Study of Transient Responses in Transformer Windings using Transmission Line Model

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Abstract— **Transformers are one of the essential and high-price elements in electrical networks in to which the occurrence of fast transients can be very dangerous. Therefore, the study of transient responses of these equipments is very important for design of the transformer insulation structures.**

This paper studies the transient responses of a 20/3.5 Kv ، 6.5 MVA transformer based on multi-conductor transmission line method (MTLM) in order to improve our understanding of transient behaviors in a continuous disk type winding. The MTLM uses a single turn as a circuit element with the capacitance, inductance, and losses calculated as distributed parameters. As such, it can be used to investigate on very fast transients over a wide frequency range. The obtained results are quite noticeable and very interesting to observe.

Keywords-Transient overvoltages, Multiconductor transmission line method, high frequency model

I. INTRODUCTION

Power transformers are one of the essential and also expensive equipments of electrical networks which play a main role in the energy transmission and distribution. Withstanding various electrical stresses is always one of the most important issues related to the transformers. In this regard, switching operations and lightning impulses are known to produce very fast transient overvoltages which are dangerous to the transformer insulation [1-2].

These overvoltages can arise by a very short rise time close to the transformer breakdown insulation level. Also, if the frequency of an input surge were equal to some of the resonance frequencies of transformer, the greater stresses would occur. Most of the time, these overvoltages can cause a flashover from the winding to the core or between the turns. The interturn insulation is particularly vulnerable to high frequency oscillation, and therefore the study of the distribution of interturn overvoltages is of essential interest [3-6].

With respect to above discussion, the analysis of very fast transients in transformer winding is one of the main priorities during its design procedure. Therefore, a suitable model is needed to simulate the voltage distribution along the transformer winding. Representing a transformer winding by a lumped circuit model requires a resolution appropriate for the chosen frequency. For example, representing each disk in the winding by a lumped RLC circuit model is valid up to 1 Mhz. To correctly model the winding at higher frequency requires that each turn in the disk (and hence the entire winding) is modeled as a circuit unit. This leads to achieving a model which is extended to tens of Mhz. The electrical parameters of the winding are calculated on a per turn basis and the entire winding is represented by distributed multiconductor transmission line model.

In this contribution, frequency behavior of a continuous disk type winding of a 20/3.5 Kv ،6.5MVA transformer has been investigated over a wide frequency range by applying the multiconductor transmission line method. The obtained results are very useful and meaningful for understanding of transient responses of transformer winding.

II. MULTICONDUCTOR TRANSMISSION LINE MODEL

According to MTLM model, transformer winding can be represented by a group of interconnected and coupled transmission lines as shown in Fig.1. $V_s(i)$ and $I_s(i)$ are the sending end voltage and current of the i-th transmission line and $V_R(i)$ and $I_R(i)$ are its receiving end voltage and current.

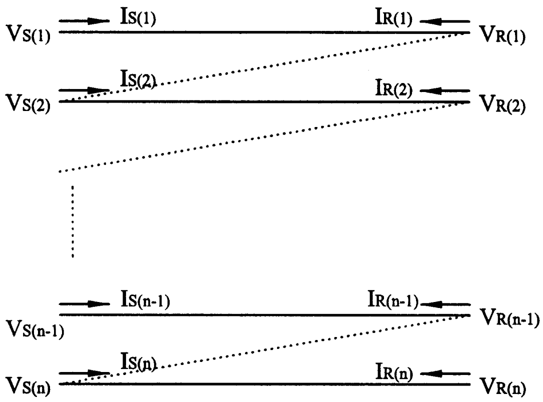

Fig. 1 . Multiconductor transmission line model.

In this transformer model, the wave propagation phenomena in the transformer turns can be described by using the telegraphs equations (1) where V_i and I_i are the voltage and current vectors. The order is equal to the number of turns in the winding. L and C are matrices of the inductance and capacitance values in the winding.

$$\frac{\partial V_i}{\partial x} = -[L](\frac{\partial I_i}{\partial t}) \qquad (1)$$
$$\frac{\partial I_i}{\partial x} = -[C](\frac{\partial V_i}{\partial t})$$

Calculation of Matrix C plays a major role in the accuracy of the model since inductance is also based on the capacitance value. In this matrix, $C_{i,i}$ represents sum of all capacitances connected to turn i and $C_{i,j}$ is the capacitance between turns i and j taken with the negative sign.

Matrix L is calculated under the assumption that the winding consists of loss-less multiconductor transmission lines surrounded by a homogeneous insulator as below:

$$[L] = \frac{\varepsilon_r}{c^2}[C]^{-1} \qquad (2)$$

where c and ε_r are the velocity of light and relative permitivity of the insulation, respectively.

After solving the telegraph equations (1), the voltages and currents of each turn of winding can be computed as below[1]:

$$V_i(x,w) = A_i \exp(-\Gamma(w)x) + B_i \exp(\Gamma(w)x) \qquad (3)$$
$$I_i(x,w) = v_s[C](A_i \exp(-\Gamma(w)x) - B_i \exp(\Gamma(w)x))$$

where w is the frequency, v_s is the speed of wave propagation and x is the distance from the sending end of line. A_i and B_i can be calculated by applying the boundary conditions. $\Gamma(w)$ is the propagation constant as below:

$$\Gamma(w) = \frac{1}{v_s d}\sqrt{\frac{w}{2\sigma\mu}} + \frac{w\tan\delta}{2v_s} + \frac{jw}{v_s} \qquad (4)$$

where σ and μ are the conductivity and magnetic permeability of the conductors and d is the distance between conductors in the disk.

The boundary conditions in MTL model including n lines are represented as the following:

$$V_R(i) = V_S(i+1) \quad \text{for i= 1to } n\text{-1} \qquad (5)$$

$$I_R(i) = I_S(i+1) \quad \text{for i= 1to } n\text{-1} \qquad (6)$$

$$V_R(n) = 0 \quad \text{winding end is earthed} \qquad (7)$$

$$I_R(n) = 0 \quad \text{winding end is opened} \qquad (8)$$

III. TRANSFORMER SIMULATION

In order to calculate the transformer voltage transients, it is very important to determine the transformer's electrical parameters with higher accuracy. Using the model described above, a high voltage continuous disk winding of a 20/3.5 Kv, 6.5 MVA power transformer has been simulated to study transient responses. Some of required transformer data used in this survey are listed in Table.1. This data has been extracted from transformer design sheets as precisely as possible. Based on above mentioned information and also analytical formulas, all electrical elements including inductances, capacitances and the frequency dependent losses can be determined.

In MTL model as described above, determination of matrix C is a very important step for computation of the fast transient inside the winding. Calculations of this matrix are based on geometry of the winding and permittivity of the insulation. There are three components of capacitance: inter-turn, inter-disk and capacitance to low voltagewinding. These capacitances and also other model parameters can be computed according to the methods represented in [7-9].

Table1. Transformer data

Transformer Power	6.5MVA
Transformer ratio	20/3.5 Kv
dielectric permittivity of oil	2,2
dielectric permittivity of wire insulation	4
Number of disks	42
Number of turns per a disk	11
Inner radius of HV winding	286.5mm
External radius of HV winding	364.5mm
Distance between LV and HV	16mm
Distance between disks(oil channel)	4.5mm
Thickness of wire insulation	0.4mm
Mean length of one turn	2.045m
wire width	4.24mm
wire height	9.5mm

In this study, the model is solved in frequency domain for a number of frequencies between 10Khz - 10Mhz. In each frequency w, a voltage with unity amplitude, is applied to the input terminal of the winding (the sending end of the first line). As result, each arbitrary transfer function H can be computed. This is a significant advantage. In fact, this method is able to compute any target voltage (or current) by multiplying the transfer function by the source function V_{in}.

$$V_{target}(w) = H(w) * V_{in}(w) \qquad (9)$$

For example, analyzing the transients of a switching impulse (SI) is easily possible through initializing $V_{in}(w)$ with the frequency components of SI extracted by Fast Fourier Transform (FFT).

The time domain results of the model can be calculated either by applying convolution or inverse Fourier transformation.

IV. SIMULATION RESULTS

According to previous sections, the simulation results are represented as the following: The results have studied the winding behavior in both frequency and time domains. Simulation is done for two different states. For the first one, the terminal at the end of the winding is grounded and it is opened for the second one. The results have been shown by the following diagrams. Fig.1 shows the voltages at the receiving end of all 462 turns of winding for a number of sample frequencies while the winding end is earthed. As can be seen, some frequency components of the applied voltage can lead to resonance phenomena inside the windings. This can be observed for frequencies of approximately 100Khz, 200Khz and 3.5Mhz in the current study. It should be noted that the resonant frequency of this winding is about 195Khz as below:

$$f = vs/l = 185e6/(462*2.045) = 195Khz$$

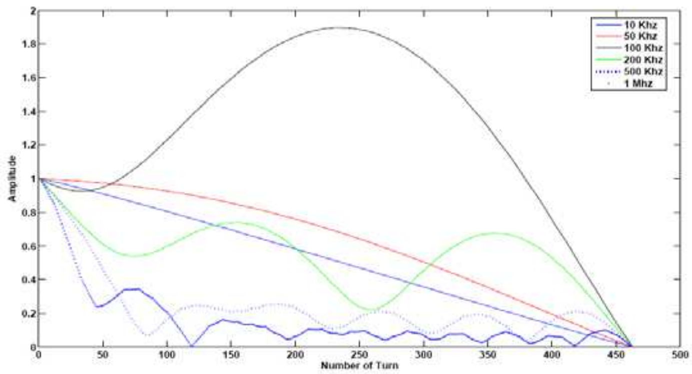

Fig.1.a. Receiving end voltage of lines for some frequencies

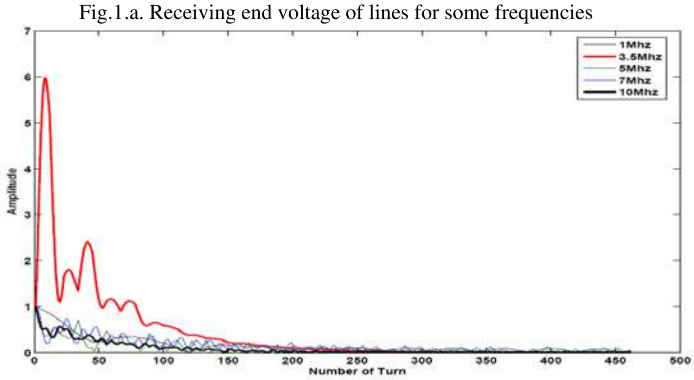

Fig.1.b. Receiving end voltage of lines for sample frequencies.

It is apparent that there are two resonant points around *f* and *f/2* . This is in accordance to the traveling wave theory. In addition, there is a severe resonance in about 3.5Mhz.

Fig.2 reveals the voltages of receiving end of lines for open end terminal condition. The voltages at the end sections of the winding have significantly increased which is a remarkable sign of capacitive behavior of the winding. This rise is very severe for the frequency of 50Khz. It approximately reaches 3 times of the input voltage. Also, Fig.3 shows the transfer voltage in the last turn of the winding due to various frequencies.

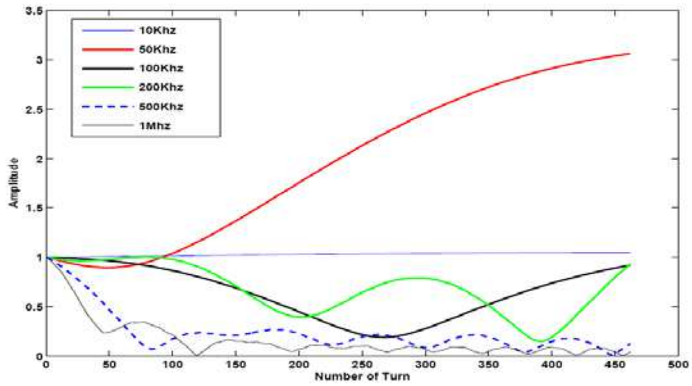

Fig.2. Receiving end voltage of lines for sample frequencies (open terminal)

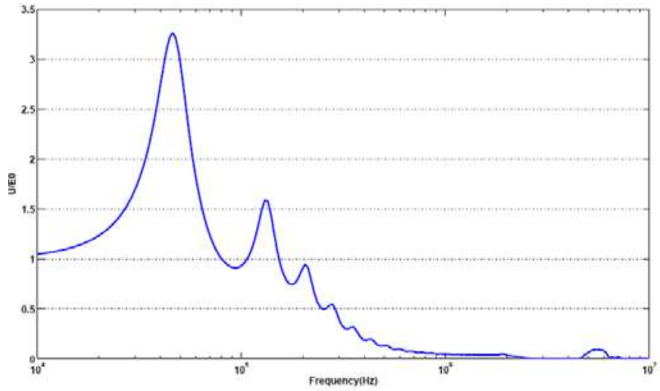

Fig.3. Transfer voltage in last turn for several frequencies(open terminal).

Voltage transfer functions at the end of all winding turns are summarized in Fig.4 and Fig.5. These curves can give us suitable information about resonant frequencies and their effects.

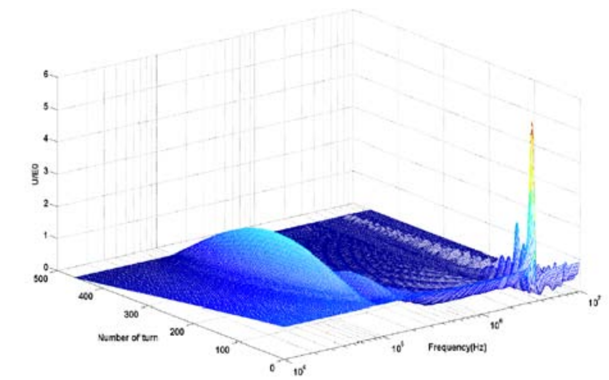

Fig.4. voltage transfer functions at the end of turns (earthed end terminal).

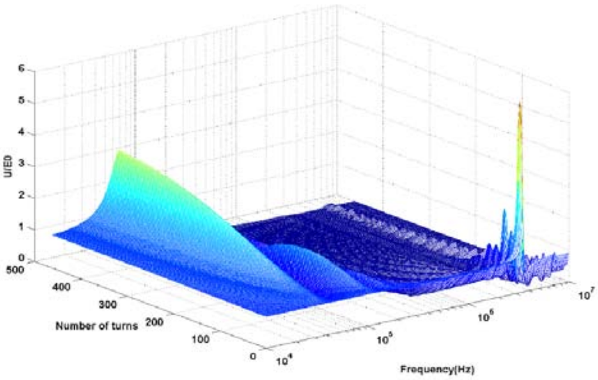

Fig.5. voltage transfer functions at the end of turns (opened end terminal).

With respect to Fig.4 and Fig.5, the main difference between the two mentioned states can be seen between 10Khz and 800Khz. In this frequency range, the distribution of voltages is completely different. This difference for higher frequencies is not significant.

The frequency analysis of the interturn voltages is illustrated by Fig.6 to Fig.9.They represent transfer functions of the interturn voltage of winding turns. The differences under 100Khz, between Fig.6 and Fig.7 is caused by the terminal condition of the winding. In fact, the first one shows an inductive trend while the second one has a capacitive trend. Also the amplitude of overvoltage for several resonances is noticeable. In frequency 3.5 Mhz the interturn voltage will rise severely .Fig.8 and Fig.9 give useful information about overvoltages which can be formed in all turns due to several frequencies.

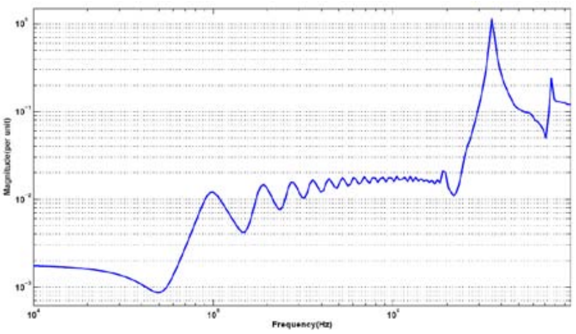

Fig.6. Interturn voltage transfer function for the first turn of winding (earthed end terminal).

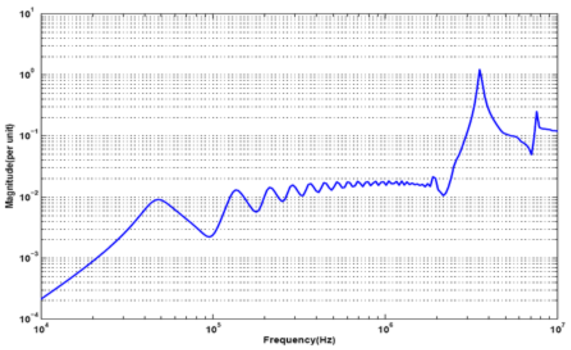

Fig.7. Interturn voltage transfer function for the first turn of winding (opened end terminal).

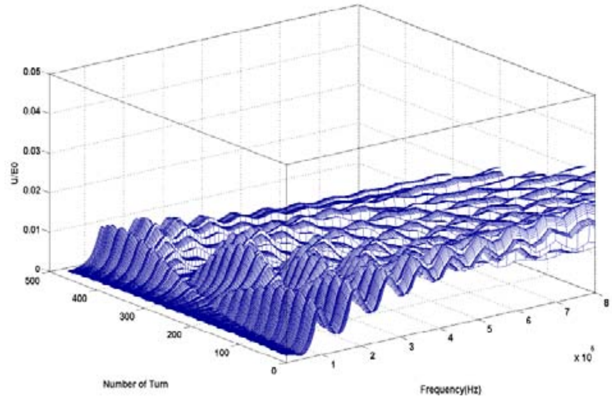

Fig.8. Interturn voltage transfer function for all turns of winding (earthed end terminal).

By applying Fast Fourier Transformation, it is possible to study the transient responses in time domain. Fig.10 and Fig.11 represent all interturn voltages of the winding for two supposed states. The overvoltages into each turn can be observed. It should be noted that in these curves, the amount of overvoltages are computed per unit. In fact, these overvoltages are formed due to a 1-volt excited voltage and can be generalized for real level of transformer.

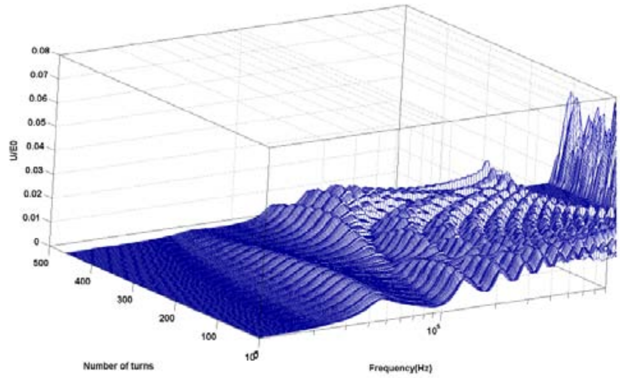

Fig.9. Interturn voltage transfer function for all turns of winding (opened end terminal).

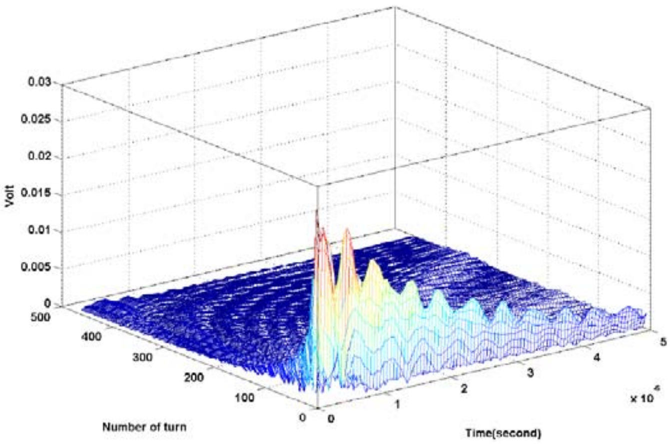

Fig.10. Interturn voltage for all turns of winding per unit (eathed end terminal).

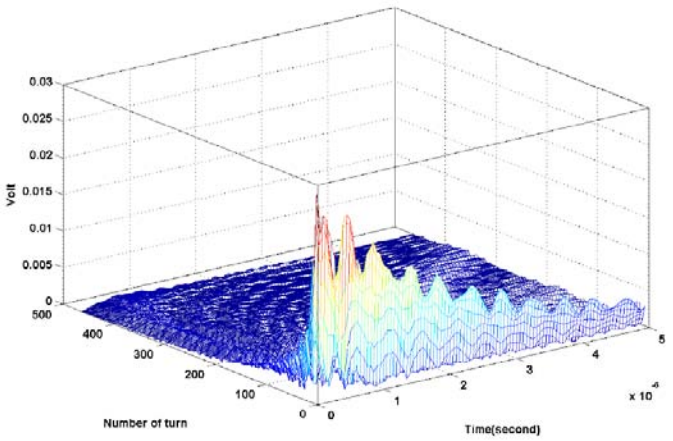

Fig.11. Interturn voltage for all turns of winding per unit(opened end terminal).

CONCLUSION

This paper has studied transient responses of a high voltage winding of a transformer. The winding is modeled by use of the transmission line method. Winding transients have been considered through frequency analysis in two opened and earthed states of winding end terminal. In addition, transient overvoltages are discussed. The results are useful and suitable in order to have a better understanding of very fast transient behaviors in transformer windings.

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