at critical points is necessary for efficient insulation coordination and protection.

Nearly a thousand of publications have been made between 1902 and 1957 on the surge performance in case of transformers and rotating machines. In the beginning, mostly analytical methods were used to model the transformer windings under transients. Later on, numerical methods were introduced to get accurate results due to the reason that geometry of the later is nearly resembling the actual transformer. Lumped parameter, single and multi transmission line models are mostly used models in numerical methods. Generally it is assumed that winding configuration, material constants and other constructional details are known. However in the majority of cases related to the power system transients, transformers, reactors and the rotating machines are system components and generally there is insufficient information about internal structure. A number of studies dealing with the modeling of the power system equipment based on the external measurements have been published. External measurements can either be performed in frequency domain or time domain [1].

When transient oscillations with a steep front enter from a system into a transformer, it reacts initially as a system of capacitances. The values of resistance, inductance and capacitance undergo temporary changes as compared to their normal conditioned values due to their frequency dependency. The transformer is generally considered as a large inductance. For high frequency transients, stray capacitances of the windings, which depend on the type of coils and the winding arrangement type, determine the transformer's transient response. At normal operating frequencies, the effect of capacitance between turns and layers of individual coils is negligible. The winding acts as concentrated inductances to give uniformly distributed voltages. In contrast to when the winding is subjected to high frequency, steep-fronted waves, the effect of capacitance is more prominent in determining initial voltage distribution. It is due to the reason that the capacitances may have lower impedance or even virtually short circuited at higher frequencies. In addition at higher frequencies the resonance frequencies condition is fulfilled for the various combinations of inductances and capacitances [19].

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 [14].

Considering the previous studies and publications on the voltage distribution along the transformer winding under transients, the emphasis was mostly on the modeling of the transformer so far. Different opinions were found by different authors. Lumped parameter, single transmission line, multi transmission line models are the most used models. Few of the authors have experimental results showing voltage distribution along the windings.

In this thesis work a combination of the two tests, the sinusoidal wave test and the step response test have been used to determine and compare the voltage stresses. The resonant frequencies for the winding have been experimentally determined with the help of a network analyzer and were counterchecked using step functions. Moreover, the voltage distribution at the lower resonant frequencies was presented in a better way. In addition the voltage distribution at higher resonant frequency was shown more clearly as one can see stress within the disc and between the layers also.

AIM OF THIS THESIS:

The aim of the current thesis work is to study and analyze high frequency transients in a transformer winding. The voltage stress along the winding under these transients is to be investigated. The resonance phenomenon is going to be studied at different resonance frequencies. Furthermore, the voltage distribution along the winding at resonant frequencies is going to be analyzed. Moreover, the magnitudes of the transient voltages that appear along the transformers winding will be presented. In this thesis work, only the voltage stress is considered.

The magnitude of the voltage stress at different resonance frequencies in time domain will be shown and compared. The voltage stress at particular nodes in a wide frequency range is going to be investigated. As a consequence, voltage distribution along the winding at resonance frequencies is going to be analyzed. Moreover, the resonance frequencies will be verified using voltage steps.

CHAPTER 2
TRANSIENT OVERVOLTAGES IN POWER SYSTEMS

Transients are disturbances that occur for a very short duration (less than a cycle), and the electrical circuit is quickly restored to original operation provided no damage has occurred due to the transient. Steady-state systems are the opposite of transient systems. In steady state, the operation of a power system is characterized by the fundamental frequency or by some low-frequency harmonic of the fundamental frequency. Passive parameters of the system such as resistances (R), inductances (L), and capacitances (C) determine the steady-state behavior of the system. The circuit model of for analysis of high frequency transients is substantially different from the steady-state representation of the system. Passive parameters R, L, and C are still big elements to determine the transient response, but their effect on the transient can change with the duration of the transient. In an electrical system, inductances and capacitances are energy-storing elements that contribute to the oscillatory nature of the transient. Resistance is the energy-dissipating element that allows the transient to dampen out and decay to the steady-state condition. [9]

An overvoltage is defined as a time-varying voltage stress that has peak value higher than the highest value of the rated voltage. It can be between phase to ground, phase to phase, or between terminals that belong to the same phase. Over voltages cannot be measured at the terminals, but occur inside the windings. Arresters at the transformer terminals cannot protect the transformer against resonance. Results of the first investigations and laboratory experiments lead us to believe that the failures were all caused by a similar combination of electrical transients, e.g. switching transients with multiple restrikes, internal resonance inside the transformer windings and material deterioration by partial discharges. The insulation deterioration by partial discharges explains why many of the failures were not directly related to a switching phenomenon or a lightning strike. The symmetrical occurrence of failures inside the winding is due to an internal resonance pattern. Finally, the fast transient phenomenon can explain why the transformers failed while they all complied with the present standards [8]. For power component design and selection of protective devices, overvoltage and insulation coordination studies are very important. The use of numerical techniques for overvoltage calculations are very useful and are widely used for high frequency transient analysis. Mathematical models for electromagnetic transient's calculations are usually very reliable but difficult to make. Digital computations can be very accurate if models and parameters of power components used in computations are adequate and accurate [9].

CLASSIFICATION OF OVER VOLTAGES

Overvoltages can be classified according to different categories. According to origin these can be classified as internal and external overvoltages. Internal overvoltages are result of switching operations and faults. External overvoltages are cause of lightning strike to the power system.

Overvoltages can also be classified according to characteristics. These characteristics are frequency range, duration, peak voltage magnitude and shape.

According to International Electro technical Commission (IEC), transients are disturbances that occur for a very short duration (less than a cycle), and the electrical circuit is quickly restored to original operation provided no damage has occurred due to the transient.

Temporary over voltages: These types are of little damped power-frequency of relatively long duration (from several milliseconds to several seconds), mostly caused by faults, resonance conditions, load rejection, or a combination of these.

Slow-front over voltages: These types are of highly damped transient overvoltages of relatively short-duration (from a few milliseconds to a few power-frequency cycles). They can be oscillatory or unidirectional, and their frequency range varies from 2 to 20 kHz. Usually caused by faults or switching operations.

Fast-front over voltages: These transient over voltages are of very short duration (<1 ms). They are highly damped and generally unidirectional. They can be caused by lightning strikes or switching operations.

Very fast-front over voltages: These transient over voltages are of very short duration (<1 ms). They can be oscillatory or unidirectional, and their frequency range can vary from 100 kHz to 50 MHz The most frequent origin, of these over voltages is faults and switching operations. [10]

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 at least 10 times 20 kHz, or 200 kHz, in order to fairly describe the characteristics of the transient. For faster transients, higher sampling rates are necessary. [4]

An electrical transient is a cause-and-effect phenomenon. If talking of cause, 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 [9]

CHARACTERISTICS OF THE TRANSIENT VOLTAGE WAVEFORM:

The most common transient is the "oscillatory transient”. This can be seen in Figure 1. It is sometimes described as a "ringing transient". This type of transients is characterized by swings above and below the normal line voltage.

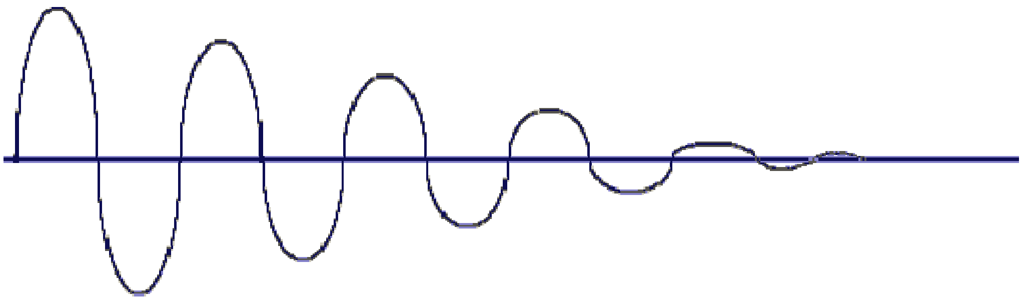

Figure 1 Oscillatory transient

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% of it being one pulse above the line voltage. A lightning strike can be composed of multiple transients of this type.

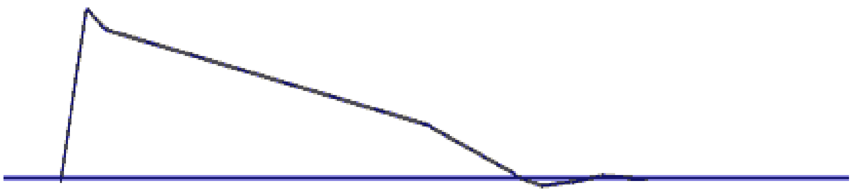

Figure 2 Impulsive transient

Even these transients can be broken up into other categories identified by their frequency. [11]

Electromagnetic transients may appear with a wide range of frequencies that vary from several Hz to several hundreds of MHz Differentiation is usually made between slow electromagnetic transients and faster electromagnetic transients. The latter type of transients can occur for a shorter duration ranging from microseconds to several cycles. Frequency ranges are classified into groups for the ease of developing models 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), also known as Very Fast Front Transients, belong to the highest frequency range of transients in power systems. According to the classification proposed by the CIGRE Working Group 33–02, VFT may vary from 100 kHz up to 50 MHz (1990). According to IEC 71–1, the shape of a very fast front overvoltage 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’’ (1993). In practice, the term VFT is restricted to transients with frequencies above 1 MHz [12]

Power Transformers under VFT

At very high frequencies, a winding of a transformer behaves like a capacitive network consisting of series capacitances between turns and coils, and shunt capacitances between turns and coils to the grounded core and transformer tank; the saturation of the magnetic core can be neglected. Inter-winding 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. [12]

Due to VFT steep fronted wave impulses, extremely nonlinear voltage distribution can appear along the high-voltage winding with high resonant voltages due to transient oscillations might be generated. Transformers can generally withstand these stresses, however, in critical cases, it may be necessary to install varistors to protect tap changers. In case of reactor, it will experience the same nonlinearity in voltage distribution along its winding as well as resonance [12]

These fast transients over voltages cause internal resonance in the winding and resonant over voltages were generated by resonance phenomena between the incoming surge wave passing through the transformer and the natural frequency characteristics of the transformer windings. The importance of internal winding resonances is very often underestimated: resonance will not necessarily result in immediate breakdown, but will very often only develop partial discharges, causing accelerated ageing of the winding insulation [4-5]. For a long period of time the influence of the resonance will not be visible, and in the case of a failure, the resonance phenomenon will most probably not be recognized. [8]

Very Fast Transient Over voltages (VFTOs) generated by switching operations are dangerous for the transformer insulation because it always has a short rise time, which can cause the unbalance of voltage distribution 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 3
INTERNAL OVERVOLTAGES DURING HIGH FREQUENCY TRANSIENTS

Transformers are subjected to overvoltages as a result of lightning, network switching phenomena and some selected failure stages. Protective devices such as arrestors can limit the peak value of overvoltages to the level determined by the insulation coordination at the transformer terminals. But, often the internal overvoltages are formed inside the insulation system, which is usually caused by internal resonance in the winding. Particularly some switching transients of oscillating character may cause high-amplitude internal overvoltages. Such overvoltages may have oscillating character and lower amplitude at the transformer terminals. In addition they may arrive at the transformer input without any changes in amplitude and waveform.

The transformer response to overvoltages is related to transient phenomena occurring inside the winding. If the oscillating frequency component of the external overvoltage is equal to the natural frequency of the windings, then the magnitude of the internal resonance overvoltage has the maximum value. The overvoltage amplitude will depend on attenuation and the duration of the oscillating components. Therefore, overvoltages generated in transients and switching stages in electrical power equipment may be dangerous for the insulating system despite the applied overvoltage protection.

Considering fast transients they may stress inter-turn insulation. Therefore, it is important to analyze and identify such internal overvoltages in order to localize winding parts and develop diagnostic methods for determining sensitive frequency regions in the winding admittance [17,18,19].

CASE STUDY - MEASUREMENT OF INTERNAL OVERVOLTAGES

In this thesis a reactor from Chalmers laboratory was taken as case study by considering it as the high voltage (HV) winding of a transformer. Proper metal shielding was made around the reactor to see the true effect of capacitance from winding to tank and the body as in real transformer. Reactor has extra terminal outlets to measure the internal voltage distribution. Network analyzer is used to measure the impedance between two nodes along the windings through our extreme frequencies and this frequency sweep for determining impedance is used to find the voltage stress points along reactor windings.

One of the recommendations is to measure the leakage inductance of the transformer. Acceptable deviation in inter phase deviation is less than 2%. Conventional methods which include ratio measurements and impedance/ inductance measurements are not much sensitive to identify winding deformations. The desired method must have a scale of sensitivity to displacements and deformations within the winding. If the idea is to open the transformer for inspection the cost will be the factor, the method must depend upon terminal measurements with minimum resources and time factor should be kept in mind. Frequency response analysis (FRA) method is nearly fulfills the requirements mentioned. [13]

Deviations seen in FRA can be related to the actual deformation occurring along the windings by means of a detailed high frequency model of a transformer.

FRA is used in this thesis work as a basic method to investigate the deformations as its required sensitivity. A FRA-signature is generally a transfer function output/ input as function of frequency (10Hz-10MHz in our case), normally investigated at a lower voltage level. Typically winding impedance/ admittance, voltage ratios between windings is measured. These results are then compared to a reference which might be other phase or other transformer results. On the basis of constructional information a detailed model can be compared with the measured data and the differences are due to any geometrical changes seen in the model. Hence the FRA method is assumed more influential and sensitive towards different types of fault when modeled detail internally. [13]

FRA is not a standardized method but a variety of setups can be used. Two common setup methods are used.

Low Voltage Impulse (LVI) is used as one of the setup techniques used for measurements. This method is used after the initial impulse test-method. The input impulse is measured along with other terminal voltages to ground. Several measurements can be made at the same time. The time domain measurements are then transferred to frequency domain and the transfer ratio is established.

Swept Frequency Response Analysis (SFRA) is the second technique of setup. This method is slower compared to LVI method as the frequency sweep for desired range using a sinusoidal excitation takes much time.

In this thesis work SFRA method is used to investigate the impedance along the winding between frequency ranges (10Hz-to 10MHz) in logarithmic scale. [1]

Table 2

	LVI	SFRA
measurements	*several measurements at the same time*	function at a time transfer one
measuring time	fast	Slower as compared to LVI
frequency resolution	Fixed	Wide range of frequency
resolution	Fixed	Resolution can be varied by taking number of measuring frequency points
equipment	Number of equipments required	Only single equipment is required for measurements
accuracy	Dependent on mathematical evaluation	
noise	Broadband noise cannot be filtered	Cancels broadband noise

TEST SETUP

Function generator which can generate sinusoidal wave up to 20MHz was taken as supply to see the voltage distribution along the windings, as shown in the Figure 3. In addition a step function setup was also studied to compare the results with sinusoidal waveform. The rise time and the time to half can be adjusted so that one can compare results. The function generator and step function setup is shown in figure

Figure 3 Function Generator

It is the study case which is made by ASEA during late 90’s. Construction of the reactor is shown in Figure 3The study case has two windings of which only one winding has been used in this thesis. There are eight disks on each winding and each disk has 300 turn numbers in such a way that a total of 10 layers have 30 numbers of turns in each.

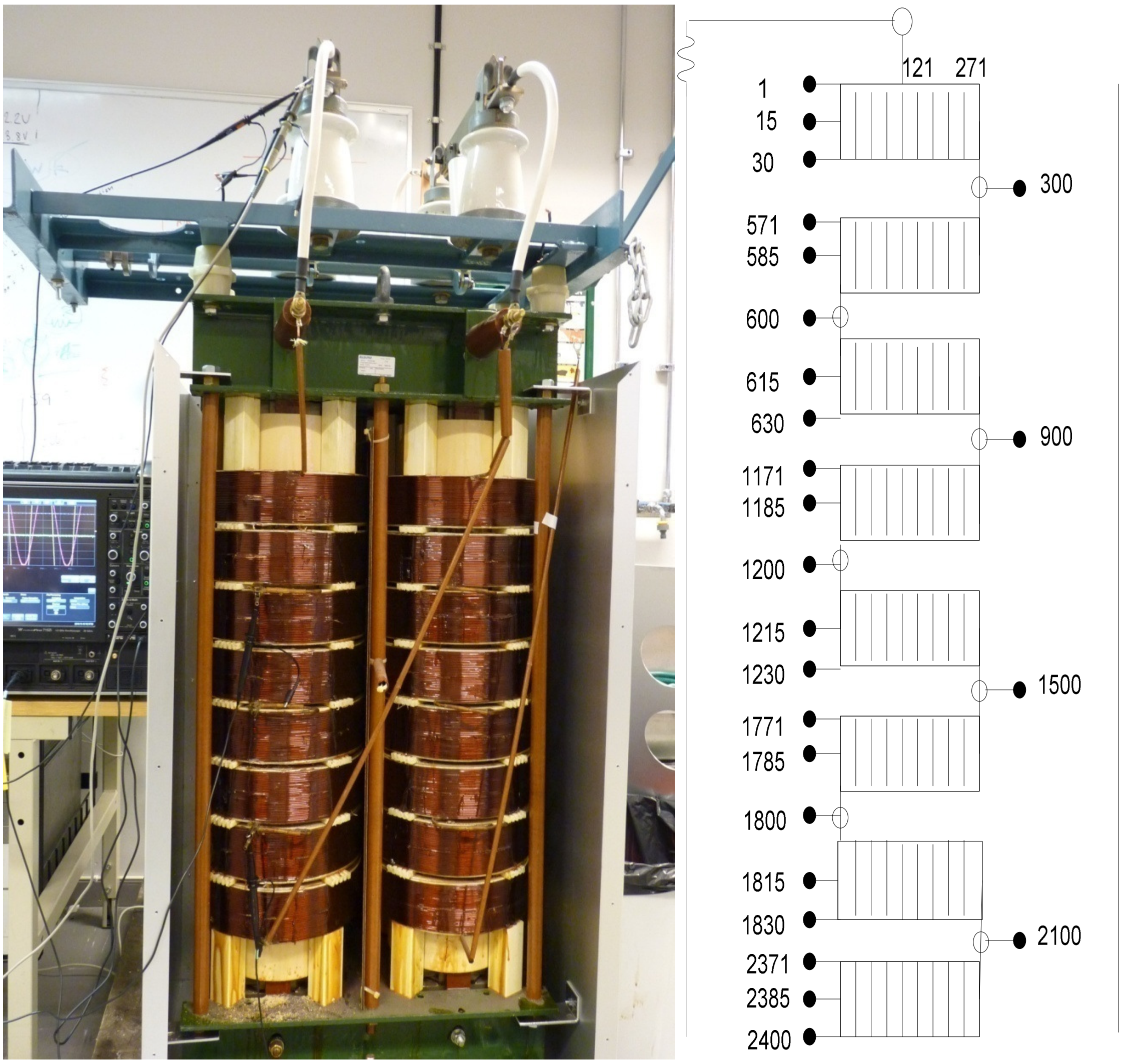

Figure 4 Device under test with nodes

In the above figure 4 different nodes along the winding has been taken for accuracy in the results. As seen from figure every disc has 300 turns so the total number of turns is 2400 and the last turn has been grounded. The turn number starts from first disk from outside to inside of disk so that the last turn number in first disk is inner most turn number (300). Conversely in the 2nd disk the turn number starts from inside of the disk to the outside of the disk so the outmost and last turn number in 2nd disk is 600. In disk 1, almost inner most and the middle node has been taken for measurements as shown in the figure 4 below. There were some limitations due to which the whole nodes could not take into account. The figure 4 shows actual picture of the test object where there are two windings shown, the left winding of the reactor has been taken for transient studies in this thesis. In the figure bushings at the upper side are shown, the input signal from the function generator and step function has been connected above bushings suggesting that the transients are producing by the CB, in addition the effect of the bushing capacitance has also been taken into account. In figure 4 different nodes along the reactor windings has been shown. These are the points where the measurements have been taken with coaxial probes. When looking at first disk from the top, the vertical lining in the disk shows the 10 number of layers of winding whereas the number of turns for each layer is 30. The points taken in the first disk for the measurements are 1, 15, 30, 121 and 271 which shows the starting, middle and the end length of the conductor. Figure 4 shows the nodes 121 and 271 at the disk 1, which are almost in the middle and the end of the first disk. One reason of taking these two points into account is that at higher frequencies the voltage stress is at the first disk so the proper distribution of voltage can be seen when these two points are considered. Another reason to take the inner winding nodes just at the first disk is that, it's very easier to take off the insulation on these points compared to the other disks.

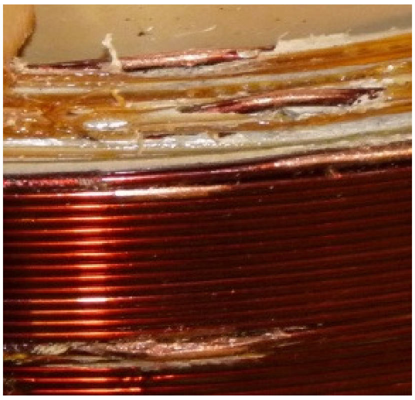

Figure 5 **outer to inner conductors**

Table 3

No of disks	No of layers in the disk	No of turns in each layer	Diameter of the conductor	Length of winding	Length of the conductor
08	**10**	**30**	**2.5mm, 2.6mm**	**Length of disk= 80mm**	
				Length of gape= 10mm	

As mentioned in previous sections about the SFRA method now we are using the same method for the measurement for complex impedance where a single network analyzer MS4630B is used to measure the impedance over a wide range of frequency. MS4630B network analyzer is used to measure impedance of the reactor winding at different nodes. This instrument has a frequency sweep upto 300MHz. In this thesis the limits for frequencies are taken between 10Hz to 10MHz.active probes with double screen coaxial cables are used for above measurements. The network analyzer has nice signal to noise ratio. Using active probes with high input impedance eliminates the influence of coaxial cables running from network analyzer to the test objects measuring points. Using active probes instead of low impedance termination reduces the value of current flowing in the cable and thus reducing the voltage drop due to the series inductance.

MEASUREMENT OF REFLECTION CHARACTERISTICS

Impedance of the test object consisting of resistance and reactance was measured with measuring reflection bridge characteristics. This impedance can be measured in any format as per options given in the network analyzer. Here the format was displayed as magnitude and phase on logarithmic scale. For the connection setup there are four probe ports as shown in the figure

Two for input and the other two for output signals, the shorted 2nd and 3rd probes for the ratio between input and output quantities.

- First the format of impedance to be displayed has been setup.
- From the user preset menu REFLECTION (reflection bridge method) has been selected to measure impedance.
- Configured a measuring system to which the DUT (device under test) is connected.
- Using the measurement group the CENTER, SPAN and RBW has been chosen along frequency scale according to our desired frequency range.
- Calibration was done for the device with disconnecting DUT and finally with connecting the DUT
- Display mode setting for the impedance.

More details for the measurement setup and the procedure for calibration and measurement of impedance is mention in appendix.

Figure 6 Network Analyzer

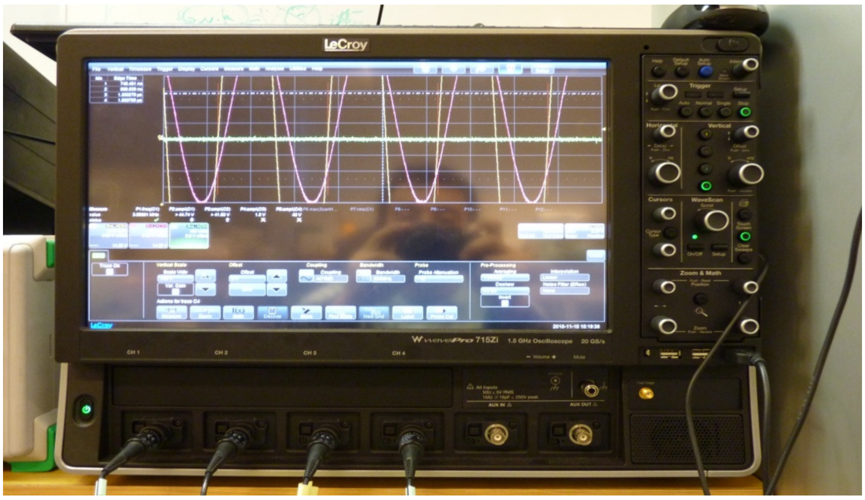

Figure 7 Oscilloscope

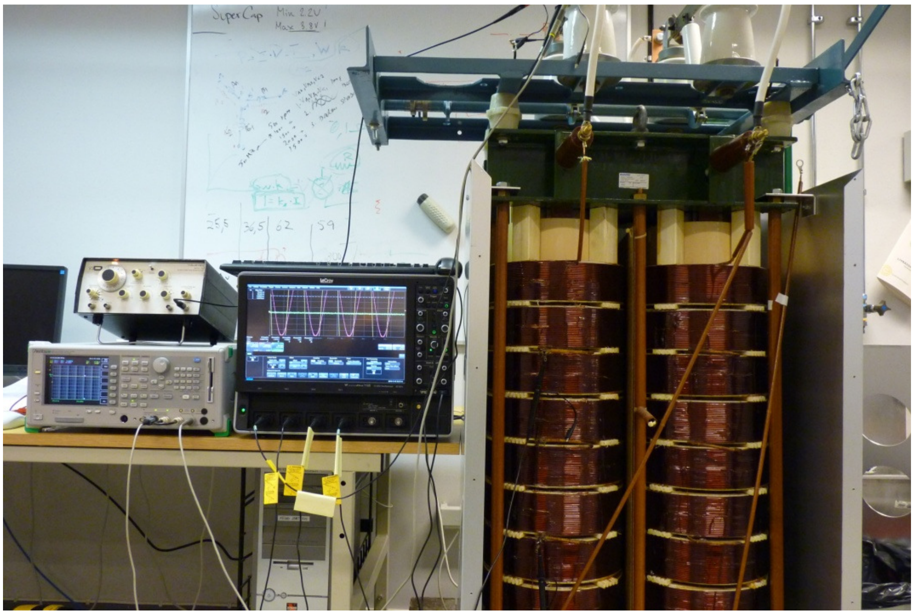

Figure 8 Measurement Setup

FREQUENCY DEPENDENT TRANSFORMER IMPEDANCE

The insulation systems of power transformers are subjected to many transient overvoltages. These are usually caused of lightning and switching operations. If the spectrum of incoming surge voltage matches the transformers winding one, then the corresponding resonance might be excited. Thus the external transients occurring in a power system might trigger internal overvoltages with large maximum value within transformer winding

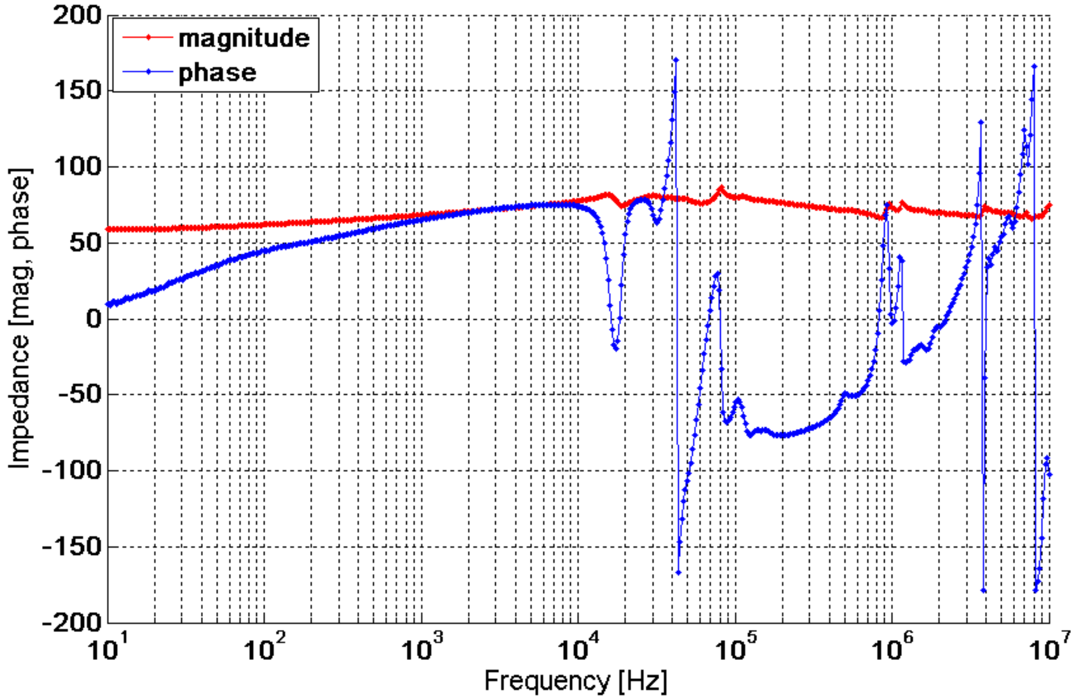

Figure 9 Impedance measurement

In an electrical circuit when inductive reactance becomes equal to capacitive reactance in magnitude resonance occurs causing electrical energy to oscillate between the electric field of capacitor and the magnetic field of the inductor. At resonance series impedance is at minimum where as the parallel impedance is at maximum. Since at resonance frequency, the impedance of inductor and capacitor is equal, the resonance frequency can be calculated as follows

$$\omega L=1/\omega C$$

$$\omega=1/\sqrt{LC}$$

$$f\_res=1/(2\sqrt{LC}).$$

Table 4

Frequency (Hz)
43k
69k
80k
824k
3.67k
4M
5.2M
8M

A finite four-terminal network consisting of distributed passive elements i.e. linear resistance, inductance and capacitance, will exhibit some limited number of resonances. The magnitude, phase and frequency of this limited resonance can be determined analytically, depending on the available network setup and geometry. These resonances can also be determined experimentally by exciting the network at the input terminals by a sine wave voltage with desired frequency range.

Consider an example of transformer which is excited between the input of the high voltage winding and ground (other end of the winding is grounded). The frequency dependent current or the voltage between two terminals can be evaluated. In the later case the frequency dependent voltage is evaluated by a gain function (V_{out}/V_{in}) in the frequency domain.

The behavior of the equivalent circuit of transformer is similar to a transmission line. From an input impedance viewpoint it is possible to relate frequency dependent performance of both devices. At some frequencies a low loss, high Q (where Q is equal to V_f/V_{60}, V_f is the voltage at any frequency), series resonant circuit with minimum input impedance is referred to as a resonant line. It exhibits a standing wave pattern of an integer number of half sine wave distributed along length and experiences a large amplitude oscillation at the anti-nodes. Transformer winding behaves same and the resonance for this particular frequency is terms as terminal resonance. Similarly at other frequencies, the low loss high Q parallel resonance circuit, with maximum input impedance. Again a standing wave pattern consisting of an odd integer number of quarter sine loop will appear. The transformer anti- resonant analogies will terminal anti-resonance.

If the transmission line analogy is retained when transformer is viewed from a gain function stand point, it will be seen that if two end points of a single disk are located out-of-phase anti-nodes in the standing wave pattern at some particular frequency a maximum voltage will appear between those two ends. This can be refer as an internal resonance for the winding section or that particular disk. At other frequencies standing wave either collapse or shift so that the anti-nodes at physically shifted to some other points. For some frequencies the standing wave will place nodes at or near end point of the particular disk. At that frequency a condition of internal anti resonance exists at the disk.

These can be summarized as.

- Terminal resonance—“terminal impedance minimum”.
- Terminal anti-resonance—“terminal impedance maximum”
- Internal resonance ---“internal voltage maximum”.
- Internal anti-resonance---“terminal voltage minimum”.

A clear and properly patterned of winding resonance can be seen in a completely uniform winding. Some older authors showed the same results for an air cored simple helical coil. The lowest order full winding resonance has nodes at the terminals and an anti node at the mid way. This resonance has the characteristic of both terminal and internal resonance. The second order full winding resonance has nodes at one quarter and third quarter points. As similar to previous case, this resonance can be recognized as terminal impedance measurements or from gain function measurements. In the same fashion higher order modes of winding oscillation can be find.

The interesting point is that lowest frequency internal resonance appears across maximum number of turns, while higher frequency internal resonance will exhibit across progressively lesser turns.

The pattern of winding oscillation is not so orderly in practical transformer, due to non-uniformities in insulation and distribution in turns [20].

Voltage Distribution at Resonance Frequencies

Resonance frequencies are found from the network analyzer at the maximum, minimum value of impedance magnitude and the points at which phase is zero as shown in Table 4. These frequencies are taken into account as we observed higher voltage stresses at these frequencies. The voltage distribution has been shown for different nodes and these nodes are being taken randomly across the full length of reactor where it was easy to measure. Voltage distribution along the length of the winding is measured by combining each node at that particular frequency. The same procedure has been done for all resonance frequencies to see the effect along the length of the winding. At lower frequencies it was observed that resonance frequency occurs when the length of the winding is equal to the multiples of the wavelength. Also it is interesting to note that, at lower frequency the travelling wave is half wave and when the resonance frequency increases the travelling wave changes to full wave and might be to one and half wave.

The amplitude for the voltage at lower resonance frequencies is higher than as of the higher resonance frequencies. This is because of damping.

Voltage Distribution at 43kHz Resonant Frequency

When the transient overvoltage is applied over the terminal, the voltage distribution is not uniform according to resistance of the turns through the winding. Generally voltage decreases with the increase in resistance but it is very clear from the results that voltage is higher at the middle of first coil at 43kHz. At different nodes across the whole winding the voltage distribution has been observed and one can see obviously the same behavior of stresses at this frequency. As the maximum voltage stress for this particular frequency is in the middle of reactor winding, this shows the wave travelling is longer in the wavelength as compare to other frequencies. The effect of distributed parameters on the propagation of transient overvoltage will depend on the contents of the frequency of the travelling wave. The resonance at lower frequencies has higher amplitude as compare to higher frequencies. [14]

The similar pattern has been found in the experimental results up to round about 100-200 kHz. For 200 KHz to 800 KHz, response in the experimental measurements is clearly resonance free. Then for the remaining higher frequencies the resonance is happening but due to damping, the amplitude is lower as it was higher for lower frequencies.

Figure 10 to Figure 13 show the voltage stress at different point on reactor winding along the length of reactor. In Figure 10 the maximum stress is at node 1200 which is the midpoint of the reactor winding. In Figure 11 it is clear the higher stress is at node 1230 so showing the same behavior of voltage stress. If we consider all the above figures it can be concluded that voltage stress is in the half way of reactor winding and gradually decreasing as we move away from the midpoint. A standing wave with maximum amplitude in the mid of the winding can be considered for this particular resonance frequency. This behavior exhibits the voltage stress between the turn to ground. The maximum stress is almost 1.3p.u, as it can be observed in Figure 12.

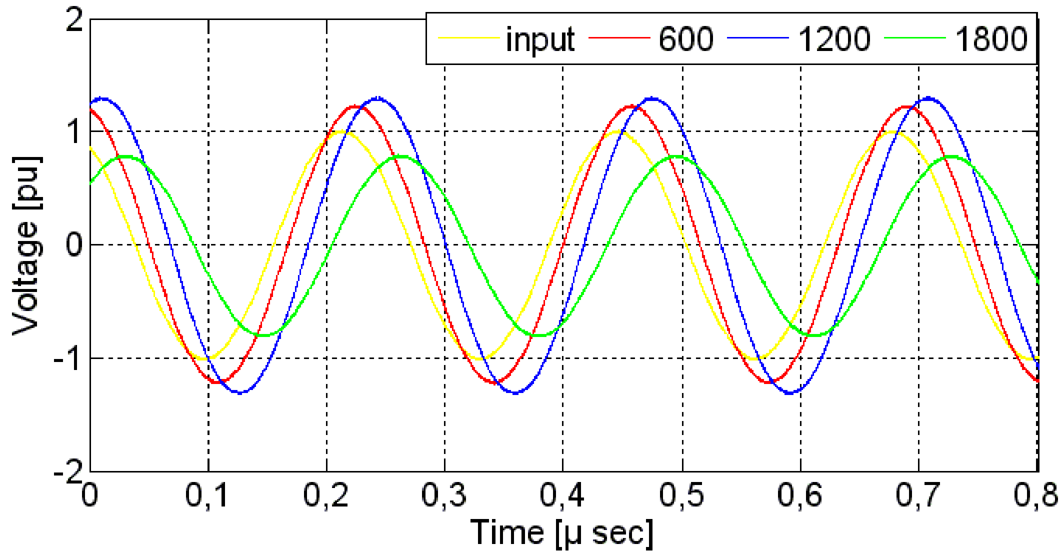

Figure 10 Voltage stress at 43 kHz (a)

For a closer observation only upper half portion with specific interval of the winding is taken for measurements, as shown in Figure 11. Nodes 30, 630 and 1230 are taken for measurements. These nodes are the last turn of the outermost layer of the 1st, 3rd and 5th disc respectively. The voltage magnitude is gradually increasing from node 30 and its maximum value at node 1230 which is approximately equal to 1.25pu. the voltages at node 30 and input is almost equal so it can be concluded that the turn to turn voltage stress for this resonance frequency specially for this particular measurement is negligible. Thus the turn to shield voltage stress is of interest at lower frequencies. Phase shift in voltages can also be observed for this case, especially at node 1230.

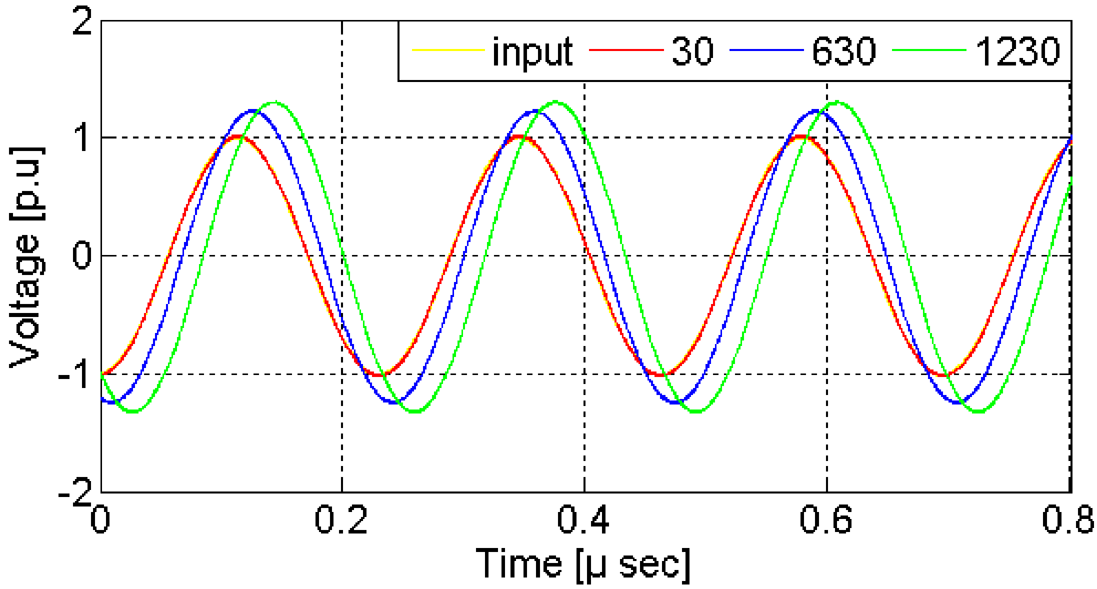

Figure 11 Voltage stress at 43 kHz (b)

Compared to the previous measurement where the nodes were taken at the lower side of the disc, here the nodes are taken from the upper side of each disc after specific intervals to observe interesting results. The nodes taken are 571, 1171 and 1771 which are first turns of the outermost layer of disc 2, 4 and 6 respectively. Voltage stress is maximum at node 1171 as shown in Figure 12 and its magnitude is about 1.3pu approximately. The lowest stressed node is 1771 which shows that the stress is gradually decreasing towards lower part of the winding from the centre. Phase shift is more prominent at node 1771 while at other nodes its lower w.r.t. input signal.

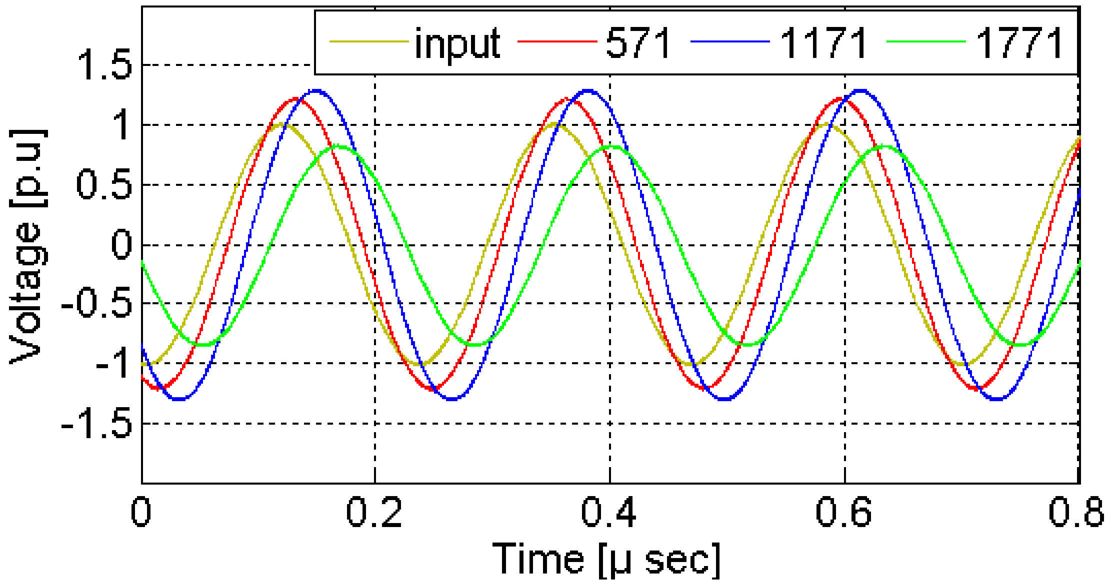

Figure 12 Voltage stress at 43 kHz (c)

Previously, for the first resonance frequency, measurements are performed at the upper part of the winding. Starting with Figure 13, presented measurements are obtained at the lower part of the winding.. Figure 13 presents measurements taken at nodes 1200, 1800 and 2400, the lowest turns of the innermost layer of 4^{th},6^{th} and 8^{th} disc respectively. Figure not only shows a voltage stress, but also a large phase shift.

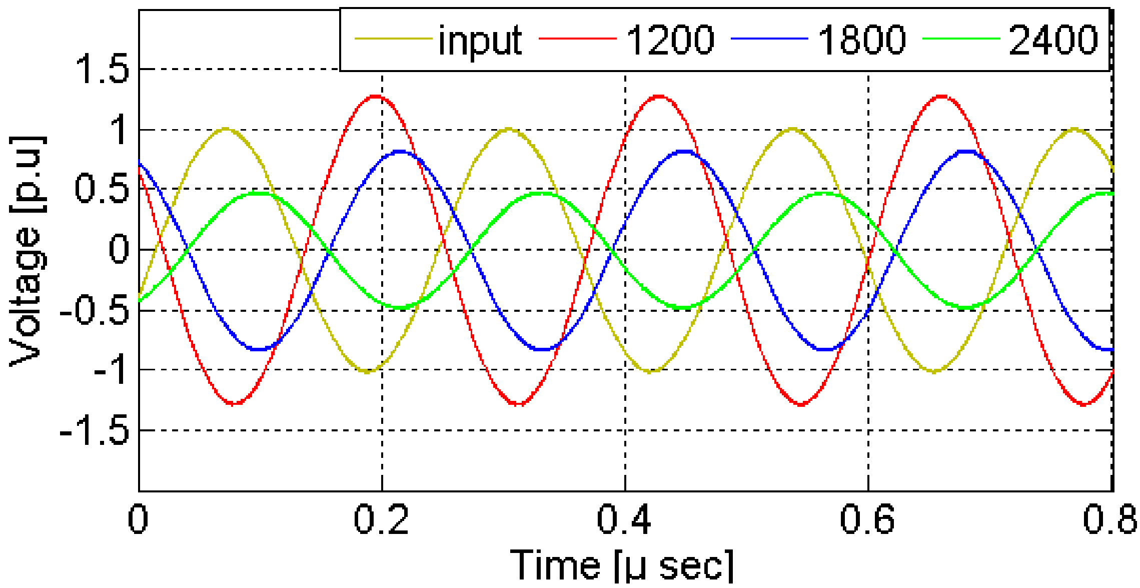

Figure 13 Voltage stress at 43 kHz (d)

Total voltage distribution across the winding has been plotted at 43 kHz in Fig. 14. The result shows a standing half wave along the length of the winding with the maximum amplitude at the mid of the winding. Maximum voltage stress arises between turn to ground. Turn to turn voltage stress is much lower at this resonance frequency.

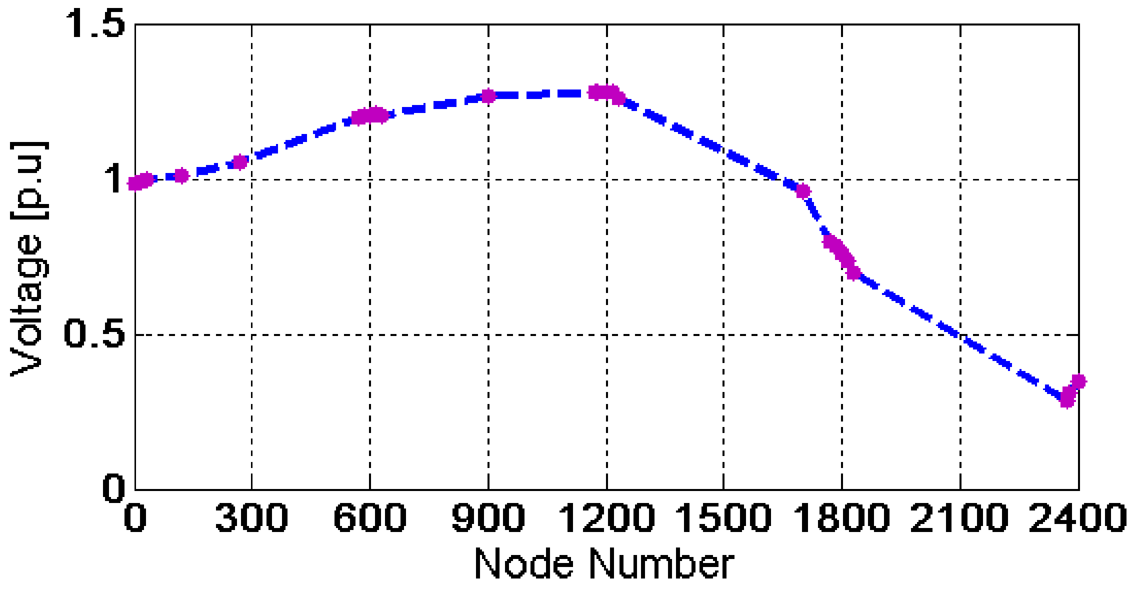

Figure 14 Voltage distribution at 43 kHz (e)

VOLTAGE DISTRIBUTION AT 69KHZ RESONANT FREQUENCY

Considering second resonance frequency of lower band, it is seen from figure 15 that the maximum turn to shield voltage stress is at the second disc of the winding. The nodes taken for measurement of voltage stress are 600, 1200 and 1800 which corresponds to third, fifth and seventh disc of the winding respectively. In addition the nodes taken at each disc is the first turn. The maximum stress is at the first turn of the third disc. The voltage is gradually decreasing from third disc to the last one. So the turn to turn stress is negligible for this case also.

Figure shows the higher stress is at node 600 which is on the first layer between 2nd and 3rd coil. The important point to be noticed here is, although the 69 KHz is the resonance frequency and we are getting voltage value which is greater than normal but the amplitude of stress is lower than the stress at 43 KHz. The highest amplitude of voltage stress is almost 1.25p.u. It is quite obvious that the voltage stress is decreasing as we are going towards bottom of the reactor. It is even lower than input signal for the node 1800 which is almost 0.5 pu. So the voltage stress at this resonance frequency is at disk 2. If we examine the wave travelling through the winding, it's a half wave with the highest amplitude in the beginning of the winding.

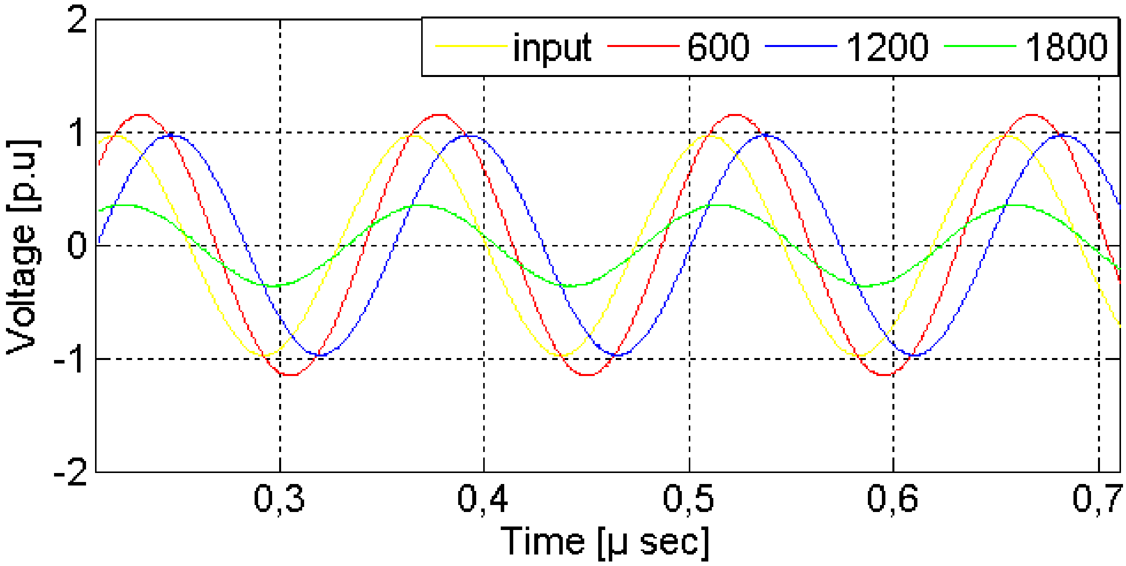

Figure 15 Voltage stress at 69 kHz

The voltage stress along the length of the winding at this particular resonance has been plotted in figure 16. Voltage gradually increasing from 1 pu to higher with increase in the number of turns at the upper part of the windings. This increase goes to its maximum amplitude at node 600 which is the first turn of the third coil. The decay in amplitudes starts from node 600 and it ends at node 1800 as shown in figure 16 and again the voltage amplitude starts to rise onwards at the lower side of the windings. If one has closer look the voltage graph resembles a sinusoidal function. As the graph does not shows exact sinusoidal wave due the limitations in taking measurements along the length of the windings otherwise it is a perfect sinusoidal wave.

This result shows a full standing wave along the length of the winding at this resonance frequency. If compared with the first resonance frequency voltage distribution, it is concluded that the voltage stress has been shifted from mid to upper part of the reactor winding. In addition here the result shows a full wave as compared to the previous half wave. The voltage stress here is considered as turn to shield as the turn to turn voltage stress is negligible.

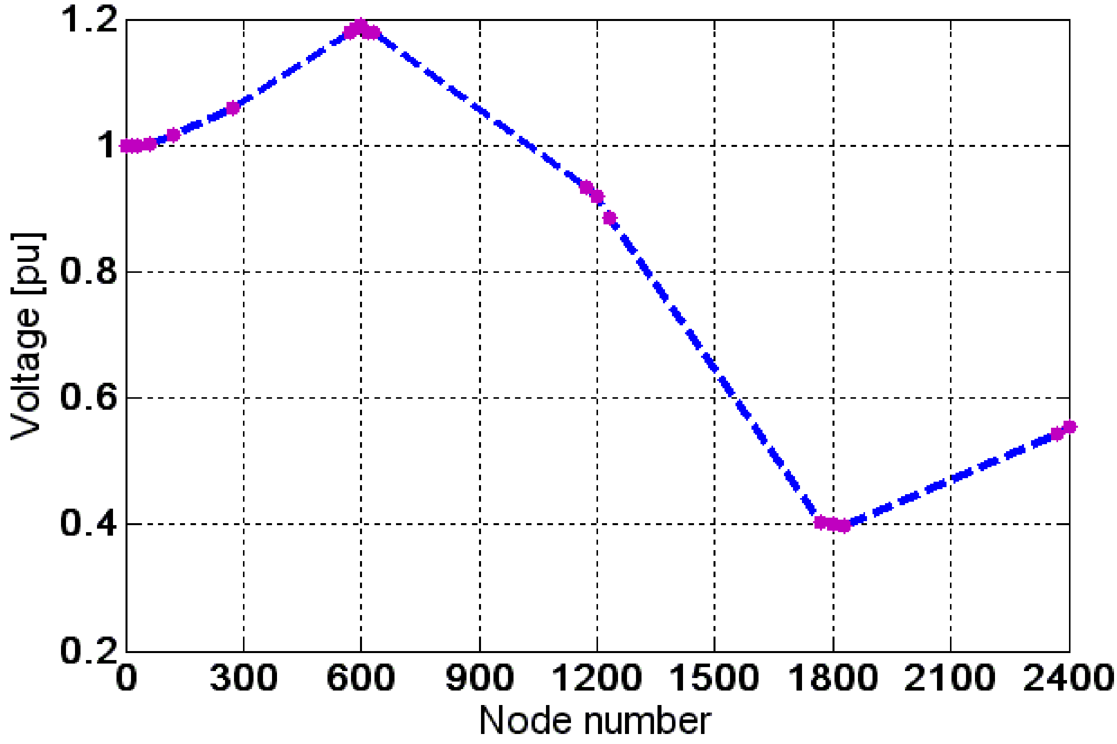

Figure 16 Voltage distribution at 69 kHz

VOLTAGE DISTRIBUTION AT 80KHZ RESONANT FREQUENCY

Third resonance frequency at lower band at which the voltage stress has been observed is 80KHz. By considering different nodes along the length of the winding the most voltage stressed region has been found. Measured voltage stress here corresponds to the voltage between turn to shield. Maximum stress was observed at node 600 and 571 which are the last and first turn of the outermost layer of disc 2 respectively. Therefore the voltage stress has been shifted to more upper part of the winding as compared to previous resonance frequencies. Figure 17 shows one of the measurement results taken at 80 KHz resonance frequency. Here the nodes taken for measurement are 571, 600 and 1171 to observe the stress. Node 1171 is the first turn of the outermost layer of the forth disc as shown in figure 4. The most stressed node is 600 which has an amplitude of about 1.25pu whereas the lowest stressed node in this case is node 1171 which has the magnitude below 1pu.

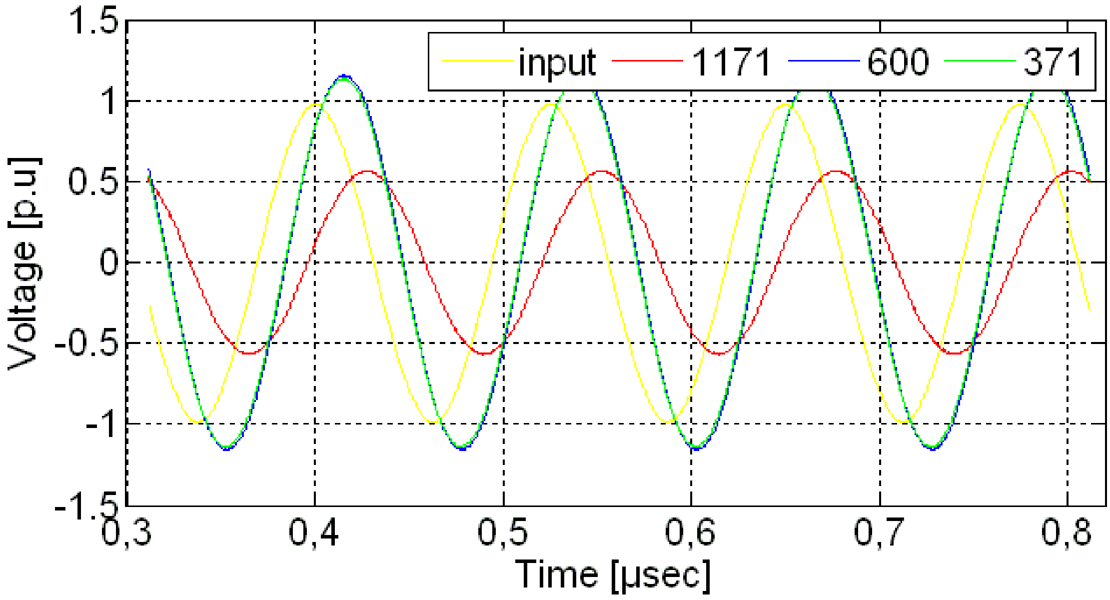

Figure 17 Voltage stress at 80 kHz

Plotting voltage stress against the length of the winding, one can have the graph as shown in the figure 18 for 80 KHz resonance frequency. Initially the stress is 1pu and then gradually increasing linearly up to node 600 which has the peak magnitude and then decreasing till node 1500. After node 1500 the magnitude again increasing gradually as shown in figure 18. Between node 1800 and 2371 there was not possible to take measurements so it was shown as of same magnitude between the two nodes. Otherwise it will also exhibit a sinusoidal shape as can be seen for other length of the winding.

Result for this resonance frequency shows a standing wave along the length of the winding. The maximum voltage stress between turn to shield is 1.25pu where as the minimum voltage magnitude is 0.4pu around node 1500. The result is considered as one and half standing wave along the length of the winding.

If the voltage distribution along the length of the winding for above three resonance is compared then it can be found that wave length is the multiple of the length of the winding. At the lowest resonant frequency half wave was observed whereas for second and third resonance frequencies a full and one and half wave is observed respectively.

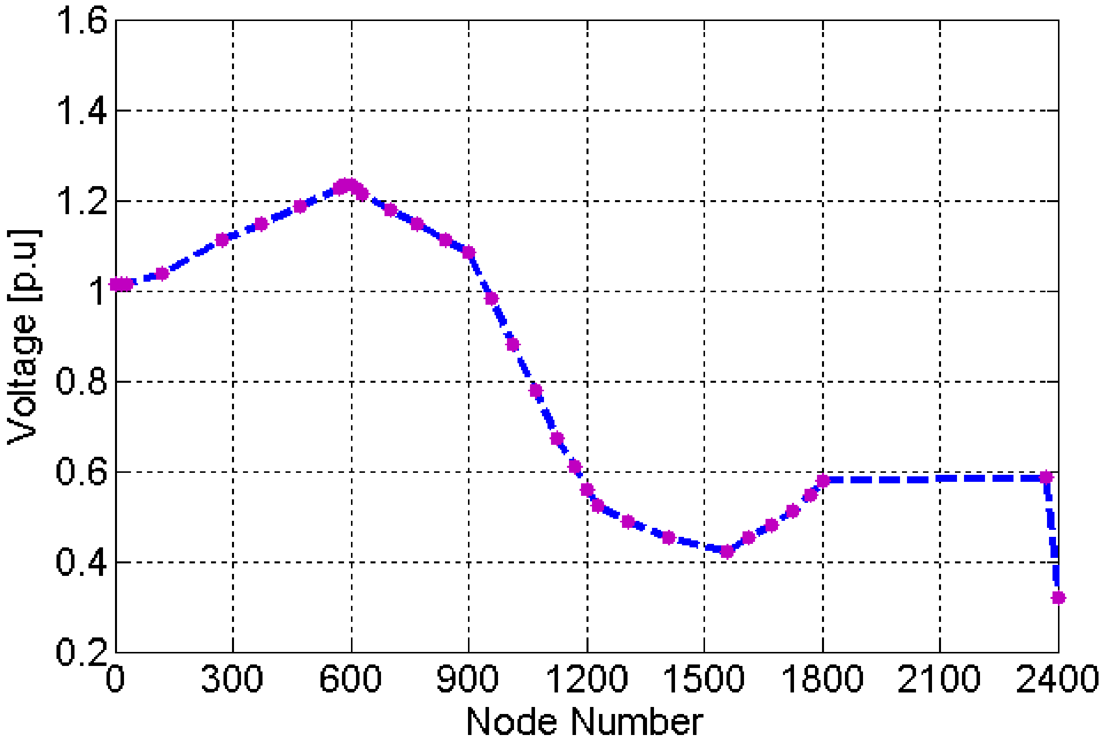

Figure 18 Voltage distribution at 80 kHz

VOLTAGE DISTRIBUTION AT 824KHZ RESONANT FREQUENCY

Voltage stress at different points for this resonance frequency is given in figure 19. Maximum voltage stress is at node 61 which is first node in the 3rd layer of the first disk. This shows that the maximum voltage is at the beginning of the first disk at this particular resonance frequency. The voltage stress at other nodes along the length of the winding was also observed which was below input amplitude.

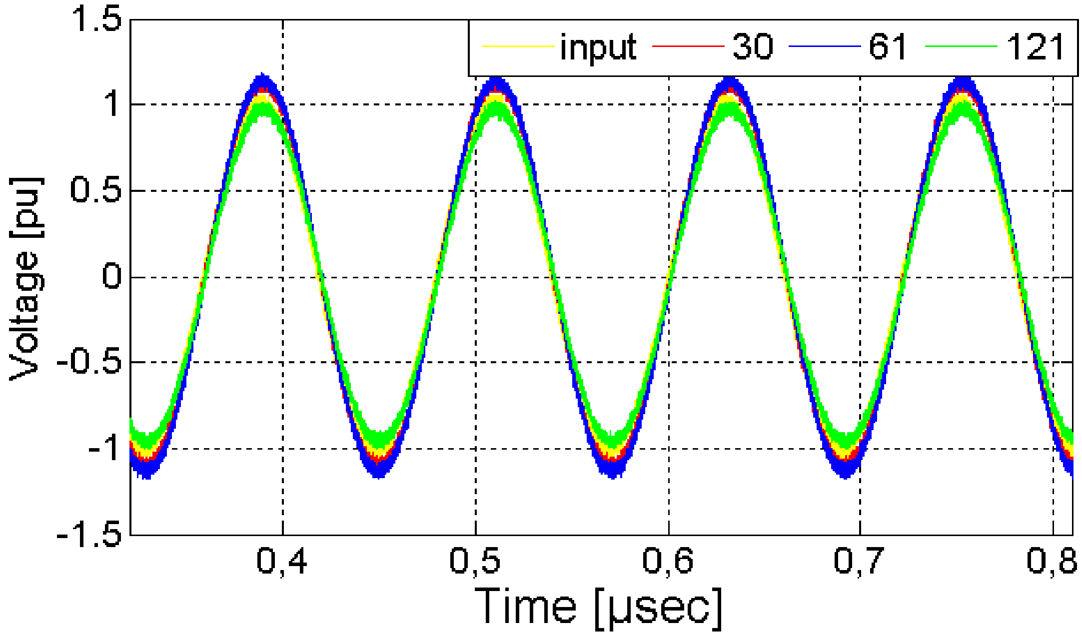

Figure 19 Voltage stress at 824 kHz

VOLTAGE DISTRIBUTION AT 3.67MHZ RESONANT FREQUENCY

This frequency is the first resonance frequency for the higher frequency band. When sinusoidal wave of 3.67 kHz frequency has given from function generator to the test object, the oscilloscope showed the results in figure 20. The maximum stress observed is about 3pu at node 30 which is the last turn of the first layer in first disk. The second node which has amplitude of approximately 2.5pu is observed in the middle turn of the first layer in the first disk so the maximum voltage is observed in the first layer and the amplitude decreases towards inner layers of the first disk. It can also be observed that there is a higher voltage difference in between the turns. If node 1 and 30 is observed there is a voltage difference of more than 1.5 pu, similarly it is shown in the figure that the difference of potential between node 1 and 15 is also quite higher which is approximately 1 p.u. this result shows that at higher frequencies, not even voltage to ground is increasing but also there is an quite enough voltage difference between turns. When one can further move towards higher frequency this higher voltage stress shifts between to alternate turns of the same layer resulting in insulation breakdown.

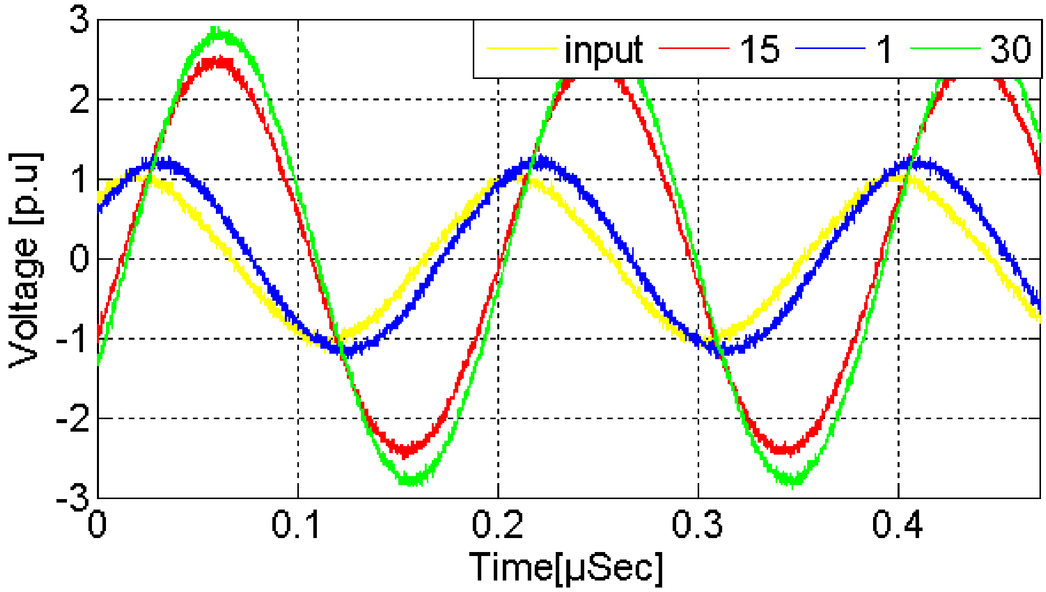

Figure 20 Voltage stress at 3.67 MHz (a)

Voltage stress at 3.67MHz resonance frequency has been observed at the upper part of the winding. Considering figure 21 it is seen that the stress is found to be near to upper most disk. Taking nodes 20, 30 and 61 for the measurement, at node 20 the voltage stress is maximum. Node 20 is the 20^{th} turn of the outermost layer of disc one. In addition at node 30 and 61 which are the 30^{th} and 1^{st} turn of the first and second layer respectively of 1^{st} disc have also the voltage stress about 1pu. For this resonance frequency the turn to turn and turn to shield stress both are present. So the stress is also on the insulation between the turns.

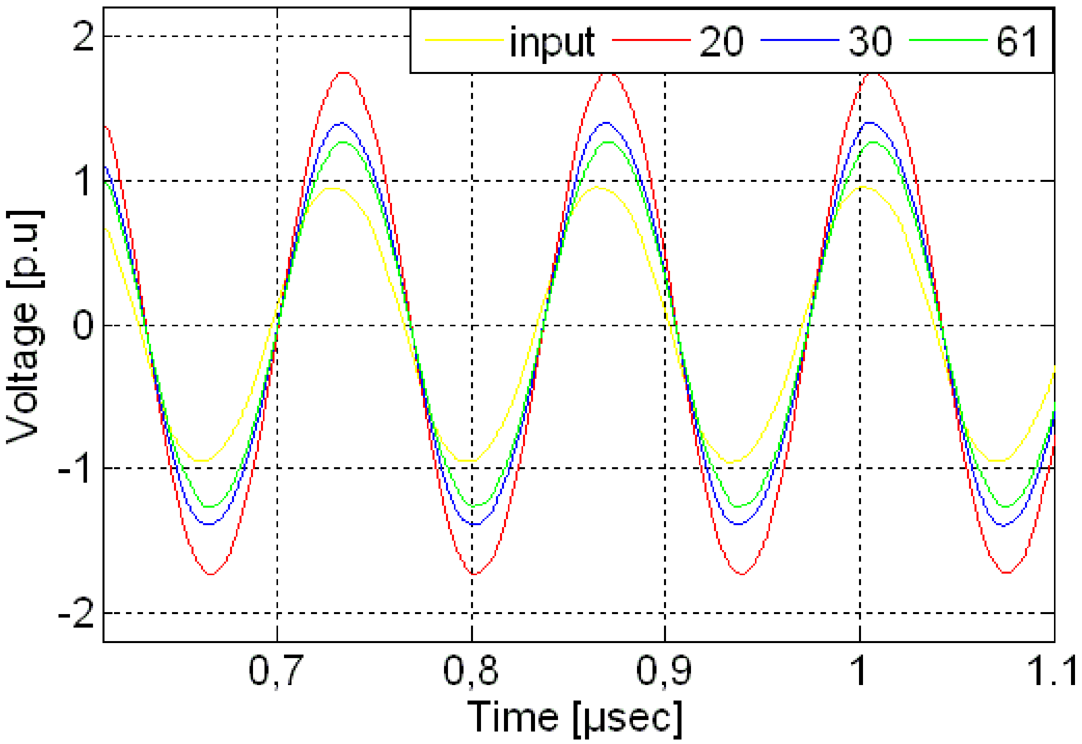

Figure 21 Voltage stress at 3.67 MHz (b)

Voltage stress at other disks of the windings is not shown here as the stress occurs only within the first disk. So the concern for the voltage stress for this particular frequency is first disk. But also one can be concern about the voltage distribution along the length of the winding at this frequency which is shown in figure 22. Stress is gradually decaying towards higher number of disks. The whole stress is concentrated within first disk. As previously described for other resonance frequencies, at this frequency also the quarter wave is travelling along the winding. Some variations can be observed within different disks. These can be more visible if more nodes are taken into account so that a clear picture of voltage distribution within each disk can be estimated. Considering figure 22 it can be observed that there is more stress between turns. This can be seen in figure at nodes below 100. Also at node 600 there is a voltage difference between turns. In addition at node 1200 and 1800 there is a variation in voltage between turns. These stresses can be more visible if the number of measured node be maximized. From figure it can be identified that more nodes between 1200 and 1800 can give more accurate results. in addition for 1st disc it is advantageous if all the nodes can be considered for measurement.

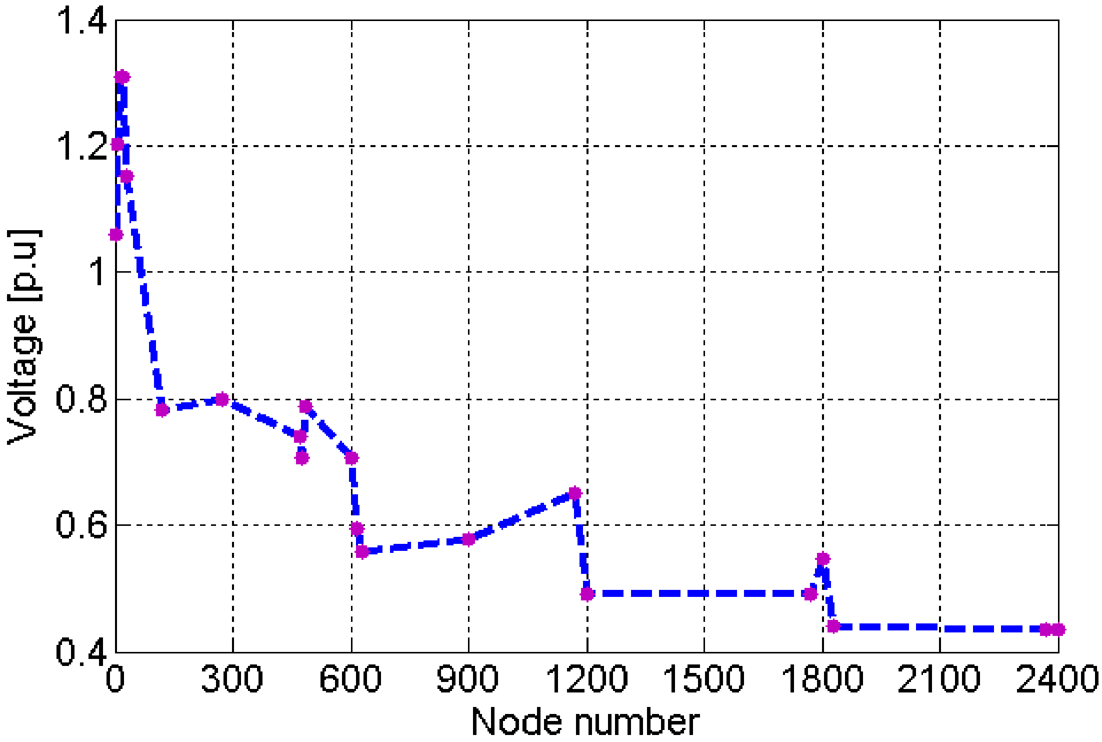

Figure 22 **Voltage distribution at 3.67 MHz**

VOLTAGE DISTRIBUTION AT 4MHZ RESONANT FREQUENCY

On going further on frequency spectrum, 4MHz was observed as resonance frequency where the maximum stress was again found at the starting of the winding. First disk is under higher voltage stress. Figure23 shows that the voltage stress is more shifted towards the first end of the winding as compared to last results. Node 22 is at highest stress which is the 22nd turn of the first layer of the first disk. In addition the voltage difference between node 1 and 22 is also higher which shows the turn to turn voltage stress is increasing with increase in frequency. Maximum voltage stress is about 1.8pu

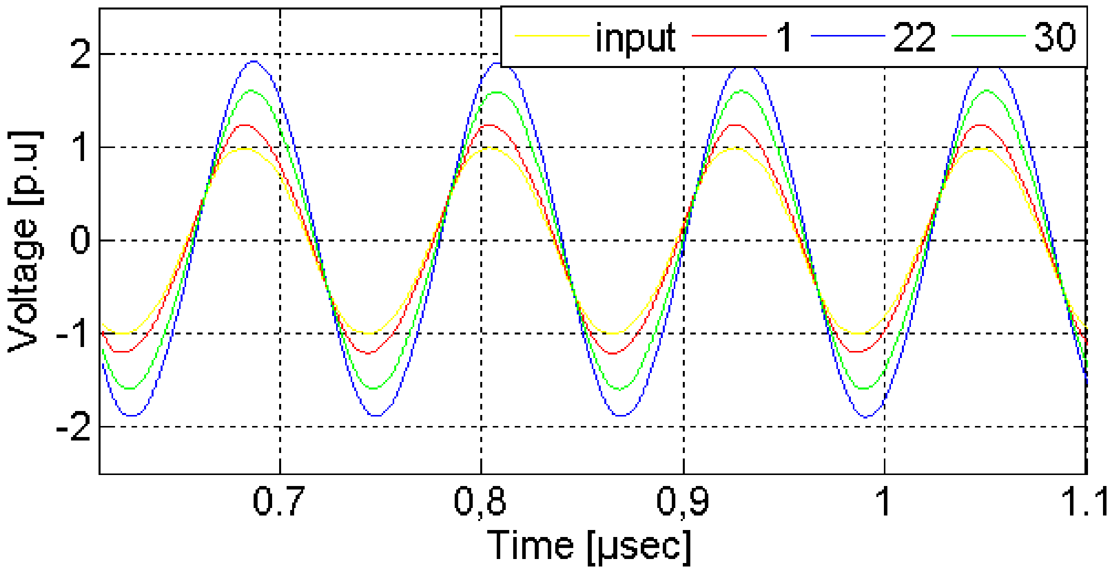

Figure 23 Voltage stress at 4MHz (a)

Considering another measurement nodes for 4MHz resonance it can be observed that the stress is more prominent towards first layer of the first disc. There is a enormous voltage difference between input and node 7 which are not far away from each other, as shown in figure 24. Node 61 is first turn on second layer of 1^{st} disc which is at lower stress, which shows that the voltage stress has been decreased in the 2^{nd} layer of the first disc. Maximum stress observed in the figure is about 1.8pu

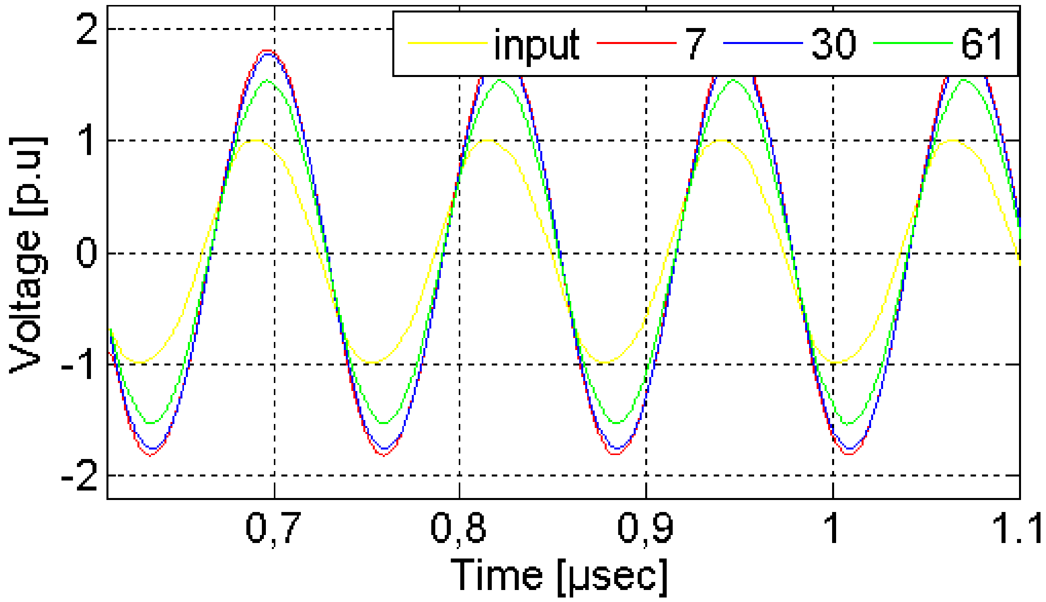

Figure 24 Voltage stress at 4 MHz

Voltage distribution along the length of the winding for this particular resonance frequency is shown in figure 25. As it was observed in early measurements that the more stress is concentrated in the first disk, voltage stress graph for this resonance frequency is in resemblance to the previous. Figure 25 shows some points where the stress abruptly changes from a higher value to lower or vice versa as can be seen at node 600 and 1200. At node 600 there are some critical points where the variation in voltage stress is more prominent which are the points where the turn to turn voltage stress is higher resulting in weakening of the insulation between the turns. Further stress will result into partial discharge initiation or failure of insulation due to direct breakdown. These voltage stresses between the turns can be more visible on taking more number of nodes into consideration. On taking more nodes at first disc at the starting layers, will result into more visible turn to turn voltage stress. Between node 600 and 1200 more turn to turn stress can be observed by considering more measurements between these nodes.

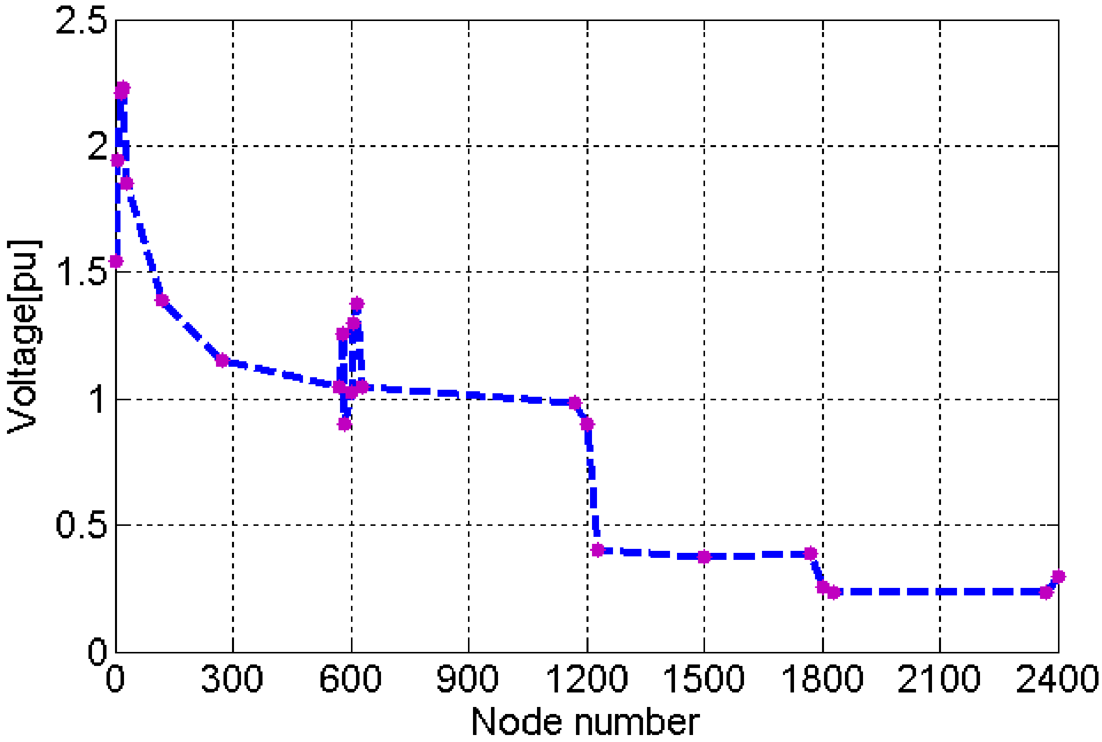

Figure 25 Voltage distribution at 4 MHz

VOLTAGE DISTRIBUTION AT 5.2MHZ RESONANT FREQUENCY

This is the 3rd resonance frequency at higher band. As observed for last two high band resonance frequencies, it is again true for this frequency that the more stress is concentrated within first disc of the reactor winding but might differ in the magnitude of the maximum stress.

Measurements taken for this particular resonance frequency is mostly within first disc. But first it was made confirm that the stress is in the first disc. Oscilloscope was connected to nodes 7, 30 and 61 to observe the stress. Figure 26 shows the voltage stress for the above nodes. Node 30 is observed the maximum stressed node with an amplitude of above 2pu. The voltage stress between node 7 and 30 is also noted to be higher enough. In addition voltage difference between node 7 and 61 is also high enough. Phase shift w.r.t input sinusoidal wave is observed for all nodes

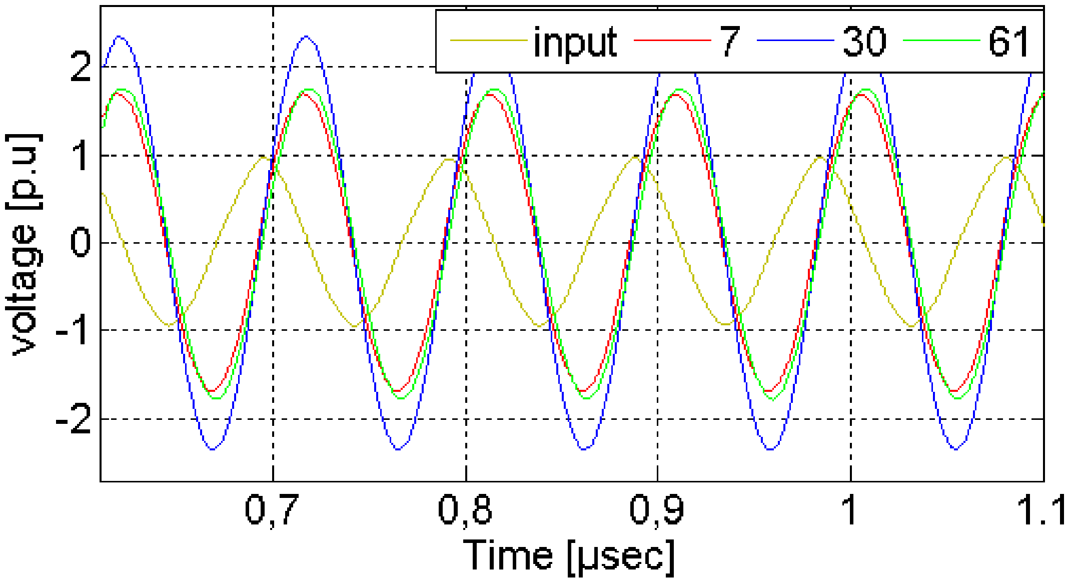

Figure 26 Voltage stress at 5.2 MHz (a)

Further measurements were taken for nodes 7, 22 and 30 to observe the voltage stress between nearer nodes. Considering node 7 and 22, there is not much voltage difference as compared to previously studied case. The same observation is made for nodes 22 and 30. Thus the same maximum voltage difference is between node 7 and 30. In figure 27 node 22 is at maximum voltage stress. Phase shift can also be observed w.r.t. input signal.

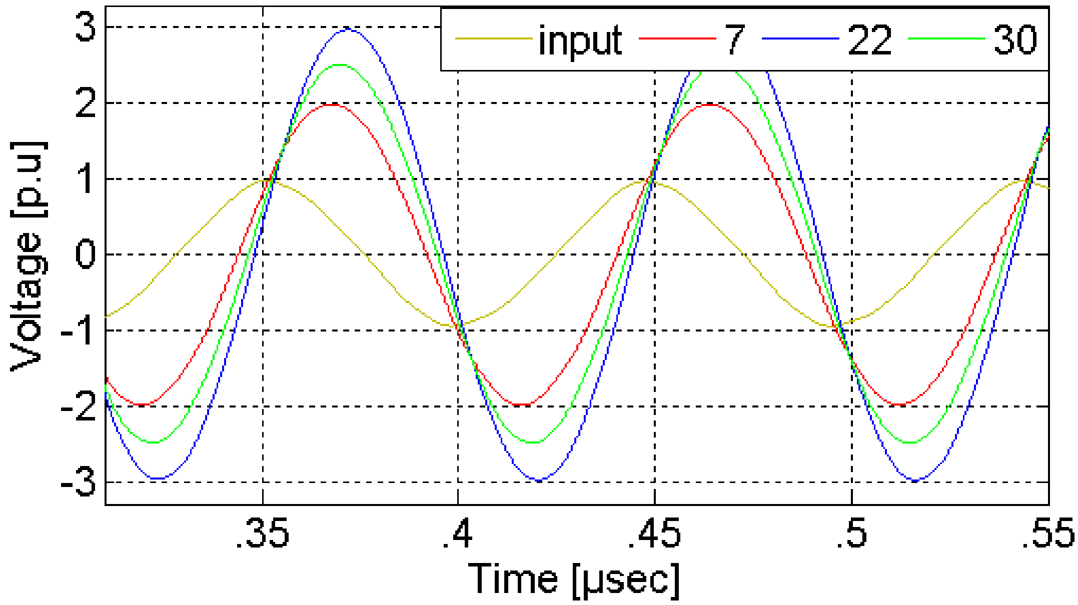

Figure 27 Voltage stress at 5.2 MHz (b)

Another case has been taken to study the stress further. The same first disc is taken as case study. Nodes 1, 15 and 30 are taken for measurement as shown in figure 28. All three nodes belongs to the first layer. From the figure the most stressed node is 30 with an amplitude of above 2pu which is almost equal to the 2^{nd} highest stress node 15. There is not much voltage difference between both nodes. If compared with node 1 then there is enormous voltage difference and this voltage stress is almost equal to 1pu. Phase shift in voltage is also considerable for both node 15 and 30.

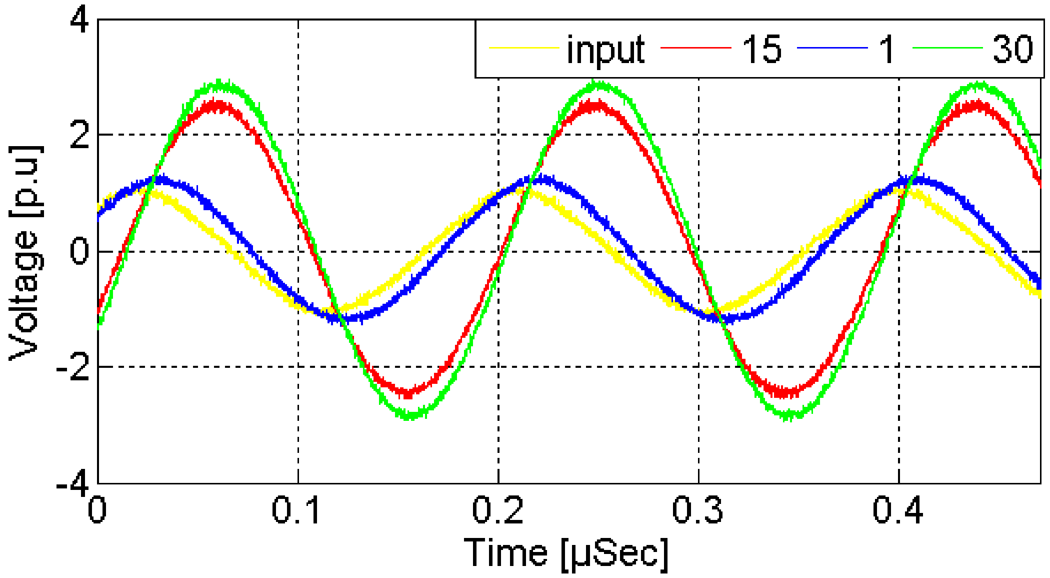

Figure 28 Voltage stress at 5.2 MHz (c)

Voltage distribution along the length of the winding for the resonance frequency 5.2MHz is shown in figure 29. As from previous figures of voltage stress for the said resonance frequency, the stress is concentrated at first disk which is the turn to shield as well as turn to turn. From figure it can also seen that there is some voltage stress between turn at node 600 and 1200 and more stresses can be visible by taking more nodes into consideration.

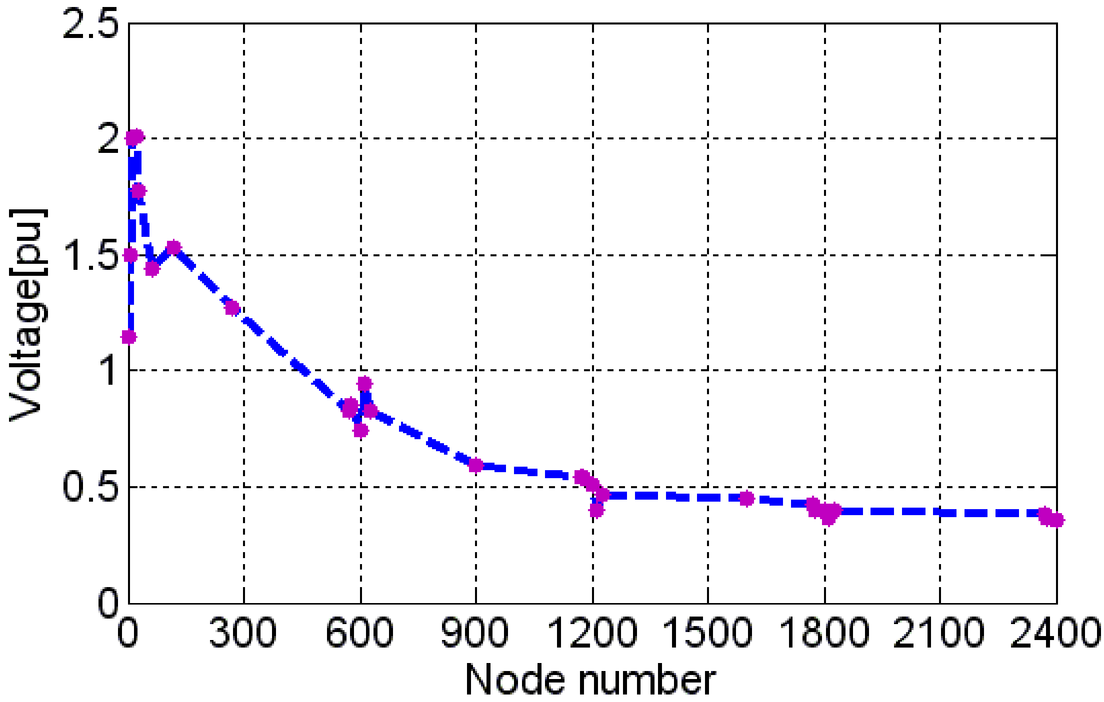

Figure 29 Voltage distribution at 5.2 MHz

VOLTAGE DISTRIBUTION AT 8MHZ RESONANT FREQUENCY

This frequency is the 4th and last resonance frequency at higher band. The voltage stress coincides within first disc as observed in last resonance frequencies. In addition to above some voltage stress from turn to ground is observed up to 600 node.

Node 15, 121 and 271 are taken as the measuring nodes to observe the voltage stress. Node 121 is in the mid of first disk whereas node 271 is the almost in the innermost part of the first disc. Mostly it is very much difficult to take nodes that belong to inner layers in any disc but at the first disk its not too much difficult as compared to other discs. Figure 30 shows the result for these nodes. Node 15 is the most stressed node with amplitude of above 2pu. Other nodes are still above 1pu. There is a much voltage difference between node 15 and 121 so are stressed. There is not a reasonable phase shift seen in this case.

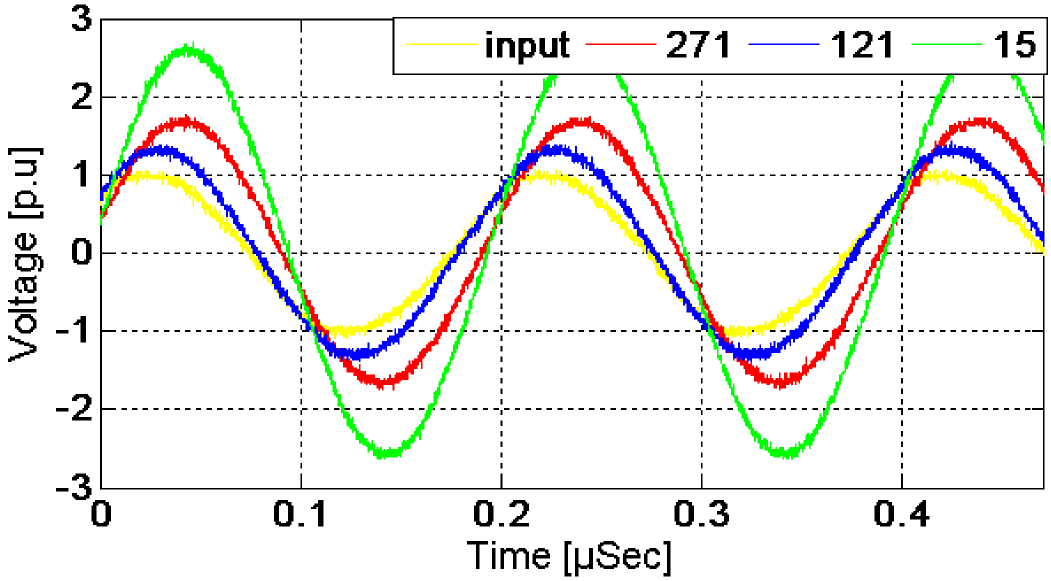

Figure 30 Voltage stress at 8 MHz (a)

Other nodes are considered in the study of 80 KHz resonance frequency. The nodes taken for measurement are 7, 61 and 271 as shown in figure 31. Node 7 is most stressed node with respect to shield with amplitude of 2pu. When talking turn to turn voltage stress for this case, node 7 and 271 are stressed, also the node 7 and 61. There are phase shift considerations with respect to input for all nodes.

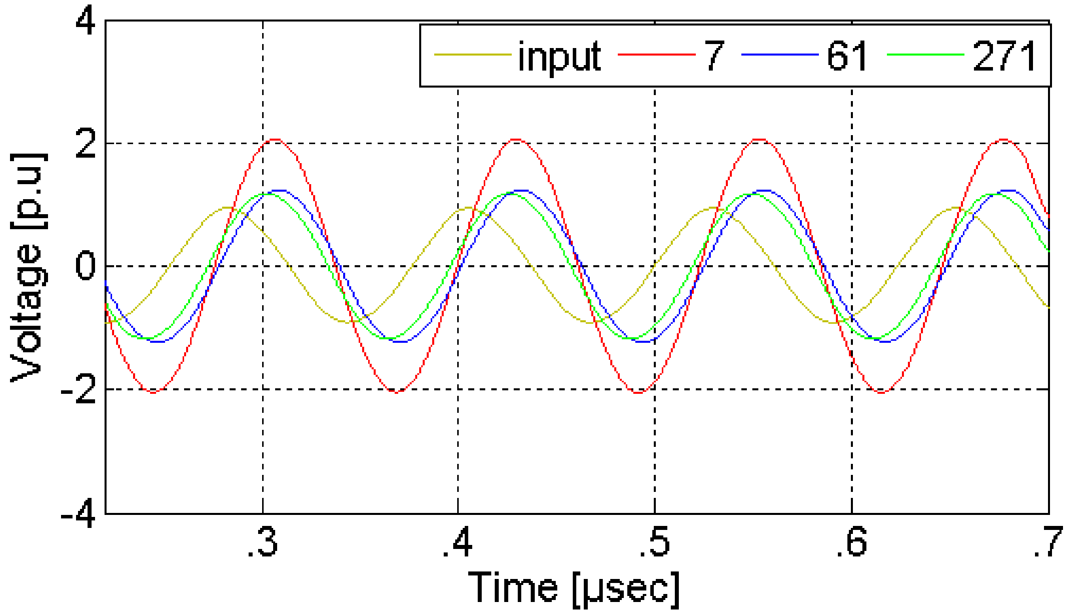

Figure 31 Voltage stress at 8 MHz (b)

Voltage distribution along the length of the winding for 8MHz resonance frequency is shown in figure 32. Voltage stress is at the starting of the first disc and that's either turn to shield or turn to turn. But here turn to turn voltage stress is more considerable at higher frequency bands. At node 600 and 1200 there some differences in voltage between nodes

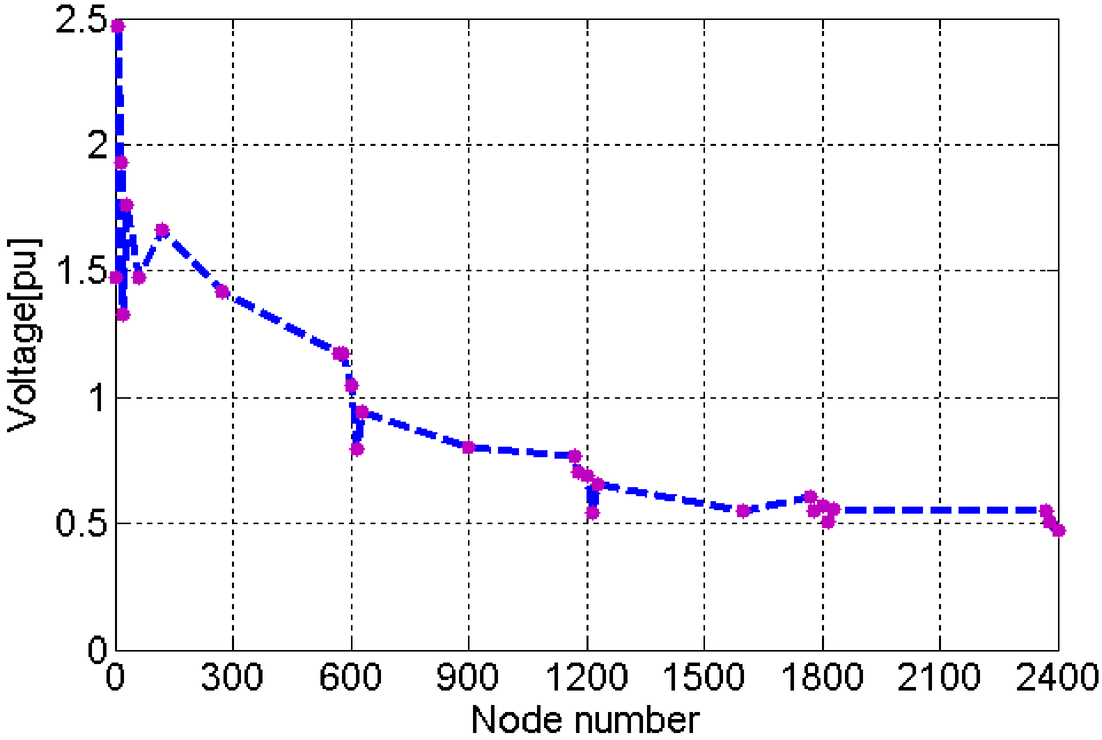

Figure 32 Voltage distribution at 8 MHz

Frequency Response Voltage Stress at Different Nodes Along the Winding

Previously voltage distribution along the length of the winding at different resonance frequencies was observed. These resonance frequencies can be counter checked by taking different nodes and taking frequency sweep for voltage stress. The voltage amplitude from node to ground has been taken for different frequency sweep (50Hz-10MHz). Different nodes have been chosen to investigate the voltage distribution.

Node 1200 was first taken as case study as previously this node was considered the most stressed node for lower resonance frequencies. According to the figure, maximum stress is at 43 kHz and at 61kHz as shown also in the previous sections. Voltage stress beyond 100 kHz at this particular node is lower as compared to the lower frequencies. This might be because of the damping of the circuit at higher frequencies. Voltage at 50Hz is about 0.5 pu and this voltage is gradually increasing with the increase in frequency. At approximately 25 kHz the voltage amplitude is almost equal to 1 pu and further increasing frequency will result to voltage stress up to 1.1pu at 30kHz as shown in the figure and finally maximum stress occurs between 43kHz and 69kHz.

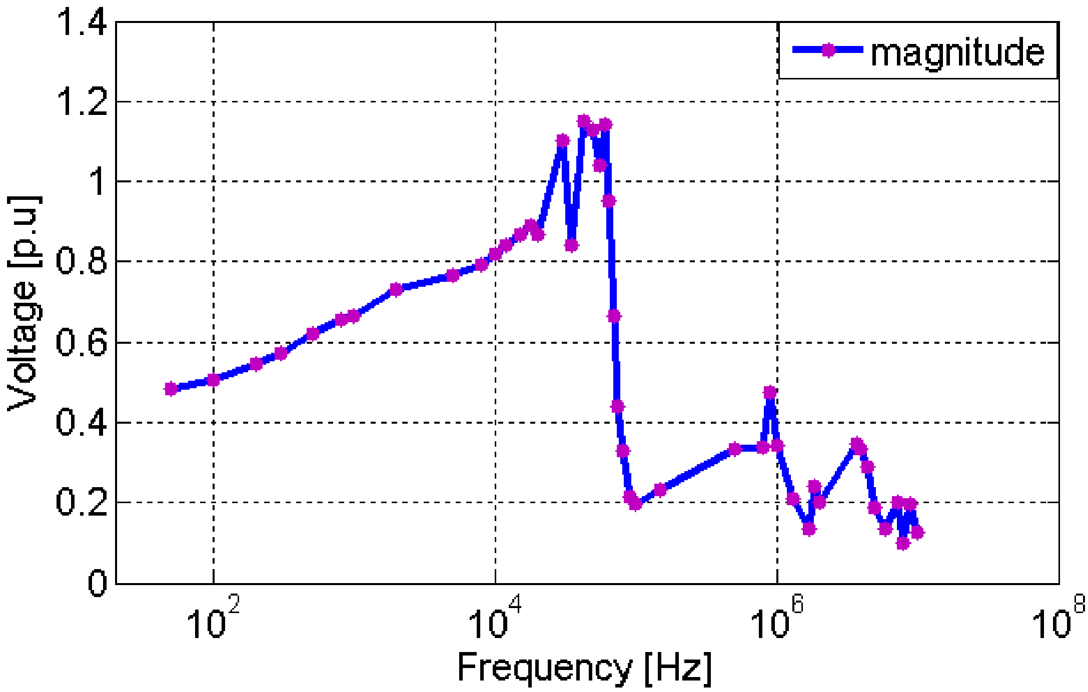

Figure 33 **Voltage stress at node 1200**

To study the voltage stress at different points along the winding, few particular more nodes have been taken into account. Next node taken to study the voltage variation with respect to frequency is node 900 which is between 3rd and 4th disc. This plot can be seen in Figure 34. Initially at 50Hz the voltage is approximately 0.65pu considering the resistive part of the impedance. This voltage is gradually increasing in accordance to increase in frequency up to 30KHz where the voltage is slightly above 1pu. At 35KHz voltage magnitude is less than 1pu, above this frequency level voltage magnitude abruptly increases to about 1.3pu at 69KHz and 1.4pu around 80KHz. If the previously voltage distribution results are compared, at lower resonance frequency band the voltage stress is higher than 1pu for all resonance frequencies. This voltage stress result also verifies previous voltage distribution determination.

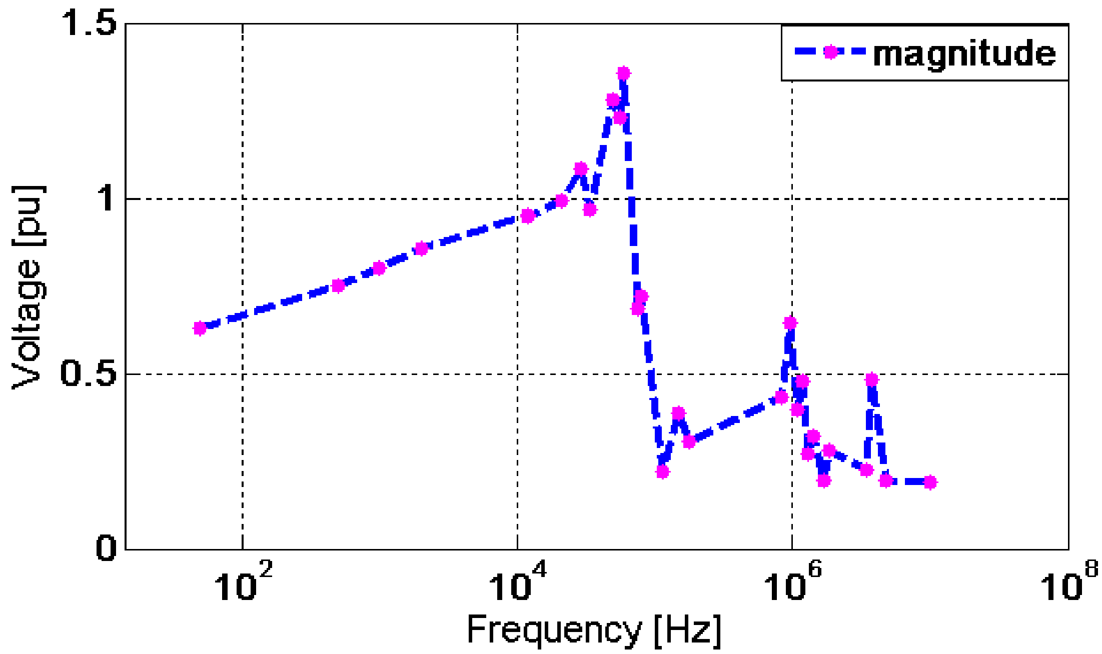

Figure 34 **Voltage stress at node 900**

Node taken to study the voltage variation with respect to frequency is node 585 which is on the first layer of second disk; this can be seen in Figure 35. Initially at 50Hz the voltage is approximately 0.75pu considering the resistive part of the impedance. This voltage is gradually increasing in accordance to increase in frequency up to 30KHz where the voltage is slightly above 1pu. At 35KHz voltage magnitude is 1pu, above this frequency level voltage magnitude abruptly increases to about 1.4pu at 69KHz and around 80KHz. If the previously voltage distribution results are compared, specially for 69KHz and 80KHz, it can be seen that the maximum voltage stress was found between 2nd and 3rd disc (node 600) which is for the same case here. So the below voltage stress plot also verifies previous voltage distribution results.

For high frequency band, all these results show lower voltage which is due to the increasing in damping at higher frequencies.

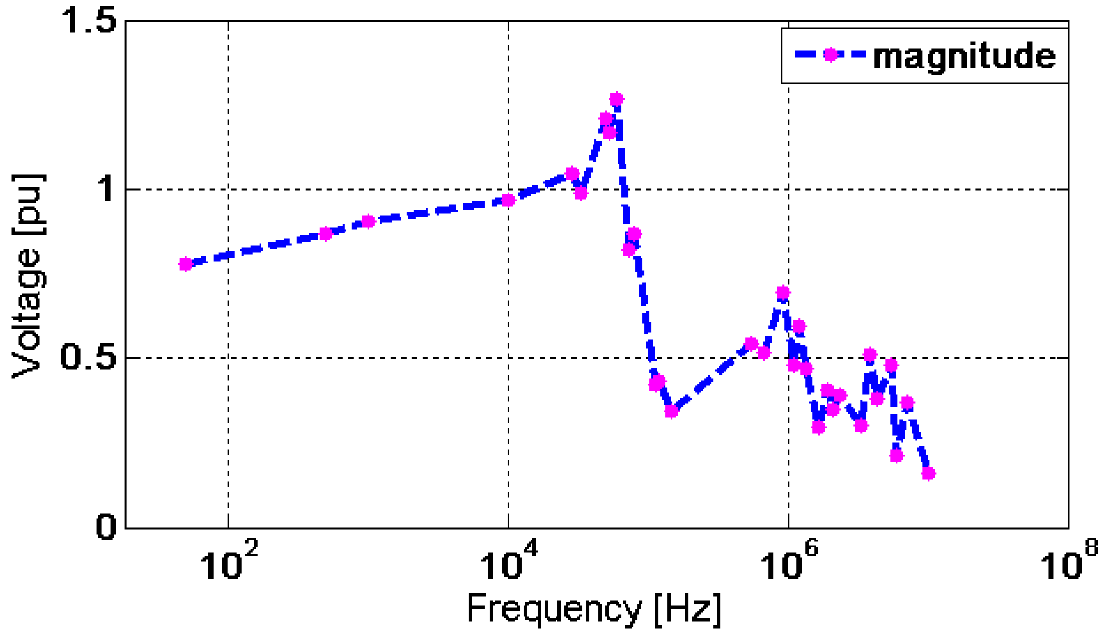

Figure 35 Voltage stress at node 585

To compare the results for higher frequency band, it was obvious to take nodes at the first disc as it was noted in the previous results for voltage distribution. Therefore, the node is taken from the first layer of the first disk i.e. node 30. Initially voltage was observed as approximately 1pu as it is situated in the starting with a lower resistance. With increasing frequency there is a small variation upto 200KHz which shows at lower frequency band there is no voltage stress. At the higher band frequencies a substantial variation in voltage can be observed. This shows a voltage differences within a disc or a layer. These results can be compared with other nearer node to see the voltage differences at different frequencies.

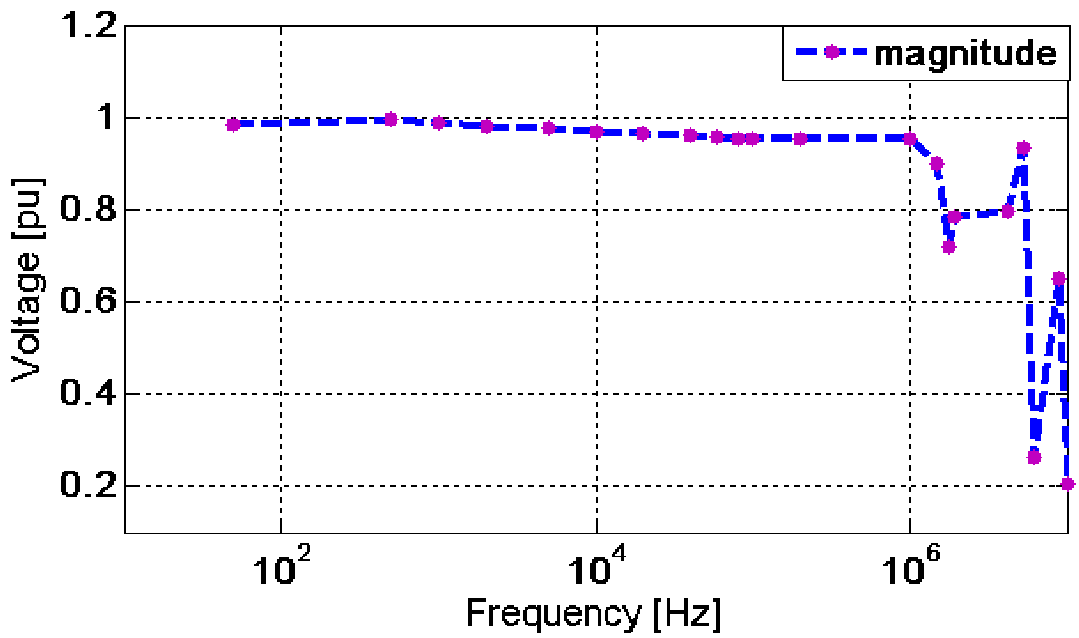

Figure 36 Voltage stress at node 30

VOLTAGE DISTRIBUTION AT STEP RESPONSE

Basic lightning impulse response measurements have been preferred from early ages due to the fact that a lightning impulse is a most common overvoltage stress that appears at transformer terminals. These impulses resemble the transient natures of surges which the power system is facing in practice. Furthermore, during switching transients, a voltage step stresses a transformer. By far this the most common voltage stress in cable grids. As a result, transformers winding is excited by a wide range of frequencies. The highest frequency level content is basically determined by the rise time or the steepness of the impulse [15].

The fundamental need for step response measurement should be that the voltage step source is producing steps that are steep enough to produce high frequency oscillations which can excite the transformer winding resonances in the relevant frequency range.

STEP RESPONSE MEASUREMENT SETUP

The accurate results for the impulse waveform will depend on the equipment, measuring bandwidth of the equipments used.

In this setup the function generator is replaced by the impulse source and the remaining setup remains same as for sinusoidal wave measurement setup. It is very important to have a well designed impulse source for getting better results. The sample source should have small tolerances when tested on different transformer windings parameter measurements.[16]

The impulse source is connected at the circuit breaker terminal of the test object so that the capacitance of the bushing can also be taken into account. The voltage probes connected to test object from step source and the oscilloscope are grounded to the shield. The step source is flexible enough to have variety in rise time and time to fall.

COMPARISION OF STEP FUNCTION RESULTS WITH SINUSOIDAL FUNCTION

Resonance frequencies can also be measured when applying step function to terminals. The studies show that these impulses resemble the transient nature of surges which in practice power system is facing. Also the step contains all frequency spectra, however, highest frequency level is determined by the rise time or the steepness of the impulse. First, the measurements are taken on 1200, 1800 and 2400 nodes and the result is shown in the Figure 38. The rise time for the step is taken as maximum. Figure 38 shows the step response results at nodes 1200, 1800 and 2400.. The green curve shows resonance overvoltage at the end of the winding. The resonance frequency for this overvoltage is measured to be approximately 15.5KHz. however, resonance overvoltage can also be seen at node 1200 but its magnitude is lower as compared to the node 1800.

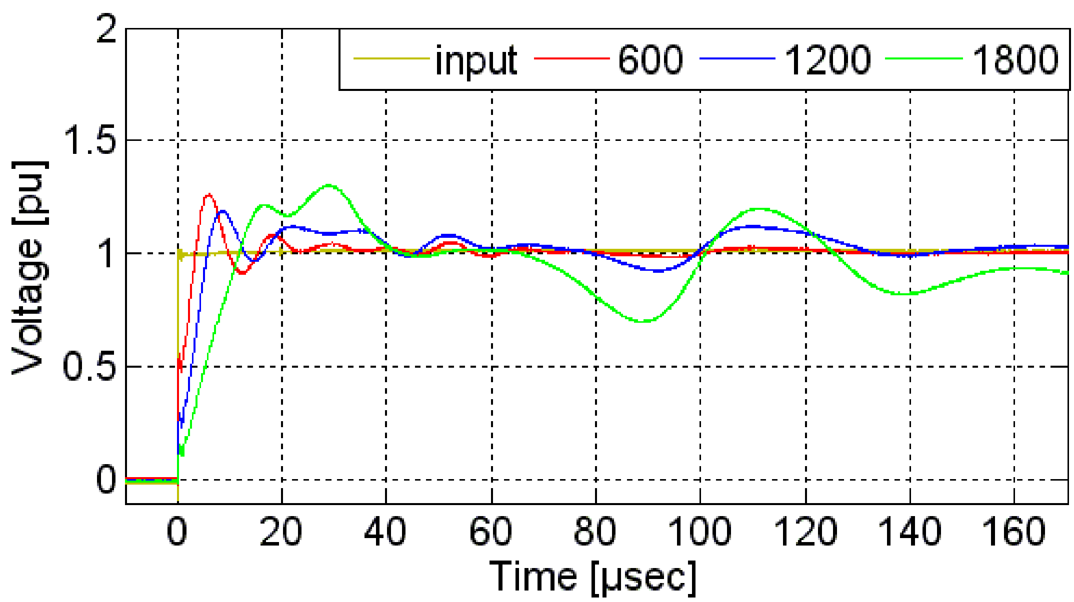

Figure 37 Voltage **Stress for step response input at 15.5KHz**

By replacing the step source with function generator in the previously made experimental set up for measurement of step function response and applying the sinusoidal wave of 15.5 kHz frequency, the same result of maximum stress at the end winding is observed as shown in Figure39. The voltage amplitude gradual increase from top to bottom of the winding is observed. The maximum voltage stress is seen at the end of the winding which shows a reflection at the terminal of the winding.

The nodes taken for measuring the voltage stress at 15.5 KHz resonance frequency are 1800 (first turn of the outermost layer of 6th disc), 2371(first turn of the outermost layer of 8th disc) and 2385(middle turn of the outermost layer of 8th disc). Figure 39 shows the results for the voltage stresses at these nodes. Maximum stress is at node 2371 and 2385 and its about 1.7pu. Phase shift w.r.t. input wave can also be observed through all nodes.

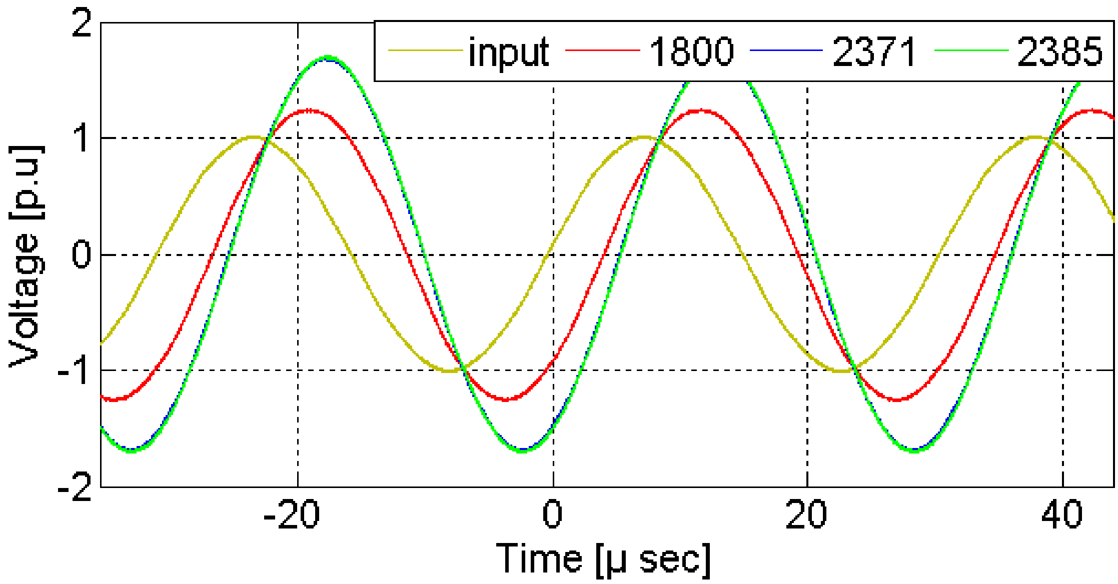

Figure 38 Voltage **Stress for sinusoidal input at 15.5 KHz**

Voltage distribution along the winding for 15.5 KHz resonance frequency is shown in Figure 40. Voltage stress at this particular resonance frequency is observed to be 1pu at the upper end of the winding and gradually increasing as the length of the winding increases. Finally gets the maximum amplitude at the lower end of the winding from this result it can be concluded that the maximum stress from turn to shield is maximum at end of the winding which shows a reflection due to open circuit. In addition the stress between turn to turn is lower.

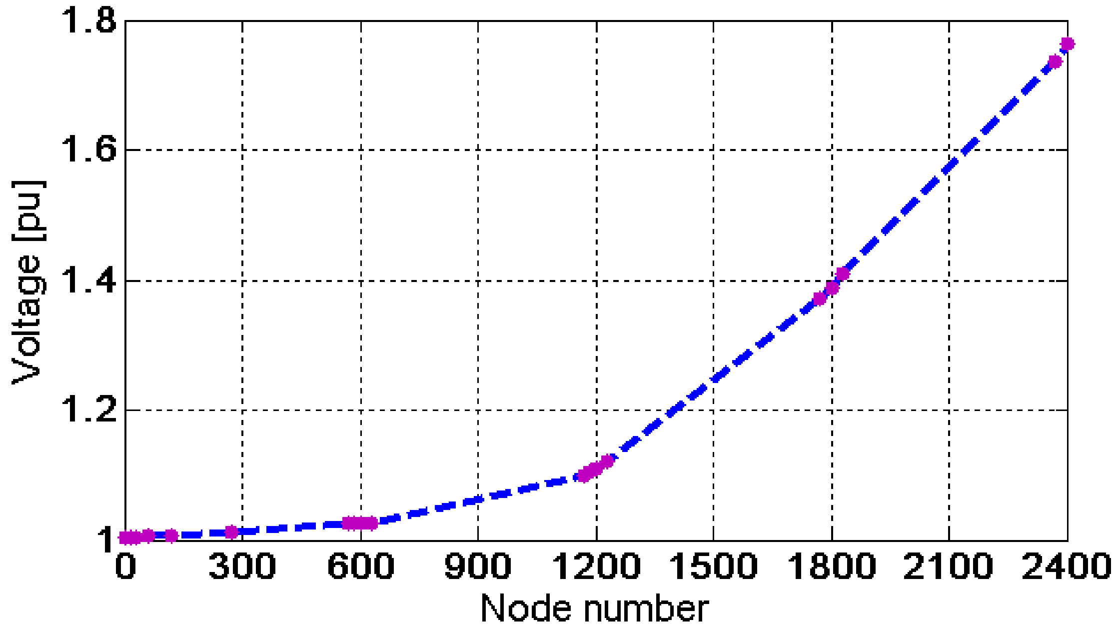

Figure 39 Voltage distribution at 15 KHz at terminal of the windings

With increasing the rise time of the step function following result can be observed at different nodes. Figure 41 shows the step response between node 600, 1200 and 1800. Sinusoidal wave between 10µs to 22µs time interval can be observed in the result. This corresponds to resonance frequency of 80 KHz which we have already observed in our previous case study.

From the result it can be seen that the maximum stress is on the 2^{nd} disc where one observe a resonance frequency.

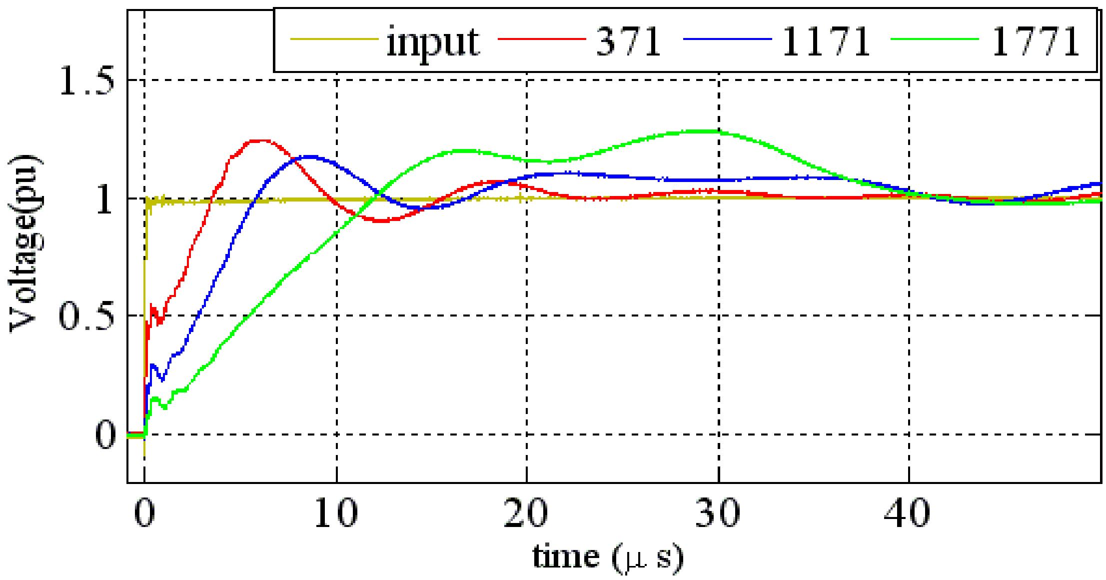

Figure 40 Voltage Stress for step response input at 80 KHz

By giving the sinusoidal input function on above resonance frequency, the following voltage stress pattern has been experienced. The maximum stress is at node 371 and node 600 which are located within the 2nd disc.

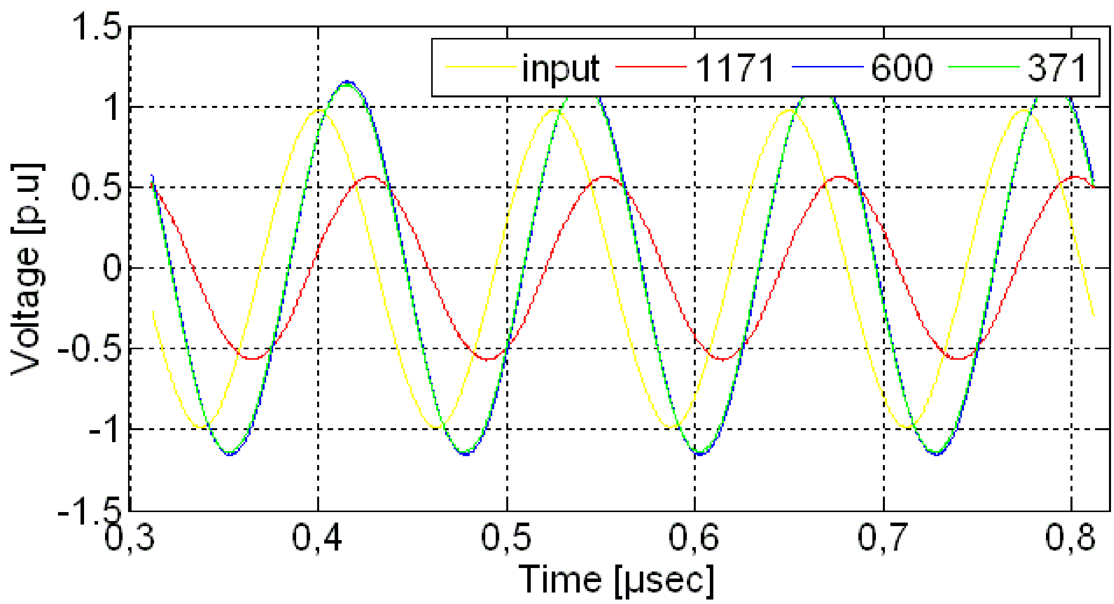

Figure 41 Voltage Stress for sinusoidal input at 80 KHz

CHAPTER 4

TRANSFORMER MODELING TECHNIQUES

An accurate transformer model is very important for transient analysis. Depending on the frequency of the transient which is studied one can identify important phenomena that need to be accounted for. Transformer modeling can be divided based on the application. In the frequency range for slow transients up to some KHz, time-domain transformer models are developed to see the non linear effects in core due to hysteresis and saturation. High frequency models are often established in the frequency domain because it is assumed that transformers behave in a linear way at higher frequencies. Usually 100 KHz frequency limit is selected as a transition to where the core can be neglected.

Analytical methods for transformer modeling are based on the approximation of the distributed parameters. Analytical methods are applicable for simple homogenous transformer geometries. In real transformer geometry complicates the analytical approach. Finite elements method can be a solution for complex design as details and variations can easily be included in the model. Simple analytical approaches have been used extensively for centuries to model the transformer. These models then got some limitations in details of complex geometry.

Numerical methods for transformer modeling are based on the numerical values of the parameters of the winding circuit. Different approaches have been taken so far to distribute the parameters along the windings. In case where the winding's length is far less than the wavelength, each coil of the winding can be represented with a lumped element, including self-inductance, shunt capacitance, resistance, mutual inductance, and series capacitance, whereas the mutual resistance and conductance are usually neglected. Electromagnetic transient program (EMTP) or other EMTP type software can calculate response of the network that represents transformer during transients.

In single transmission Line Models (STLM), the windings are assumed to be the replica of the single transmission line. Some papers deal with the computation of very fast transient overvoltages (VFTO) in transformer windings with the Single-Transmission Line Model (STLM). With this model, the voltages stress at the end of each coil is computed. Then, these values are used in the MTLM to determine the distributed over voltages along the turns. This method reduces the number of linear equations that needs for each frequency to determine the required voltages in frequency domain. The algorithm is based on a modified continuous Fourier transformation that provides an accurate time domain computation [7].

Using combination of Single transmission model and multi transmission model is helpful to rectify the demerits when using single model. In some cases it is advantageous to use combination of single-transmission line model (STLM) and multi conductor transmission line model (MTL). Lumped model has a disadvantage in the sense that it does not consider travelling wave for each coil. Due to which it is not enough accurate when the rise/fall time is shorter. In addition to above when the coils are longer as compared to wavelength. In such situation, each coil should be taken as a distributed line. The voltage distribution along each coil can be calculated by solving the telegraphist's equations with given boundary conditions. The most recent research on the wave's propagation in windings used the combination of MTL and STL models [7]. Transmission line modeling treats transformer as multi conductor transmission line. Single transmission line STL models and multi transmission line MTL models are further improvements to avoid the limitation that this approach is applied only to homogeneous windings. The STL describes each elementary unit such as disk whereas MTL model is extended to model the interaction between the units [13].

Full wave solution is another way of modeling. Although Lumped and MTL model simplify the "field" problem to a "circuit" problem, the measured and numerical values show the simplification is reasonable and sometimes accurate enough. Nonetheless, the direct field solution is more attractive but hard to obtain due to the complexity of model and lots of degrees of freedom [7].

Modeling based on terminal measurements (Black Box Modeling) is not suitable in studying geometrical effects such as mechanical deformations but still this model is feasible for implementing frequency domain models into time domain. Many number of high frequency models have been derived from measurements. The main methods used for implementing black box measurements are Model analysis, pole/ zero- representation and vector fitting. Analysis based on electromagnetic fields is a tool for establishing the parameters for black box method designers use electromagnetic field approach for design parameter calculations the technique of finite element method (FEM) is the most used and accepted numerical solution for field problems [13].

There is a general agreement that three dimensional field analyses are important while designing specially for evaluation of eddy current stray losses. These methods are impractical due to cost factor for the calculation of transients, at least for 3D calculations. SUMER is a finite element method (FEM) based software developed by EdF in France. This is based on the method of self and mutual inductances, and is giving better results in all types of frequency dependencies including losses. This is made possible by special techniques reducing mesh size [13].

Many publications have combined the model methods as above. Self and mutual inductance model has been combined with the black box to extend from lower frequency to a bit higher one.

One way of calculating transients in transformer winding is using a lumped parameter network in commercial software where resulting equations are solved numerically. In numerical methods one can introduce inhomogenities so that non-uniformity in windings and insulation is also considered, as compared to analytical methods. In addition numerical method has an advantage for modeling the inductive coupling between winding sections. Winding parameters can either be determined through design data or experimental results [6].

Parameter Estimation

The most complex task in the process of transformer modeling is to model inductance. Modeling on the basis of self and mutual inductances is by far the most utilized method due to its simplicity and easily understandable. Some early authors proposed a ladder network neglecting mutual inductance. Later on this procedure was improved by many others. Computer based approach and then this method was supported by experiments to add losses and modify inductances. Recent improvement is by adding core and winding losses and getting accurate results in the calculation of self and mutual inductances for the windings, sections or turns of transformers. This method is usually applied in high frequency models and is used in initial sensitivity of frequency response analysis (FRA). Numerically values of self and mutual inductances are almost equal at lower frequency band which could result in ill conditioned equations.

Modeling based on leakage inductance is based on presenting three-phase multi winding generalization. These models are frequently used to represent the leakage inductances at lower frequency band. One drawback is that at low frequency band core properties are not included in this model. This method is used for representing short circuit data at lower frequency band and can be extended to higher frequencies with discrediting in small parts.

Modeling based on principle of duality, the iron core can be modeled accurately at lower frequencies by using an equivalent circuit with dual to the reluctance of the core. Disadvantage is that the leakage inductances are not correctly represented as they are directly derived from leakage flux neglecting the thickness of the windings. Later this method was improved by correcting this inaccuracy by assuming that the magnetic field is axial. This method is also used in the modeling of highly saturated conditions, this method is used for low and intermediate range of frequencies, since details in the leakage field becomes important at higher frequencies [13].

Inductance can be estimated in a number of ways. Here it is assumed that the core-influence is negligible, all are based on coreless theory.

If all materials are assumed to be linear then the total magnetic flux through the winding is proportional to the applied current and the proportionality constant L represents the self inductance of the segment.

The flux that links the other segment out of the total flux indicates the mutual inductance M, between the segments. Equality in L and M shows the strong linkage between winding parts. The difference shows the leakage field setup by the first winding segment.

The capacitances can be calculated either by using traditional analytical methods or by doing FEM where the geometry and material parameters are important. Shunt or parallel capacitances that represent capacitance between windings or windings to ground. This represents the electric field between individual disks and ground (tank or core) as well as the electrical field between different windings. Series capacitance is the capacitance between different turns of the same windings and is determinant for the electrostatic voltage distribution.

Capacitances between windings and from the windings to ground can be calculating by assuming winding as cylindrical capacitors.

The losses in a detail model are important when internal stresses are evaluated in the design process. Without the losses, the stresses will be affected in the model as compared in reality. Transformer windings behavior towards electric and magnetic are subjected to damping mechanism, which is due to

1. Core Losses (hysteresis and eddy current in core).
2. Losses in windings and insulations (direct current losses in turns, eddy current losses in turns and dielectric losses) [18].

OTHER PHENOMENON THAT EFFECT LOSSES ARE:

Frequency dependent losses in the conductor occur as eddy currents due to time varying magnetic fields. The eddy currents cause a decrease in the net amount of flux and increase in the total losses which can be further elaborated as increase in the resistance and a reduction in the inductance of the equivalent impedance representing the winding

- Skin effect: frequency dependent current density distribution due to the current in the conductor itself.
- Proximity effect: eddy currents due to the external magnetic field generated from current in the other conductors
- Eddy currents in the core laminations due to magnetic field in the core. They are considered as important for lower frequency range. Eddy currents have a penetration depth in relation to frequency.
- Dielectric losses: within the insulation due to conductivity and different polarization mechanism. These conductances are either in series or shunt. Normally the effect of these losses is not included in the modeling as the magnitude is lower [13].

At higher frequencies the magnetic penetration depth is so low that the core loss can be neglected.

CHAPTER 5
CONCLUSION AND FUTURE WORK

CONCLUSION

The test at 43kHz shows that the highest voltage is developed in the middle of the winding. From this result it can be concluded that the lowest resonance frequency is the winding resonant frequency. Similarly the second test at 69kHz shows the highest voltage stress at node 600 which is $1/4^{th}$ of the winding, so 69kHz is the half of the winding resonant frequency. Going further on the higher frequency bands, this resonant frequency corresponds to a single disc resonant frequency and finally the corresponding layers resonant frequency.

At lower frequency bands, the voltage stress between turn to ground in terms of standing wave was observed whereas at higher frequency bands, inter layer stress could be seen.

The amplitude for the voltage during the voltage stress at lower resonance frequencies is higher when compared to the voltage stress at higher resonance frequencies due to increased damping.

Step functions can be applied to determine the resonance frequencies either for the entire winding length or any particular disc. It was observed that with different rise times, the applied step response initiated a sinusoidal wave with a resonance frequency for a specific disc or for entire winding. The amplitude of the wave will be higher when compared to the input. This all concludes that for step response with lower rise time, resonance frequency will be lower and the wave is travelling throughout the length of the winding. This shows a turn to ground voltage stress. For step response with high rise time, resonance frequency will be higher so the stress is concentrated within any disc showing a turn to turn stress.

Finally these step response resonance frequencies were compared with the ones from the network analyzer and a resemblance was found. Step response results have shown the same resonance frequencies when compared to those measured using the network analyzer.

FUTURE WORK

In this test setup, the number of measurement points were limited. This prevented us to obtain a better understanding of internal voltage distribution inside the disc during the voltage stress at higher frequency band. Therefore it is needed to measure more points inside the disc. Extension of the nodes for better results can be included as one important future work.

The modeling of transformer for high frequency transient analysis could be very useful for such a study. It can be done in a number of ways depending on the application. Lumped parameter, STLM and MTLM are the most used examples of the modeling. Calculation of voltage stresses with these models can be done to compare the experimental results. Comparing of models themselves and also with the experiment results can be done as future work

Usually the effect of the iron core is more of concern at lower frequencies due to its saturation at higher frequencies. The effect of the iron core on the voltage stress can be included as future work.

In this thesis project the reactor winding was taken as the high voltage winding of the transformer, the lower voltage winding can also be added to see the voltage stresses transfered to the low voltage windings.

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