A NEW MODEL OF TRANSFORMER WITH COAXIALLY INSULATED WINDINGS FOR TRANSIENTS STUDIES

F. Karimzadeh[1*], A. Akbari[1], M. Ardebili[1]
[1]K.N. Toosi University of Technology, Tehran, Iran
*karimzadeh@ee.kntu.ac.ir

Abstract: This paper presents a new model of coaxially insulated windings. The coaxially insulated windings are used in a kind of high voltage oil free transformer, which is called Dryformer. The main advantage of the proposed model is the simplicity of its implementation in comparison with the other high frequency models. The proposed model is the extended version of multi-conductor transmission line model of conventional transformer. The validity of the proposed model is verified by applying it to a single layer coil. The results demonstrate that the proposed model is slightly accurate up to few MHz. The model is also generalized to the winding of designed Dryformer. It is shown that the model can be utilized for calculating inter-turn voltages of Dryformer windings.

1 INTRODUCTION

Lightening discharges and switching operations are the most important sources of transients in power system. These transient overvoltages can be harmful to the insulation of power devices. It is necessary to consider these overvoltages in the design of electromagnetic power devices, specially in high voltage transformers, which are so expensive apparatuses.

Dryformer is a high voltage transformer that its windings are made of coaxial insulation system. The coaxial insulation system consists of cylindrical conductor and a polymer insulation which is embedded between two semiconductor (semicon) layers as shown in Figure 1 [1]. The coaxial insulation system is very similar to power cable which is used for transmission. In contrast with power cable the outer semicon layer is not continuously grounded by an outer conductive screen. However, the outer semicon layer is grounded in regular intervals (usually once per turn). Hence, it is reasonable to assume that the outer semicon layer is in low potential in compare to the conductor potential [2]. It means that the most of the electric field is concentrated between the inner and outer semicon layers. Hence, the electric field is low in out side of winding. As a result, the only capacitance should be considered in coaxial insulation system is the capacitance between the inner and outer semicon layers and the inter-turn capacitance between the turns can be neglected. Thus, most of the capacitive current (displacement current) will flow along the outer semicon layer to one of the grounded point. In [2], it has been presented that the semicon resistance between to grounded point play the striking role in internal transient response of Dryformer.

Because of the basic difference between conventional insulation system and coaxial insulation system, application of high frequency models of traditional transformer is useless in Dryformer. In [2] a wideband lumped circuit model has been proposed for coaxial insulation system. This model has been called the ‘preferred model’. In this model, the magnetic relation between turns is considered by self and mutual inductances. The capacitive current and its losses are modelled with discrete RC circuit [3]. The eddy current in cylinder conductor is divided to skin effect and proximity effect. In [4] the skin effect has been modeled with dual Cauer circuit, whilst the proximity effect has been modeled with Cauer circuit. In order to validate the preferred model, a single layer coil has been employed in [2-4]. An extended version of preferred model has been used in [5] to simulate the transient response of high voltage Dryformer. In this model, some alterations have been imposed to preferred model. The effect of iron core has been considered and simple change in RC model has been performed. The eddy current has been also neglected to avoid the complication of model.

Figure 1: The coaxial insulation system, (1) Conductor, (2) Inner semicon layer, (3) Polymer insulation (XLPE), (4) Outer semicon layer.

Although, the aforementioned papers claimed that the preferred model is rather accurate, it seems, it is so complicated when it would be applied to more complex coils, like Dryformer windings.

In this paper, a new model of coaxially insulated winding is proposed. The main advantage of proposed model is the simpler implementation in compare to preferred model. The proposed model is similar to multi-conductor transmission line

(MTL) model of conventional transformer, but it is extended by the adding of a resistance in order to consider the influence of outer semicon layer.

This paper is organized as follows: Section 2 presents the detail of proposed model. In section 3, the proposed model is applied to the single layer air core coil, the case study which has been used in previous works to verify the preferred model in frequency domain. The results show that the proposed model has same accuracy as preferred model. In section 4, the model is extended to the winding of designed Dryformer. It is shown that the model can be utilized for calculating inter-turn voltages of Dryformer windings.

2 PROPOSED MODEL

In transient condition, the voltage is nonlinearly distributed along the winding. To resolve the distribution of voltage, the winding of Dryformer must be divided in to a number of sections. In the proposed method, each turn of winding is considered as a section. Each section starts and ends at a point of the outer semicon that is grounded. Figure 3 shows the proposed model that can be considered for each section of winding. The voltage induced in each section is modeled with self and mutual inductances. The capacitance current and its losses are modeled with capacitance and conductance in parallel branch. The outer semicon layer resistance is also considered by a resistance in the bottom branch. The capacitance current will flow along this resistance to both grounded points.

2.1 Assumptions of the model

Most of the assumptions of the proposed model are similar to the assumptions that are considered in the preferred model [2-4]. In both models, the losses in inner semicon layer are neglected. To simplify the model, the capacitive coupling between outer semicon layer and the outside environment is ignored. The resistive contact between outer semicon layers and the losses due to induced voltage in the outer semicon layer are also neglected.

When the magnetic field is calculated for obtaining self and mutual inductances, an asymmetrical geometry is considered for coil. Hence, it is assumed that the current is nearly constant along the conductor throughout one turn.

2.2 Detail of the model

Figure 3 shows the dx length of coaxial insulation system model. $V(x)$ and $I(x)$ are the voltage and current along the conductor and $V_a(x)$ and $I_a(x)$ are the voltage and current along the outer semicon layer. The distance to the left side of the model is called x. According to the circuit model, $V(x)$ and $I(x)$ can be presented by following differential equation in the frequency domain:

$$\frac{\partial^4 V(x)}{\partial x^4} = (ZY + ZYR_S Z^{-1})\frac{\partial^2 V(x)}{\partial x^2} \quad (1)$$

$$\frac{\partial^3 I(x)}{\partial x^3} = Y(R_S + Z)\frac{\partial I(x)}{\partial x} \quad (2)$$

where $Z = R + j\omega L$ and $Y = G + j\omega C$ and R, L, G and C are the per-unit-length resistance, inductance, conductance and capacitance of the model, respectively.

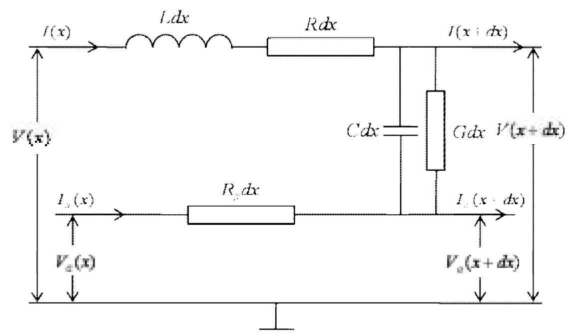

Figure 3: dx length of proposed model of coaxial insulation system**.**

In MTL model the tranformer winding is represented by a group of interconnected and coupled transmission lines [6]. Correspondingly, we can use the proposed model for each turn of Dryformer winding. Hence, we have a network with n proposed model as shown in Figure 4. In this network all the lines are considered to be of the same length. The differential equations (1) and (2) will be changed to the matrix form. Thus, $V(x)$ and $I(x)$ are altered to the voltage and current vectors and Z, Y and R_s are changed to the impedance, inductance and semicon resistance matrixes, respectively.

If the equations (1) and (2) are solved, The following formulas are obtained for $V(x)$ and $I(x)$:

$$V(x) = e^{-[P]x}v_1 + e^{[P]x}v_2 + xv_3 + v_4 \quad (3)$$

$$I(x) = [Y_0](e^{-[P]x}v_1 - e^{[P]x}v_2 - [P]^{-1}v_3) \quad (4)$$

where:

$$[P]^2 = [Z][Y] + [Z][Y][R_s][Z]^{-1} \quad (5)$$

and

$$[Y_0] = [Z]^{-1}[P] \quad (6)$$

In above formulas v_1, v_2, v_3 and v_4 are the vectors that defined by imposing the boundaries condition to (3) and (4).

As it can be seen in Figure 4 the terminal condition can be stated as following:

$$V_{Ri} = V_{S(i+1)} \qquad (7)$$
$$I_{Ri} = -I_{S(i+1)} \qquad \text{for } i = 1,\ 2, \ldots, n-1$$

where V_{Si} and V_{Ri} are the voltages at sending and receiving end of i th line. I_{Si} and I_{Ri} are the currents at sending and receiving end of i th line. As mentioned before, the outer semicon layer is grounded at the beginning and the end of each turn. So the grounded points impose two boundary for differential equations: $V_a(0) = 0$ and $V_a(l) = 0$. l is the average length of winding turns. By imposing above boundaries to equation (3) and (4), the relationship between the sending and receiving voltage vectors, and the sending and receiving current vectors is obtained as following:

$$\begin{bmatrix} I_S \\ I_R \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [C] & [D] \end{bmatrix} \begin{bmatrix} V_S \\ V_R \end{bmatrix} = [F]_{2n \times 2n} \begin{bmatrix} V_S \\ V_R \end{bmatrix} \qquad (8)$$

where:

$$[A] = \{Y_0 + Z^{-1} l^{-1} (l A^{-1} - I_n + e^{-Pl}) + [Y_0 - Z^{-1} l^{-1} \sinh(Pl)] \csc h(Pl) e^{-Pl}\} P^{-2} ZY \qquad (9)$$

$$[B] = \{Z^{-1} l^{-1} A^{-1} + [-Y_0 + Z^{-1} l^{-1} \sinh(Pl)] \mathrm{csch}(Pl) e^{-Pl}\} P^{-2} ZY \qquad (10)$$

$$[C] = \{l^{-1} Z^{-1} - Z^{-1} A^{-1} - (Y_0 - Z^{-1} l^{-1}) e^{-Pl} + [-Y_0 \cosh(Pl) + Z^{-1} l^{-1} \sinh(Pl)] \mathrm{csch}(Pl) e^{-Pl}\} P^{-2} ZY \qquad (11)$$

$$[D] = \{-Z^{-1} l^{-1} A^{-1} + [Y_0 \cosh(Pl) - Z^{-1} l^{-1} \sinh(Pl)] \csc h(Pl)\} P^{-2} ZY \qquad (12)$$

By substituting the terminal conditions (7) in to (8) and simplifying:

$$\begin{bmatrix} V_{S1} \\ V_{S2} \\ \vdots \\ V_{Sn} \\ V_{Rn} \end{bmatrix}_{(n+1)\times 1} = [T]_{(n+1)\times(n+1)} \begin{bmatrix} I_{S1} \\ 0 \\ \vdots \\ 0 \\ I_{Rn} \end{bmatrix}_{(n+1)\times 1} \qquad (13)$$

Suppose the end terminal is terminated to resistance R_e , then:

$$V_{Rn} = -R_e I_{Rn} \qquad (14)$$

By substituting above equation in (13), I_{S1} and I_{Rn} can be stated as following:

$$I_{S1} = \frac{V_{S1}}{T_{1,1} - \dfrac{T_{1,n+1} T_{n+1,1}}{R_e + T_{n+1,n+1}}} \qquad (15)$$

$$I_{Rn} = \frac{-T_{n+1,1}}{R_e + T_{n+1,n+1}} I_{S1} \qquad (16)$$

where V_{S1} is the input voltage and $T_{1,1}$, $T_{1,n+1}$, $T_{n+1,1}$ and $T_{n+1,n+1}$ are the elements of matrix $[T]$. By calculating I_{S1} and I_{Rn} from (15) and (16) and substituting in (13), all the internal voltages of winding will be obtained.

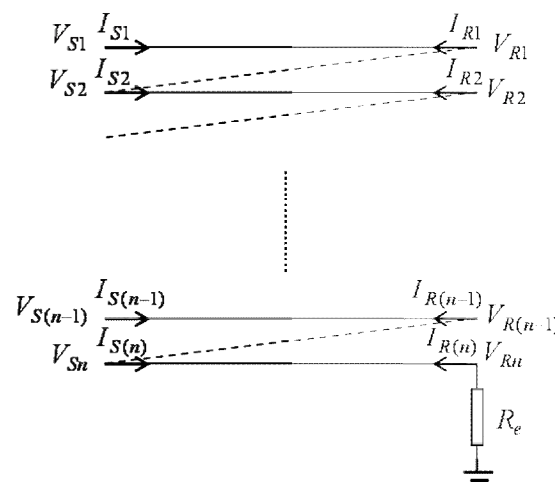

Figure 4: The model of coaxially insulated winding with proposed model for each turn.

2.3 Calculation of parameters

Calculating the parameters of transfer matrix $[T]$ is the first step in obtaining the internal voltages and currents of winding. The main parameters of matrix $[T]$ consist of resistance matrix $[R]$, inductance matrix $[L]$, capacitance matrix $[C]$ and conductance matrix $[G]$. The values of these parameters are dependent on the geometry of winding and material properties of conductor and insulation.

2.1.1 Resistance Matrix The resistance matrix $[R]$ is a diametric matrix that the diametric elements are the series resistance of conductor. Due to the skin effect and proximity effect, the series resistance of conductor is frequency dependent. For considering the skin effect in cylindrical conductor, an analytical formula is proposed in [4]:

$$Z_c(\omega) = \frac{R_{cDC}\sqrt{\frac{j\omega}{\omega_{c0}}}I_0(\sqrt{\frac{j\omega}{\omega_{c0}}})}{2I_1(\sqrt{\frac{j\omega}{\omega_{c0}}})} = R_c(\omega) + j\omega L_c(\omega) \quad (17)$$

where $Z_c(\omega)$ is the internal impedance of cylindrical conductor. I_0 and I_1 are the modified Bessel function of first kind. $\mathrm{R_{cDC}}$ is the DC resistance of cylindrical conductor and ω_{c0} is limiting angular frequency which is calculated as below [4]:

$$\omega_{c0} = \frac{1}{\mu_{rc}\,\mu_0\,\sigma_c r^2} \quad (18)$$

where μ_{rc} is relative permeability of cylinder and μ_0 is the permeability of empty space. σ_c and r are the conductivity and radius of cylinder, respectively.

The real part of the internal impedance of cylinder is equal to series resistance of conductor and the imaginary part is equal to inside self inductance of conductor. By calculating the series resistance of conductor, the resistance matrix as function of frequency can be expressed as:

$$[R] = R_c(\omega)\, I_n \quad (19)$$

where I_n is unite matrix.

2.1.2 Inductance Matrix There are two parts of inductance in inductance matrix. L_{ii} is the outside self inductance of turn i and L_{ij} is the mutual inductance between turns i and j of winding. Here they are calculated in MAXWELL, a finite element program which is used for solving the magnetic potential. In this program, the current I_i in turn i is set to 1 A. The current in the other turns are set to zero. The inductances can then be calculated from the magnetic flux linkage for each of the turns [7]:

$$L_{ij} = \frac{\lambda_{ij}}{I_i} \quad (20)$$

where L_{ij} is mutual inductance between turns i and j. In the case $i = j$, L_{ij} denotes the outside self inductance of turn i. λ_{ij} is the magnetic flux linkage for section j.

As stated before, the skin effect in conductor gives rise to inside self inductance that should be considered in inductance matrix. Hence, the total inductance matrix can be expressed as following:

$$[L] = [L_a] + L_c(\omega) I_n \quad (21)$$

where $[L_a]$ is the inductance matrix that is calculated by finite element program and $L_c(\omega)$ is the imaginary part of $Z_c(\omega)$.

2.1.3 Capacitance Matrix The only capacitance that should be considered in coaxial insulation system is the capacitance between the conductor and outer semicon layer. This capacitance can be estimated from the formula for two cylindrical coaxial tubes [2]:

$$C_c = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(r_2/r_1)} \quad (22)$$

where r_1 is the inner radius of the outer semicon layer and r_2 is the outer radius of the outer semicon layer, respectively. ε_0 is the permittivity of empty space and ε_r is relative permittivity of polymer insulation. The capacitance matrix of model can be stated as:

$$[C] = C_c I_n \quad (23)$$

2.1.4 Conductance Matrix The conductance is due to the capacitive losses in insulation. It depends upon the frequency f, the capacitance C_c, and the dissipation factor $\tan\delta$ [6]:

$$[G] = 2\pi f [C]\ \tan\delta \quad (24)$$

2.1.5 Semicon Resistance Matrix The resistance of semicon layer between two grounded points can be calculated as following:

$$r_s = \frac{\rho_s}{\pi(r_2^2 - r_1^2)} \quad (25)$$

where r_2 and r_1 are the outer and inner radius of the outer semicon layer, respectively. ρ_s is the resistivity of semicon layer. The semicon matrix can be stated as below:

$$[R_s] = r_s\, I_n \quad (26)$$

3 RESULTS AND VALIDATION

3.1 Case study

A single layer coil with air core is employed in this paper to verify the validity of the proposed model. This coil has been used in previous works by Holmberg [2-4] to show the validity of preferred model. The specifications of coil are introduced in [3,4].

3.2 Comparison of results

In order to solve the equations of proposed model, MATLAB software is chosen and a m-file is compiled to obtain the voltage distribution in single layer coil. The model is grounded through a small resistance of 0.04 ohm. This represents a contact resistance, which has influence on the measured resistance for low frequency [4]. To verify the proposed model, an input impedance of the coil is calculated and compared with measured result and the result obtained from preferred model. To compute the input impedance of the coil by proposed model, a sinus voltage with 1 p.u magnitude and frequency f is considered for input voltage V_{S1}. The input current I_{S1} is calculated from (15) and so the input impedance is obtained as:

$$Z_{in} = \frac{V_{S1}}{I_{S1}} \tag{27}$$

By changing the frequency in an arbitrary interval, the spectrum of input impedance is obtained. Figure 6 and 7 show the magnitude and the phase of input impedance of the coil. It can be seen that the results obtained from proposed model and preferred model are coincident. It seems that the coincidence is due to the same assumptions that have been considered in both models. The spectra of two aforementioned methods almost overlap the measured spectrum at least up to few MHz. The measured response shows that in high frequency the coil is mainly capacitive, while the simulated response shows it is more resistive. The deviation between the simulated and measured response can be explained by either stray capacitance from the outer semicon to the environment or neglected intrinsic capacitance of the semicon that were ignored in both models. Another reason could be resonance phenomena in the wires to the coil, which are 1-2m long [4].

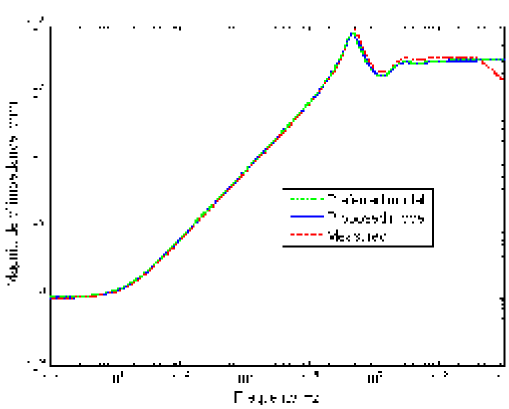

Figure 6: Magnitude of input impedance.

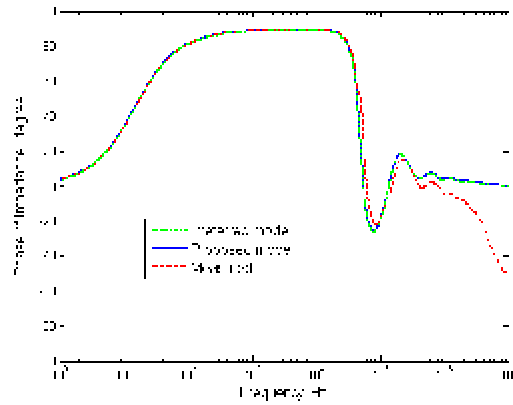

Figure 7: Phase of input impedance

4 EXTENTION OF THE MODEL FOR DRYFORMER

There are some differences between studied single layer coil and Dryformer windings. First, in Dryformer windings, apart from being grounded once per turn, the outer semicon layer is in contact with several floating conductive vertical bars [5]. These bars are used to brace windings against electromagnetic forces that will occur in event of short circuit [1]. The bars reduce the capacitive current paths in outer semicon layer that causes the effect of semicon resistance to be diminished. The resistance of semicon layer can be modified as following [5]:

$$r_s' = \frac{r_s}{(m+1)^2} \tag{28}$$

where m is the number of bars and r_s' is modified semicon layer resistance which must be substitute for r_s in (26).

The existence of iron core is the second difference of Dryformer windings. In [5] has been discussed that the transient response of Dryformer is insensitive to the permeability of the core when the Dryformer has been put under the standard impulse test. The insensitivity can be explained by the grounded secondary winding, which short circuits the flux in the core. As the aim of this section is to calculate the voltage of distribution along the winding in standard impulse test, the Dryformer winding is assumed as an air core coil.

The inter-turn voltages of winding in frequency domain are calculated by multiplying the input voltage with transfer function:

$$V_{Ri}(j\omega) = H_i(j\omega) \times V_{S1}(j\omega) \tag{28}$$

where $V_{Ri}(j\omega)$ is output voltage of ith turn in frequency domain and $V_{S1}(j\omega)$ is input voltage in frequency domain. $H_i(j\omega)$ is the transfer function from output terminal of i th turn to input terminal which can be calculated from the equations of proposed model:

$$H_i(j\omega) = \frac{V_{Ri}}{Vs1} \tag{29}$$

where V_{S1} is a sinus voltage with 1 p.u magnitude and frequency f and V_{Ri} is output voltage of i th turn which is calculated from equation (13). By changing the frequency of input voltage in an arbitrary interval, the spectrum of transfer function will be obtained.

The fast fourier transform (FFT) function in MATLAB can be used to convert the input voltage from time domain to frequency domain in equation (28). Vice versa, the inverse fast fourier transform (iFFT) function can be utilized to convert the out put voltage in equation (28) from frequency domain to the time domain.

The proposed method is employed to determine the distribution of voltage in 30 MVA 63/20 kV Dryformer. The Dryformer is under designing. Thus, it is necessary to evaluate the insulation of winding when it is excited with a lightening standard impulse. As each turn of Dryformer winding is surrounded by the grounded semicon, the turn to turn stress is not interested in the coaxial insulation system. Therefore, it is only the turn to ground stress that is of interest [5]. The inter-turn voltages of high voltage (HV) winding are calculated when a standard impulse is applied to the line terminal of HV winding. Some of the inter-turn voltages are represented in Figure 8. The maximum positive voltage is occurred in 28 i th turn, while the maximum negative voltage is occurred in 76 i th turn. Both positive and negative voltage should be considered in insulation designing.

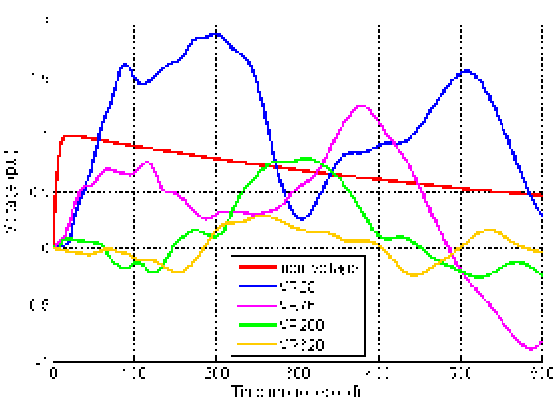

Figure 8: Inter-turn voltages of High voltage winding of Dryformer

5 CONCLUTION

A new high frequency model of coaxially insulated winding has been presented. The MTL model of conventional transformer has been modified by addition of resistance to consider the effect of semicon layer in coaxial insulation system. The proposed model has been utilized to calculate the input impedance of a coil with coaxial insulation system. The comparison of simulated and measured results demonstrated that the proposed model is slightly accurate up to few MHz. The main reasons of inaccuracy of model in high frequency are non-consideration of the intrinsic capacitance of semicon layer and ignorance of the capacitance from the outer semicon to the environment.

The proposed model has been extended to the Dryformer winding. It has been shown that the inter-turn voltages of Dryformer winding can be calculated by using the proposed model. As the outer semicon layer of each turn is remained in ground potential, only the conductor to ground stress is of interest and investigation of turn to turn stress is not important.

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