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Transient Voltage Distribution in Stator Winding of Generators using R, L, C Ladder Network

S. M. H. Hosseini[1], S. M. Hosseini[2], H. R. khezri[3]
[1,2]Islamic Azad University, South Tehran Branch (IAU), Tehran, Iran
[3]Islamic Azad Universities, Bafgh Branch (IAU), Yazd, Iran
([1]Smhh110@yahoo.com, [2]Mojtaba.Hoosiny@gmail.com, [3]Hamidreza.Khezri@yahoo.com)

Abstract- The fast and very fast transient phenomena cause a high overvoltage in a generator winding, this situation is very dangerous for a power system. The most important use of generators is production of electricity, something which has greatly played a commendable role of boosting industrialization. Electrical stresses in winding generator may have a detrimental effect on the consumers. In order to analyzing electrical stresses in the generator a model is needed which is able to simulate the voltage distribution along the generator winding. The paper presents an analysis of the calculated and measured voltages along the high-voltage winding. For this purpose, RLC Ladder Network theory is applied. The parameters of this model are determined based on numerical field analysis methods (e.g. finite element method), by using maxwell software. Simulations were performed by using multisim software. The model is validated by means of a comparison between measured and calculated voltages in windings a 6kV/250KW generator with 11 turns.

Keywords- *Generators; RLC Ladder Network; transients fast; voltage distribution*

I. INTRODUCTION

The generators is one of the most important and expensive equipment in power systems [1]. Once a generator is damaged, replacement costs of a large HV generator might reach up to a few million pounds in the UK. If an incipient failure of a generator is detected before it leads to a catastrophic failure, the generator may be repaired on site or replaced according to a scheduled arrangement [2]. Therefore, conditions of critical assets, i.e. generator, for utilities should be closely and continuously monitored in order to ensure maximum uptime [3]. The so-called condition-based maintenance may reduce risks of forced outages and damages to adjacent equipments. Generators interruptions in service and failures usually result from dielectric breakdown, winding distortion caused by short circuit withstand, winding and magnetic circuit hot spot, etc. Winding distortion faults may cause catastrophic failures of generators such as dielectric breakdown and short circuit [4]. Most of the time, the greatest problem is the internal resonance which occurs when the frequency of the input surge is equal to some of the resonance frequencies of the generator. These overvoltages are characterized by a very short rise time [5]. The experience shows that VFTOs within generator can be expected to have even a rise time of 0.1 μs and amplitude of 2.5 p.u. Most of the time, resonant overvoltages can cause a flashover from the windings to the core or between the turns [6]. The inter-turn insulation is particularly vulnerable to high-frequency oscillation and therefore the study of the distribution of inter-turn overvoltages is of essential interest. The VFTOs produced by voltage source in generator depend not only on the connection between the voltage source and generator, but also on the generator parameters and type of the winding. Different models of generator windings have been suggested for transient studies. The most of them have been approved by different researchers [7]. The generator engineers use this model to predict the surge voltage distribution along the generator winding [8]. It is well known that, there is a direct relationship between the geometric configuration of the winding and core within a generator and the distributed network of resistances, inductances and capacitances that make it up. In a wide range of frequency domain (2 kHz < f < 2MHz), a generator winding behaves as a complex ladder type network consisting of a series of inductances, capacitances, resistances and conductances. To study the transient overvoltages in power generator, manufacturers provide sophisticated computer programs in design procedure which convert physical geometry and material characteristics into a RLCM Detailed model. The paper deals with the computation of very fast transient over voltages (VFTO) in generator windings. [5-7]

II. RLC LADDER NETWORK MODEL

To calculate the very fast transient overvoltages in generators windings, a model based on the modified RLC Ladder Network (RLC) theory is proposed in this paper. It is well known that, there is a direct relationship between the geometric configuration of the winding and core within a generator and the distributed network of resistances, inductances and capacitances that make it up. In a wide range of frequency domain (2 kHz < f < 2MHz), a generator winding behaves as a complex ladder type network consisting of a series of inductances, capacitances, resistances and conductances [9]. For a generator winding with n sections, a simplified equivalent circuit is shown in Fig.2. Each unit contains a self inductance Li (in node i), mutual inductances between the sections i and j (Lij), series resistance Ri (which model insulation losses in section i) and series and ground capacitances Ki and Ce, respectively, Ui lower voltage source signal and Uo the voltage of the end coil. In theory, the distributed parameters of a ladder RLC network can then be determined based upon its frequency dependent responses.

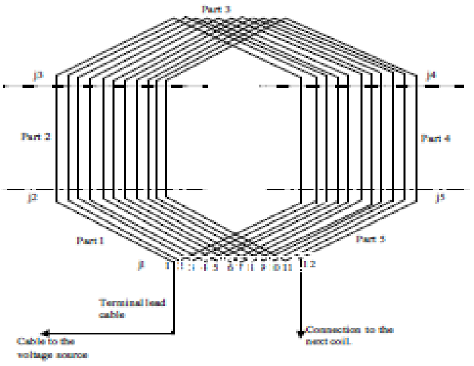


Figure.1. Coil and its subdivisions in to parts [4]

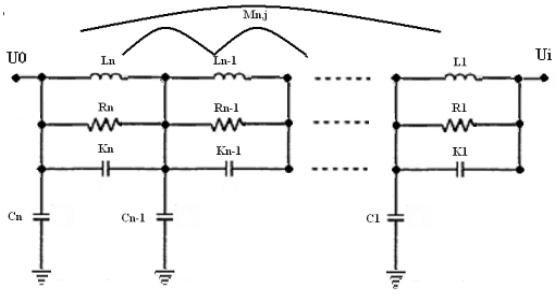


Figure.2. Ladder network model for single generator winding

The end of winding is grounded and the input signal is applied to the node n. The detailed model of the transformer winding can be presented by the following equation:

$$I^{\circ} = \Gamma e + Ge^{\circ} + Ce^{\circ\circ} \tag{1}$$

Where Γ, G, C, I and e are inverse nodal inductance, nodal conductance, nodal capacitance matrices, nodal current and voltage vectors respectively. Assuming:

$$V = e^{\circ} \tag{2}$$

$$V^{\circ} = e^{\circ\circ} \tag{3}$$

Eq. (1) can be rewritten in the state variable form:

$$\begin{cases} X^{\circ} = \bar{A}X + \bar{B}U \\ Y^{\circ} = \bar{C}X \end{cases} \tag{4}$$

Where

$$X = \begin{bmatrix} V \\ e \end{bmatrix}, \quad A = \begin{bmatrix} -C^{-1}G & -C^{-1}\Gamma \\ E_n & 0_n \end{bmatrix} \tag{5}$$

And

$$\bar{B} = \begin{bmatrix} C^{-1} \\ 0_n \end{bmatrix}, \quad \bar{C} = \begin{bmatrix} 0_n & I_n \end{bmatrix} \tag{6}$$

The extended form of Equation (4) is:

$$\begin{bmatrix} V^{\circ} \\ e^{\circ} \end{bmatrix} = \begin{bmatrix} -C^{-1}G & -C^{-1}M \\ I_n & 0_n \end{bmatrix} \begin{bmatrix} V \\ e \end{bmatrix} + \begin{bmatrix} C^{-1} \\ 0_n \end{bmatrix} I^{\circ} \tag{7}$$

In equations (6) and (7), I_n and 0_n are unit and zeros matrices with the order n and therefore the order of system matrix are 2n and as a result we have 2n eigenvalues. By Laplace of the eq. (1) voltage transfer function will:

$$\begin{cases} \dfrac{U_1(S)}{U_n(S)} = T_{1,n}(S)\dfrac{1}{Zin(S)} \\ \vdots = \vdots \\ \dfrac{U_j(S)}{U_n(S)} = T_{j,n}(S)\dfrac{1}{Zin(1)} \\ \vdots = \vdots \\ 1 = T_{n,n}(S)\dfrac{1}{Zin(S)} \end{cases} \Rightarrow \begin{cases} \alpha_1(S) = \dfrac{T_{1,n}(S)}{Zin(S)} \\ \vdots = \vdots \\ \alpha_j(S) = \dfrac{T_{j,n}(S)}{Zin(1)} \\ \vdots = \vdots \\ T_{n,n}(S) = Zin(S) \end{cases} \tag{8}$$

Where Zin(s) is Input impedance of the coil and $a_j(s)$ is Voltage transfer function at the node of j. So all internal voltages and therefore all sectional winding transfer functions that are necessary for PD localization can be obtained from (8) at all frequencies

A. Calculation of model parameters

RLC model parameters consist of capacitance, inductance, resistance and conductance matrices. They depend on conductors and insulations geometry and characteristics, geometrical dimensions of the generator, winding type and position of each winding [10, 11].

III. CAPACITANCE MATRIX

There are various capacitances between different conductors. The capacitance between two adjacent turns in a coil can be calculated by assuming parallel plate capacitor approximation as: [12]

$$C_T = \frac{\varepsilon_{\circ}\varepsilon_P \times \pi D_m (w + t_P)}{t_P} \tag{9}$$

Where D_m is the winding diameter, w is the width of the conductor in axis direction, t_p is paper thickness in both sides of the conductor, $\varepsilon_0 = 8.85 \times 10{-}12$ F/m and ε_p is the relative permittivity of paper.

IV. INDUCTANCE MATRIX

In high frequencies it can be assumed that the penetration of magnetic flux into the laminated iron core of generator is neglected, so the winding can be regarded as a conductor in free space surrounded by insulation. nt × nt inductance matrix is formed by self and mutual inductances between different turns of the winding [13] [14]. Mutual inductance between two circular filaments is calculated using the formula developed by Maxwell is obtained:

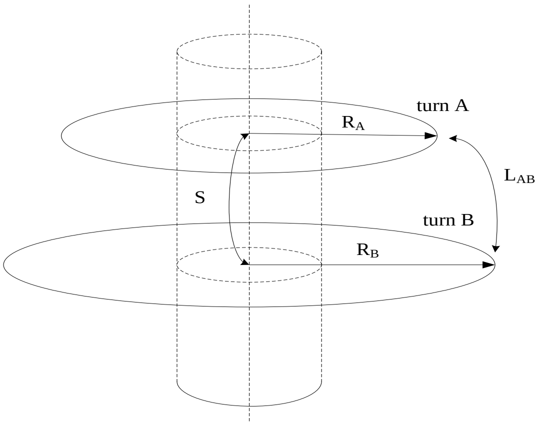


Figure.3. mutual inductance between two circular conductors

$$\begin{cases} L_{AB} = \dfrac{2\mu_\circ}{K}\sqrt{R_A R_B}\left\{\left[1-\dfrac{K^2}{2}\right]K(k)-E(k)\right\} \\ k = \sqrt{\dfrac{4R_A R_B}{(R_A+R_B)^2+S^2}} \end{cases} \tag{10}$$

Where R_1 and R_2 is the radius of the circular filaments 1 and 2, S is the distance between circular filaments, μ_0 is the permeability of free space and K (k) and E (k) are the complete elliptic integrals of the first and second kind. Inductance calculations are based on geometric entities. The formula developed to compute the self-inductance (in Henry) is as follows:

$$L_{AA} = \mu_\circ a\left[\frac{1}{2}(1+\frac{1}{6}(\frac{C}{2a})^2)LN\left(\frac{8}{\left(\frac{C}{2a}\right)^2}\right) - 0.84834 + 0.2041(\frac{C}{2a})^2\right] \tag{11}$$

Where μ_0 is the permeability of free space, a geometric mean radius of each coil and C is the length of the winding cross section is square.

V. SERIES RESISTANCES

The per unit length resistance of conductor can be obtained by (12): [9]

$$R = \frac{1}{2(h+w)}\sqrt{\frac{\pi F \mu}{\delta}} \tag{12}$$

Where δ is copper conductivityall, F is frequency and terms have been defined before. Other dimensions have been shown in Fig. 4.

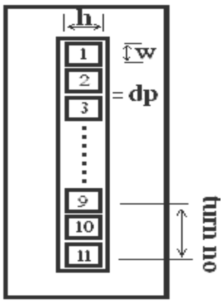


Figure.4. the structure of the generator winding

VI. PARALLEL CONDUCTANCES

Parallel conductances are due to dielectric losses and can be obtained by:

$$[G] = 2\pi F [C] \tan\delta \tag{13}$$

The parameters of RLC model are determined based on numerical field analysis methods (e.g.finite element method), by using maxwell software.

Figure.5. the coil of 6kv generator tested

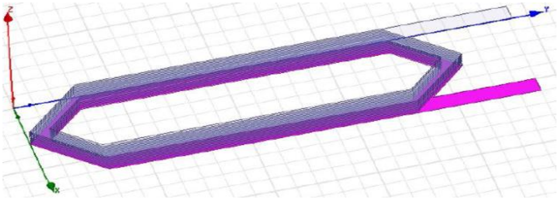


Figure.6. Three-dimensional shape of the winding 6kv simulation in Maxwell software

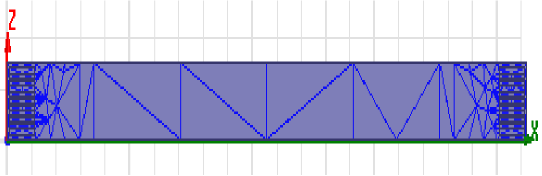


Figure.7. Shape mesh two-dimensional of the coil

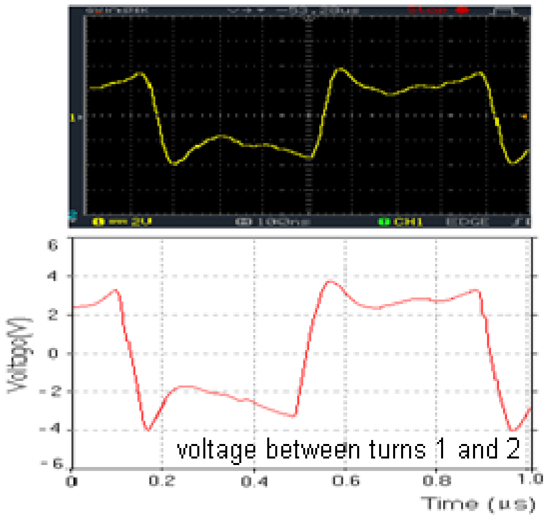
A. *Comparison of measured and computed results*

The analysis was carried out for a 6kV/250KW test generator. The results of the voltage transients computed layers were compared with laboratory measurements.

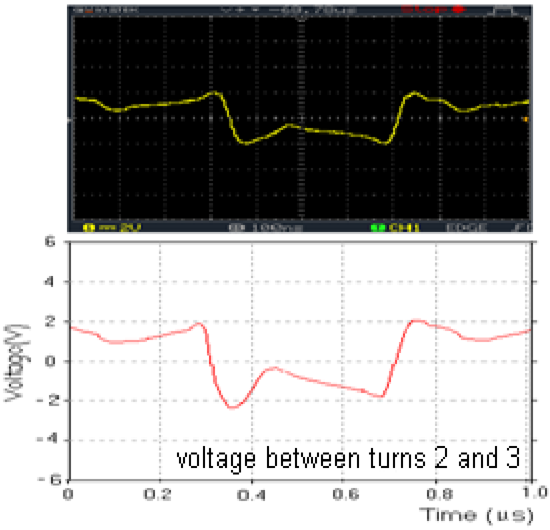
TABLE I. PARAMETERS OF THE MACHINE UNDER TEST

Rated voltage	6000	v
Rated power	250	kw
Rated speed	1500	r.p.m
Rated frequency	50	hz
Winding Connection	star	---
Number of turns per phase	176	---
Number of coils per phase	16	---
Number of turns in a coil	11	---
Conductor dimensions	11.5*236	mm

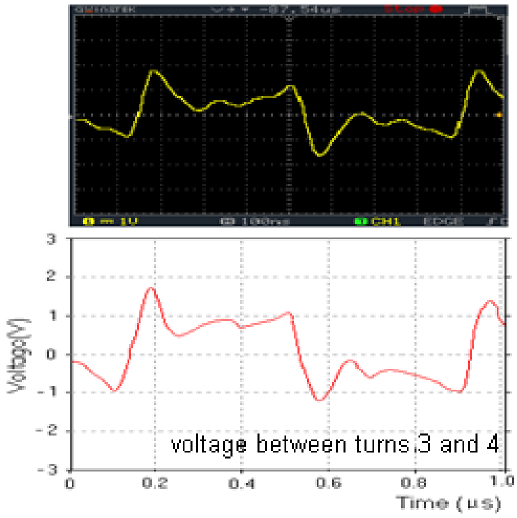
Simulations were performed by using multisim software. the Square-shaped pulse of the step under frequency 1 MHz given to outset winding and voltage waveform was recorded at the end of each turn of the coil.Fig(8).



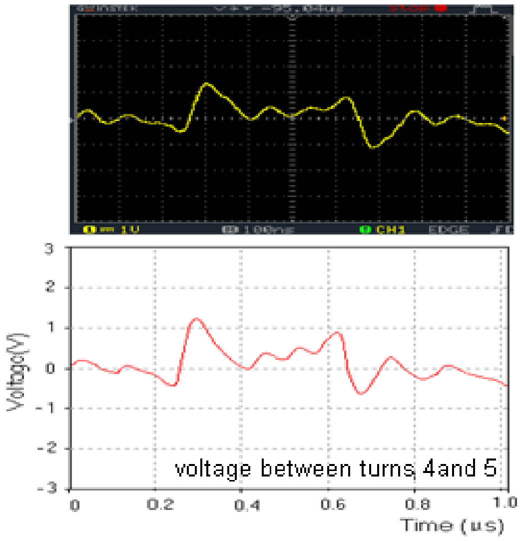
(a)



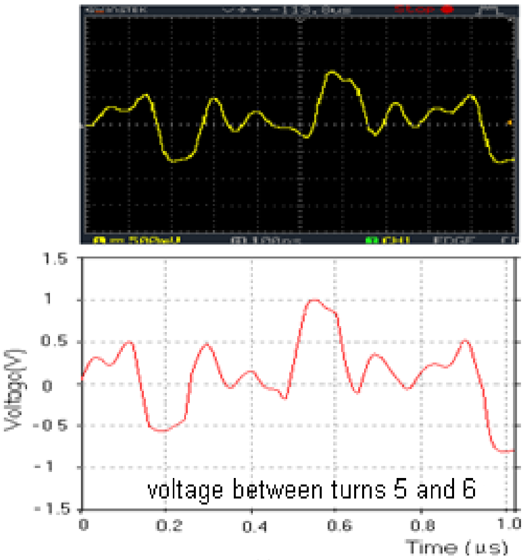
(b)



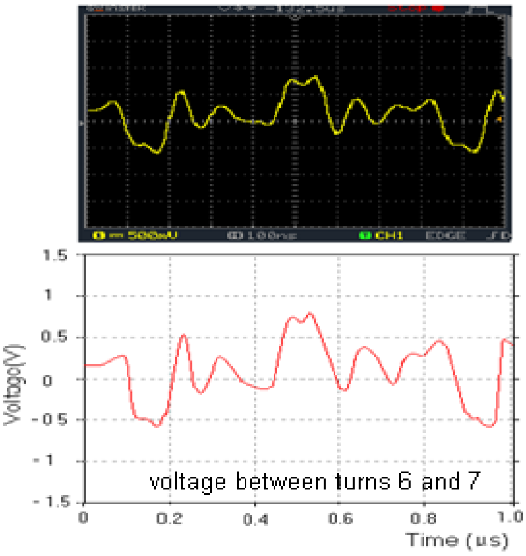
(c)



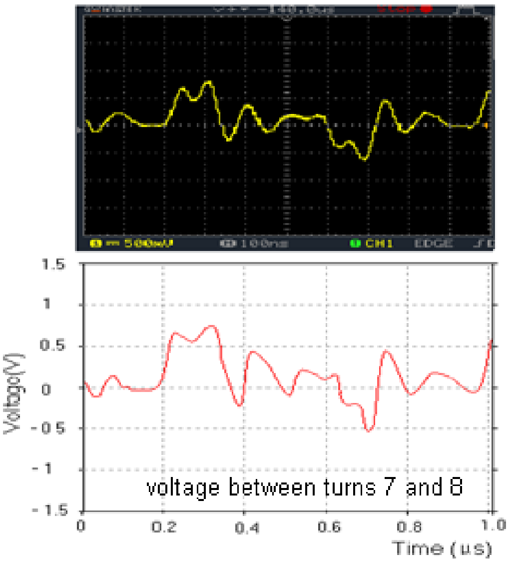
(d)



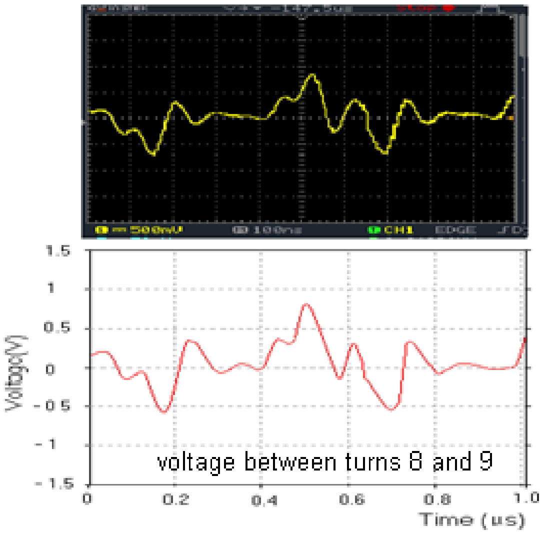
(e)



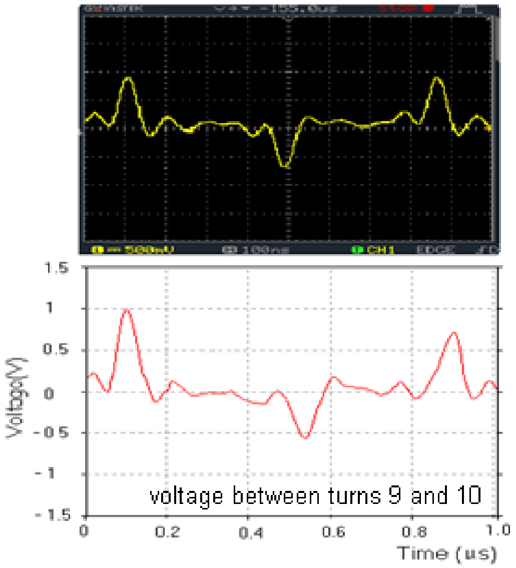
(f)



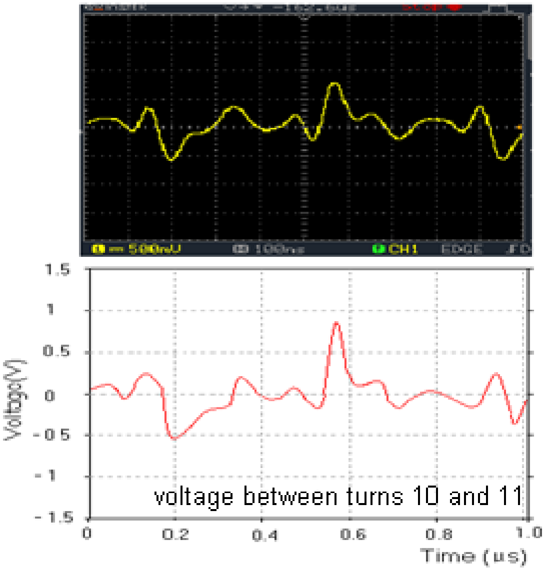
(g)



(h)



(i)



(j)

Figure 8. Voltage waveform at the end of each turn, measured and computed (a - j)

Figure.9. Schematic machin with the coil under test

By means of comparison between measured and calculated voltages in windings a 6kV/250KW generator with 11 turns can be inferred that each turn of the generator windings, voltage waveform is unique. The method of analysis could be used for general design purposes.

VII. CONCLUSION

This paper deals with the measurement, modelling and simulation of very fast transient overvoltages in windings a 6kV/250KW generator. Voltages along the generator windings were computed by applying RLC Ladder Network theory. By using RLC Ladder Network with their equations of high frequency phenomena and voltage distribution for stair waveform in winding generator is studied. Techniques of lumped parameter models are presented. Simulations were performed by using multisim software. The results of the voltage transients calculated at the turns of a winding coil were compared with laboratory measurement. In order to extend the range of a few hundred KHz to a few MHz, it is necessary to use a turn-to-turn modeling procedure instead of coil-to-coil modeling. The importance is modeling in determining the insulation condition of generators in the construction and positioning errors of the common occurrence of partial discharges in generator windings during its operation.

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S. M. Hassan Hosseini was born in Tehran, in 1969. He received his B.Sc. degree in electrical power engineering from Mashhad Ferdowsi University, Mashhad, Iran in 1993. He received his M.Sc. and Ph.D. degrees in electrical power engineering in 2000 and 2005 from Azad University South-Tehran Branch and Science & Research Branch, Tehran, Iran, respectively. He held the position of Assistant Professor in Azad University South-Tehran Branch from 2005. From 2008 to 2009 he was as deputy and from 2009 till 2011 he was as the manager of electrical engineering department of Azad University South-Tehran Branch. His research interest is transient modeling of transformer, Partial Discharge, High Voltage Engineering, Electrical Insulation, Substation and Hydropower.

S. M. Hosseini Bafghi was born in Bafgh, Iran, in 1986. He received the B.Sc. degree in electrical power engineering in 2009 from Islamic Azad University of Mehriz, Iran, and the M.Sc. degrees in electrical power engineering in 2013, from the Islamic Azad University, Tehran, Iran. Since 2011, He joined as a lecturer of Electrical Engineering Department, Faculty of Engineering, and Islamic Azad University Bafgh Branch. His research interest is transient modeling of transformers and Generators.

H.R. Khezri was born in Bafgh, Iran, in 1980. He received the B.Sc. degree in electrical power engineering in 2011 from Islamic Azad University of Abarkooh, Iran, and the M.Sc. degrees in electrical power engineering in 2013, from the Islamic Azad University, Bafgh, Iran. Since 2012, He joined as a lecturer of Electrical Engineering Department, Faculty of Engineering, and Islamic Azad University Bafgh Branch. His research interest is transient modeling of transformers and Generators.