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Calculation of internal overvoltages using a wide band transformer model based on limited information about transformer design

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Abstract

Specific insulation coordination studies might require an accurate modeling of power transformers. This is the case for instance when transfers of fast front overvoltages from the high voltage side to the low voltage side of a transformer are involved. Modeling accurately the transformer’s electromagnetic behavior for the frequency range of fast front overvoltages requires special care. There are numerous existing transformer models which are intended to model the wide band transformer’s behavior. However, many of them are too complex or require confidential information about the transformer design. This makes them not suitable for power engineering applications.
In this paper a wide band transformer model based on limited information about the transformer design and compatible with an electromagnetic transients program is presented. Then, its application on calculating internal overvoltages distribution along transformer windings, taking into account different conditions on the outer transformer terminals, is shown for lightning impulse.

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Keywords: Transformer modelling; Grey Box; Complex permeability; ElectroMagnetic Transients Programme; Internal overvoltages

1. Introduction

Transformer outages can sometimes happen due to dielectric failures inside the transformer caused by lightning or switching operations (fast and very fast front overvoltages) [1]–[3]. Consequently, internal overvoltages distribution along transformer’s windings in the case of high frequency overvoltages are of interest to power utility

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engineers. However, even though many transformer models for high frequency exist today, because of the lack of data and the complexity of these transformer models it is not always possible to accurately represent transformer's high frequency electromagnetic behavior. With the introduction of the Grey Box transformer models it becomes possible to make a model detailed enough, usable for power utility engineers, without having access to the detailed transformer design data.

This paper first presents a wide band transformer model based on limited information about the transformer design and compatible with an electromagnetic transients program [4]. Then, its application on calculating the internal overvoltages distribution along the transformer windings, taking into account different conditions on outer transformer terminals, is shown for a lightning impulse. Finally, a method to detect the resonant frequencies of a transformer winding is explained.

2. Wide band transformer model based on limited information about transformer design

In this paragraph a wide band transformer model is presented. The model is based on finite element calculations, rational approximation and derived from limited information about the transformer geometry. It can be classified as a Grey Box model [1]. The model can be used to simulate external overvoltages as well as internal overvoltages that might occur in the transformer. That said, it can be separated into two successive steps: first step related to the calculation of external overvoltages and the second step devoted to the calculation of internal overvoltages. Because of the specificities of the model interaction with the electromagnetic transient software program (EMTP-RV), it is more efficient to have only external transformer terminals represented in EMTP-RV. Note that the voltages that occur on these terminals depend on the electromagnetic interaction between the power network and the transformer [1]. Once the values of voltages at the external terminals are known, it is possible to calculate the internal distribution of overvoltages taking into account the current power network configuration. A similar approach for interfacing with EMT-type programs has been already proposed in [5] on the example of the Black Box model.

2.1. Parameters determination

The model presented in this paper is based on a lumped *RLCG* equivalent network and a segmentation of the transformer geometry. Similar models can be found in [6]–[8]. In this model the parameter values are calculated from the transformer geometry and properties of the materials. Each *RLCG* element represents a physical part (segment, some authors refer to them as "electrical elements" [9]) of the transformer's winding. See Fig. 1 for the example of a *RLCG* network which represents one phase of a two windings transformer represented with only one segment per winding.

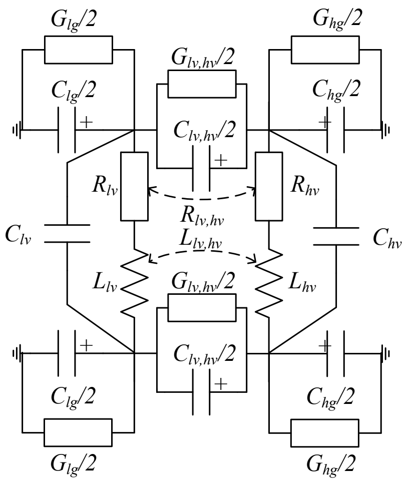

Fig. 1. *RLCG* network for one phase of a two winding transformer.

From Fig. 1, it can be seen that the transformer is represented with the inductances, resistances and capacitances of the windings itself, the mutual inductance and resistance (related to proximity effect), capacitance and conductance between the windings and the capacitances and conductance to the ground of each winding.

Note that when calculating the overvoltage distribution along the transformer windings, each segment represents a turn of the transformer windings.

Since the model is intended to be used for lightning studies and vacuum circuit breaker switching simulations for which the overvoltages have most of their energy stored in the range from tens of kHz up to several MHz, besides the dense segmentation the model's parameters have to be accurate in this frequency range. It is assumed that the capacitance parameters are constant for this frequency range while the resistance, inductance and conductance values vary versus frequency. Therefore, to calculate the model's parameters two problems have to be solved: a magnetic one and an electrostatic one.

The most efficient way to solve these problems is to build a model in an electromagnetic field software program (i.e. a software program which includes a FEM solver for quasi-static problems such as FEMM [10]). Another possibility would be to use analytical expressions. However, it is not always possible to derive analytical expressions for complex structures such as transformer's windings, especially when it comes to the calculation of resistances inside a transformer at high frequencies. This is due to the calculation of the eddy currents effects: skin and proximity effects.

To calculate the R and L parameters of the transformer in a reasonable time, a method to approximate eddy currents by substituting the conductive material for a non-conductive hysteretic material described with a complex permeability (see Fig. 2) is implemented. In that way the magnetics FEM problems can be solved more efficiently [11]–[14], which makes the calculation time compatible with the one of an engineering study.

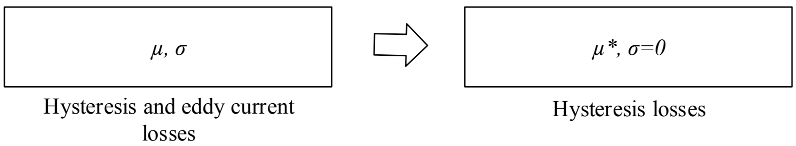

Fig. 2. Complex permeability equivalence principle.

By setting the material's conductivity to zero, the conductors can be observed macroscopically since it is not necessary to calculate eddy currents locally. The physical explanation of the complex permeability behaviour in the conductive material is that the real part of the permeability represents the ability of the conductive material to conduct the magnetic flux while the imaginary part of the permeability represents the losses generated by the eddy currents circulating in the material. Note that only eddy currents due to the proximity effect are taken into account since the only magnetic field that is taken into consideration is the external one [4]. The contribution due to the skin depth has to be added afterwards using analytical formulas [4].

To calculate the C and G parameters of a transformer, the electrostatic problem has to be solved with an electromagnetic field software program. For the model, two different types of capacitances (capacitances of the segments to the ground, capacitances between the segments) and conductances are calculated (conductance of the segments to the ground and conductance between two segments). Contrary to the capacitances, the conductances are considered as frequency dependent. Nevertheless, their values can be derived from the values of the capacitances by using a linear approximation derived from Buckow's experimental results [15] already used for transformer modelling in [4], [6], [16].

2.2. Nodal frequency dependent admittance matrix calculation

In order to use the model in a power system studies, when all the $RLCG$ parameters of the model are calculated, it is necessary to compute its admittance matrix. This procedure is not straightforward. Therefore it is explained further in the paper.

From FEM software program the *RL* branch matrix and the *CG* nodal matrix are calculated:

$$\boldsymbol{Z}_{\boldsymbol{RLbranch}}(f) = \boldsymbol{R}(f) + j\omega\boldsymbol{L}(f) \tag{1}$$

$$\boldsymbol{Y}_{\boldsymbol{CGnodal}}(f) = \boldsymbol{G}(f) + j\omega\boldsymbol{C} \tag{2}$$

Both matrices $\boldsymbol{Z_{RLbranch}(f)}$ and $\boldsymbol{Y_{GCnodal}(f)}$ are symmetrical. All the elements of the matrices given above, except the capacitances, are frequency dependant. Dimension of $\boldsymbol{Z_{RLbranch}(f)}$ is determined by the number of segments taken into consideration while the dimension of $\boldsymbol{Y_{GCnodal}(f)}$ is determined by the number of nodes.

To calculate a transformer nodal admittance matrix, first, it is necessary to calculate ***RL*** nodal matrix, $\boldsymbol{Y_{RLnodal}(f)}$ from the $\boldsymbol{Z_{RLbranch}(f)}$ matrix:

$$\boldsymbol{Y}_{\boldsymbol{RLnodal}}(f) = \boldsymbol{A} * \boldsymbol{Z}_{\boldsymbol{RLbranch}}(f)^{-1} * \boldsymbol{A}^T \tag{3}$$

$\boldsymbol{A}$ is the incidence matrix which contains the relations between the inductive branch currents and the nodal currents [4]. The $\boldsymbol{Y_{RLnodal}(f)}$ matrix is a square matrix of the dimension equal to the number of nodes.

Complete nodal matrix of a transformer, $\boldsymbol{Y_{nodal}(f)}$ can be calculated as follows:

$$\boldsymbol{Y}_{\boldsymbol{nodal}}(f) = \boldsymbol{Y}_{\boldsymbol{RLnodal}}(f) + \boldsymbol{Y}_{\boldsymbol{CGnodal}}(f) \tag{4}$$

This nodal matrix includes information about all external and internal nodes. To make the model as simple as possible it can be divided into 4 sub matrices. If the external winding's nodes are marked with the subscript *e* (consequently its current, voltage and admittance are also marked with the subscript *e*) and if the internal winding's nodes are marked with the subscript *i* then the nodal admittance matrix can be written as:

$$\boldsymbol{Y}_{\boldsymbol{nodal}}(f) = \begin{bmatrix} \boldsymbol{Y}_{\boldsymbol{ee}}(f) & \boldsymbol{Y}_{\boldsymbol{ei}}(f) \\ \boldsymbol{Y}_{\boldsymbol{ie}}(f) & \boldsymbol{Y}_{\boldsymbol{ii}}(f) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \boldsymbol{Y}_{\boldsymbol{ee}}(f) & \boldsymbol{Y}_{\boldsymbol{ei}}(f) \\ \boldsymbol{Y}_{\boldsymbol{ie}}(f) & \boldsymbol{Y}_{\boldsymbol{ii}}(f) \end{bmatrix} * \begin{bmatrix} \boldsymbol{V}_{\boldsymbol{e}}(f) \\ \boldsymbol{V}_{\boldsymbol{i}}(f) \end{bmatrix} = \begin{bmatrix} \boldsymbol{I}_{\boldsymbol{e}}(f) \\ \boldsymbol{I}_{\boldsymbol{i}}(f) \end{bmatrix} \tag{6}$$

$\boldsymbol{V_e}$ and $\boldsymbol{I_e}$ respectively stand for the voltages at the external terminals and currents flowing into the external terminals while $\boldsymbol{V_i}$ and $\boldsymbol{I_i}$ stand for the voltages at the internal terminals and currents flowing into the internal terminals. To form a nodal matrix as it is shown in equation (5) the rows and columns of the nodal matrix have to be restacked.

Since the currents that are flowing into the internal nodes are zero, $\boldsymbol{I_i}=0$, the system can be reduced from the equation (6) to, $\boldsymbol{Y_{nodal\_reduced}(f)}$:

$$\boldsymbol{Y}_{\boldsymbol{nodal\_reduced}}(f) = \boldsymbol{Y}_{\boldsymbol{ee}}(f) - (\boldsymbol{Y}_{\boldsymbol{ei}}(f) * \boldsymbol{Y}_{\boldsymbol{ii}}(f)^{-1} * \boldsymbol{Y}_{\boldsymbol{ie}}(f)) \tag{7}$$

This is done to reduce the number of terminals that will be a part of the model for calculating the voltages at external terminals of the transformer since the time needed to include the model in EMTP-RV depends significantly on the number of model's terminals.

An example of the reduced nodal admittance matrix is shown in Fig. 3 for the one phase of a *64* MVA, *24/6.8/6.8* kV *YNd11d11* power transformer unit, whose geometry has been represented with a number of segments equal to the number of turns).

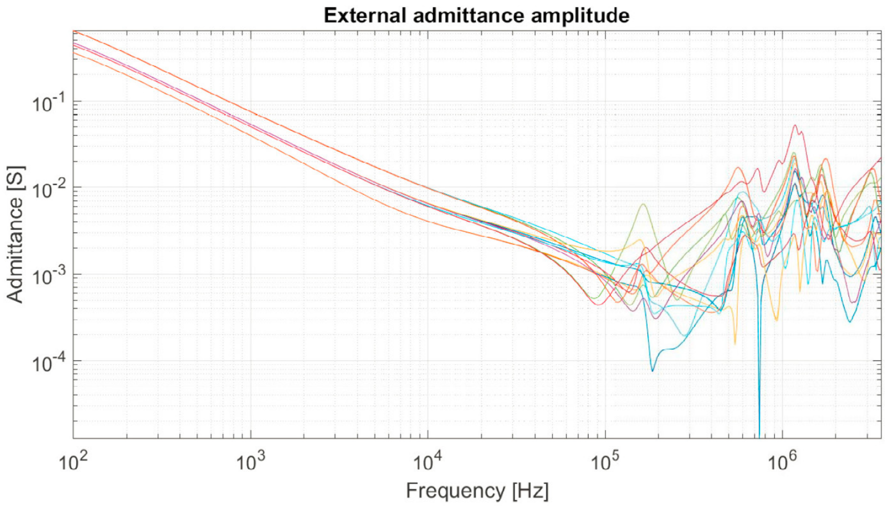

Fig. 3. Amplitude of the transformer's reduced nodal admittance matrix elements.

When observing the admittance matrix elements from Fig. 3, it is clear that the transformer acts as an inductive element in lower frequency range while for the frequencies around *100* kHz its behavior starts to be capacitive and resonances occur.

2.3. Inclusion of the model in EMTP-RV

To include the frequency dependent nodal admittance matrix of the Grey Box model, $\boldsymbol{Y}_{nodal\_reduced}(f)$ in EMTP-RV, the procedure consists of fitting the admittance matrix coefficients using a rational approximation and enforcing the passivity of the model. Such approach is widely used when it comes to representing multiple-input, multiple-output systems (MIMO) such as power transformers [17]–[21].

The fitting of the admittance matrix element $Y_{ij}(f)$ is done using a rational expression [22]–[24] of the type given below:

$$Y_{ij}(s) \approx Y_{ij,fit}(s) = \sum_{n=1}^{Np} \frac{c_{n,ij}}{s - a_{n,ij}} + d_{ij} \tag{8}$$

In (8) $a_{n,ij}$ represents the poles which can be either a real or a complex conjugated pair, $c_{n,ij}$ represents the residues which can also be either a real or a complex conjugated pair, d_{ij} is a real value constant. s stands for $j2\pi f$ where f is the frequency. Np is the number of poles used for approximating each matrix element. Prior to rational approximation, the frequency dependent admittance matrix $\boldsymbol{Y}_{nodal\_reduced}(f)$ should be rewritten to form a function of variable s, $\boldsymbol{Y}(s)$ instead of f.

The rational functions have to be simultaneously stable and passive since the transformer is a passive component of the electricity grid. The stability is ensured by keeping only the poles which are stable. The passivity is enforced by the perturbation of the residues and the constant values in order to match the passivity criterion [19], [24]–[30]:

$$\boldsymbol{P} = Re\left\{\boldsymbol{u}^{*} \boldsymbol{Y}_{\boldsymbol{fit}}(s) \boldsymbol{u}\right\} > 0 \tag{9}$$

In (9), $\boldsymbol{Y}_{fit}(s)$ represents the matrix of the fitted rational functions. Expression (9) means that the transformer will not produce power for any complex vector $\boldsymbol{u}$. The expression above will be positive only if all the eigenvalues of the real part of $\boldsymbol{Y_{fit}}(s)$ are positive:

$$eig(Re(\boldsymbol{Y}_{\boldsymbol{fit}}(s))) > 0 \tag{10}$$

The rational expression (8) enables the use of the state space equations as shown below:

$$s\boldsymbol{X}(s) = \boldsymbol{A} * \boldsymbol{X}(s) + \boldsymbol{B} * \boldsymbol{U}(s) \tag{11}$$

$$\boldsymbol{I}(s) = \boldsymbol{C} * \boldsymbol{X}(s) + \boldsymbol{D} * \boldsymbol{U}(s) \tag{12}$$

The matrices ***A*****,** ***B*****,** ***C*****,** and ***D*** for the state space representation can be input directly into the state space block in EMTP-RV. These matrices are obtained by using the values of the poles and the residues from the rational functions (8) to form the function given below:

$$\boldsymbol{I}(s) = \boldsymbol{Y}(s) * \boldsymbol{U}(s) = \left[\frac{\boldsymbol{C} * \boldsymbol{B}}{\left(s[\boldsymbol{I}] - \boldsymbol{A}\right)} + \boldsymbol{D} \right] * \boldsymbol{U}(s) \tag{13}$$

Expression (13), in which [***I***] is the identity matrix, can be obtained from equations (11) and (12). It represents the relationship between the terminal currents and the voltages of the transformer, suitable to represent the rational functions given by expression (8). The state space representation is used to describe a linear network. Therefore, it can be used to represent a transformer, since it is a linear system at high frequencies. The main advantage of using these equations is that they can be used both in the frequency and the time domain.

For inclusion of the model in EMTP-RV, Semi-Definite Programing constrained fitting method is used, as this method exhibited a sufficient accuracy in solving these problems [20], [31].

3. Calculation of internal overvoltages from given external ones

The wide band transformer model described in this paper is very efficient so it is possible to get its results quite fast (for a power transformer within few hours) even in the case when the transformer geometry is segmented down to the level of turns. Taking that into account, it is possible to calculate the voltage at each turn of the transformer windings. However, these calculations have to be done in two steps, as mentioned earlier in the paper. At first the voltages on the transformer external terminals shall be calculated using the EMTP-RV software program and at second the voltage distribution along the transformer windings shall be calculated from a vector of external voltages, $\boldsymbol{V_e}$.

If in equation (6) we set all the currents that are entering in internal transformer nodes, $\boldsymbol{I_i}$ to *0*, then it can be written:

$$\boldsymbol{V_i}(f) = -\boldsymbol{Y_{ii}}(f)^{-1} * \boldsymbol{Y_{ie}}(f) * \boldsymbol{V_e}(f) \tag{14}$$

As the vector of external voltages, $\boldsymbol{V_e}$ (which is calculated using the EMTP-RV) is in the time domain, Fast Fourier Transform has to be used to transform it to the frequency domain. Once the external voltages are transformed in the frequency domain, equation (14) can be applied. To show the internal voltages, $\boldsymbol{V_i}$ in the time domain, Inverse Fast Fourier Transform has to be used.

In this paper, for sake of the simplicity, the turn-to-turn voltages and disc-to-disc voltages are shown for the high voltage winding of the *64* MVA, *24/6.8/6.8* kV *YNd11d11* power transformer unit, when 1,2/50 µs, 170 kV lightning impulse wave has been applied to its phase A terminal. All the other terminals of the model were grounded.

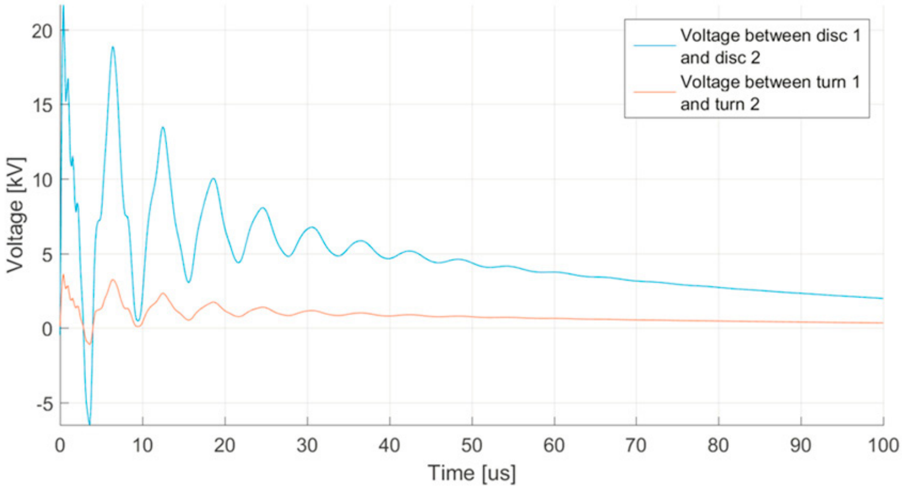

Fig. 4. Calculated voltages disc-to-disc and turn-to-turn for HV winding.

The overvoltages calculated above shows the expected results and the intention is to compare it with the measurement data in a second step.

When observing equation (14), it appears that a transfer function, $\boldsymbol{H}$ can be calculated as follows:

$$\boldsymbol{H}(f) = -\boldsymbol{Y_{ii}}(f)^{-1} * \boldsymbol{Y_{ie}}(f) \tag{15}$$

This transfer function $\boldsymbol{H}$ allows us to calculate the voltage of a given turn or disc of the winding from the voltage applied to the outside terminals. It is shown in Fig. 5 for the high voltage winding of the transformer (for each disc) studied in this paper, considering the phase A terminal.

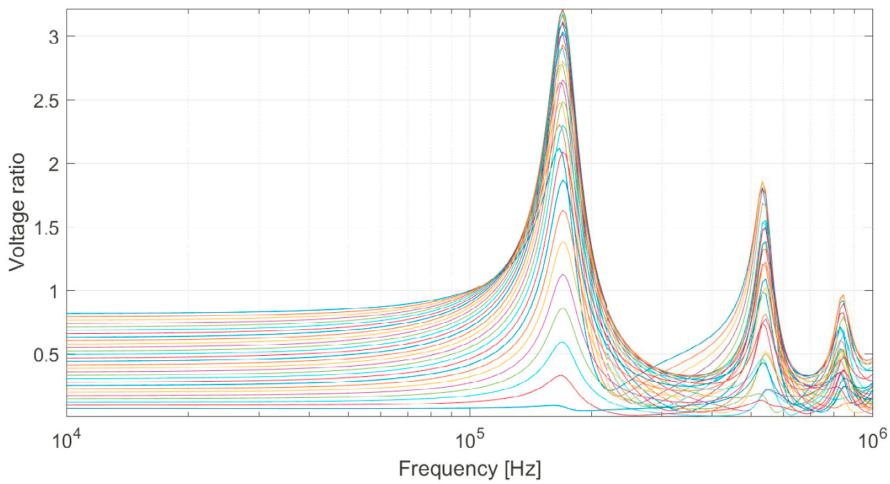

Fig. 5. Transfer functions of the HV winding (for each disc) in respect to phase A terminal.

From the transfer functions it can be seen that the HV winding of the *64* MVA, *24/6.8/6.8* kV *YNd11d11* power transformer unit has significant resonant frequencies around *170* and *534* kHz. At these frequencies the voltages that can occur along the transformer winding can be extremely high. It can also be seen that for frequencies lower than

30 kHz voltage distribution along the high voltage winding of the transformer is linear, as expected.

4. Conclusions

In this paper a model based on limited information about transformer geometry is presented. This model is based on segmentation, finite element calculation, complex permeability approximation and rational approximations. The model includes two dependent stages: the first one related to calculations of the external overvoltages (with an electromagnetic transient software program) taking into account the power network configuration and the second one devoted to the calculation of the internal voltage distribution along the transformer windings as functions of the external voltages.

The model has proved to be efficient and easy to use. It provides reasonably good results without requiring a too detailed knowledge of the transformer design. Consequently, the model can be used by power utility engineers for power system studies requiring a sufficiently accurate representation of a transformer behavior in the high frequency range.

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