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High frequency transformer model for calculations of transferred overvoltages

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SUMMARY

Equipment in the power grid have to be protected against overvoltages. Lightning or some switching operations can cause high frequency overvoltages. The choice of the rules adapted at design stage regarding insulation coordination is usually based on Electromagnetic transient simulations (EMTP), therefore it is particularly important to model properly apparatuses. Since transformer behavior at high frequencies is mainly dependent on its capacitances, classical, low frequency transformer models cannot be used for high frequency transient simulations. Therefore, some other models have to be developed. Nevertheless, nowadays high frequency models of the transformer which are compatible with the EMTP-like tools are neither standardized nor easy to use.

In this paper an overview of a complete procedure for establishing a state of the art transformer model for high frequency based on terminal measurement is given. Procedure includes measurements of the scattering parameters of the transformer, calculation of transformer admittance matrix, rational approximation and usage of the state space equation block in EMTP-RV. The developed model represents a transformer as a black box and is suitable for calculation of transferred high frequency overvoltages through a transformer. A case study is included in the paper.

KEYWORDS

Transformer - “Black Box” Model - Transient Simulation - Rational Approximation - State Space Equation - Scattering Parameter - Electromagnetic Transient Program (EMTP)

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INTRODUCTION

Events such as lightning, switching of vacuum circuit breaker or switching operations in gas insulated substation (GIS) generate high frequency overvoltages. Apparatuses in transmission and distribution systems have to be protected against such phenomena. The choice of appropriate measures aiming at protecting equipment is usually done by using numerical simulations with an EMTP-like tool.
As the transformer behavior for high frequency introduces resonances due to inductive and capacitive coupling between windings, core and tank, classical low frequency transformer models cannot be used. During the last decades, several approaches have been used to establish the principles of a transformer model which can represent a transformer when high frequency overvoltages occur, in order to calculate voltage transmitted through transformer or overvoltages distribution along the transformer windings.
Nevertheless, it remains quite complex nowadays to study high frequency transformer transients with EMTP-like tools. For instance, transformer model included in EMTP-RV [1] standard library (FDBFIT), explained in [2], is not straightforward and does not achieve sufficiently good results in some practical configurations.
Therefore, in this paper the “Black box” model based on state space equations and compatible with EMTP-RV is derived from the measurements of the scattering parameters.

In the first section of the paper a short bibliography survey is given in order to determine the differences between the methodologies. Then, principle for establishing the “Black box” model of a transformer is proposed. In the third section, the measurements which are conducted on a real transformer are explained in details. Furthermore, a short case study of a lightning impulse test is presented. Finally, discussion of the case study results and a conclusion are included.

HIGH FREQUENCY TRANSFORMER MODELLING

In order to model the transformer behavior in the higher frequency band (from few kHz to few MHz), different approaches from those used for the classical low frequency transformer modeling have to be adopted. Four basic model methodologies can be distinguished: Simplified models; “Black box” models; “Grey box” models; “White box” models [3].
This terminology for transformer models is widely accepted and used in the transformer modeling field. A short overview of the mentioned models is given in the following sections.

Simplified models are based on small RLC networks. Model parameters can be easily obtained from the nameplate, test reports, typical surge capacitance to earth or FRA measurements. Simple models are useful in some practical cases when high accuracy is not needed as it is recommended in IEC 60071:4 Standard [4]. For a more rigorous approach of calculating the transferred overvoltages, standard suggest to use more detailed models.

Models which represent a transformer from its terminals are called “Black box” models. The main advantage of these models is that they can be built from data obtained by measurements conducted only on the transformer terminals. Since the geometry data of the transformer is not used for building these models, they can only be applicable to analyze the interactions between a transformer and the network. These models are widely used within power utility companies since they do not have transformer design data which is generally the property of transformer manufacturer.

Several measurement techniques can be used in order to establish “Black box” models. The adopted technique usually depends on the choice of the parameter which will be measured. Scattering (S) parameters, impedance (Z) parameters, admittance (Y) parameters and transfer function can be measured directly from the transformer terminals. To interact with an EMTP-like software, S and Z parameters are usually converted into Y parameters, as it is explained in [5]. Pure transfer function cannot usually be used directly in EMTP-like software programs, in time domain. Nevertheless, for the calculation of transmitted overvoltages in software programs like MATLAB the practice is to use transfer functions [6].

Depending on which parameter is measured, different apparatuses have to be used for measurement. For S parameters, a network analyzer should be used [7]. For Y and Z parameters measurement, both current sensor and network analyzer have to be used. For measurements of the transfer function of the transformer, equipment specified in the standard [8] has to be used. It is a standard test which is done in order to check the transformer condition.

Measurements are usually done with low voltage impulse due to equipment constraints. It does not have any effect on the accuracy of HF transformer model since there is no magnetic flux in the core and consequently the transformer is acting as a linear component. Therefore, transformers can be represented as a linear function of input voltage (except the non-linear core effects, i.e. magnetization of the core) for high frequency transient simulations.

Furthermore, four different approaches on how to make a model compatible with the EMTP-like programs from measurement results can be defined: approximation with the rational functions [2], [9]; direct construction of an equivalent network [3]; indirectly usage of the transfer function (i.e. in MATLAB) [6]; usage of modal analysis [10].

The most used approach is to approximate the admittance curves with rational functions. This approach is based on the method proposed by Levy in [11]. Recently, the method has been improved. An algorithm based on this method was implemented in MATLAB environment by Gustavsen [12], as an open source code, called “Vector fitting”.

As the final representation of a model in an EMTP-like software the following representations can be adopted: lumped parameters [13]; Norton equivalent (by using recursive convolution) [14]; state space representation [15].

Note that parameters which are obtained by using these methods are not physical and therefore cannot be calculated directly from transformer geometry.

Physical or “White box” models are mainly used for the calculation of the voltage distribution across the transformer windings during the transient occurrence. These models are very detailed and they are usually used by the transformer manufacturers since the knowledge of the transformer geometry is necessary. “White box” models have been in application for several decades as it can be seen from a bibliography survey on transformer design [16].

Models used by transformer manufacturers have to be very detailed and advanced since overvoltages of very high frequencies (tens of MHz) can occur inside the transformer windings, caused by reflections between different parts of the windings. Overvoltages of very high frequencies easily attenuate since losses inside a transformer increases with frequency and they do not always appear on the transformer terminals. Therefore, too detailed modelling is not necessary in the studies of transmitted overvoltages through a transformer. When modeling for transmitted transient studies it is suggested to model transformer just from the geometry of the transformer window, without detailed modeling of the transformer winding geometry. Nevertheless the knowledge obtained with these models can be used for the interpretation of the FRA measurements or for construction of less complex models [17].

Recently, some studies were done in the area of practical determination of the “Black box” transformer model from the terminal behavior of “White box” models [18], [19]. Hence, by simulating the terminal behavior of a “White box” model and gathering those data, a “Black box” can be constructed in EMTP-like software. The advantage of this approach is that the transformer manufacturer can provide utilities with a very accurate transformer model without providing the transformer geometry data.

Models which are ranging between “Black box” and “White box” models, should be classified as “Grey box”. These models can be used both for calculation of the voltage distribution along the windings of transformer and for calculation of the transferred overvoltages. The aim of the “Grey box” models is to obtain a physical model of the transformer from the data which can be provided by the transformer manufacturers.

There are two different approaches to construct these models. The first is based on building an equivalent network from the geometry of the transformer window and from measured capacitance inside the transformer, whose measurements can be requested during the transformer production process [20]. The second is based on deriving a model from the frequency response measurements, done on the transformer terminals. Model response can be approximated with mathematical functions as it is already explained before (“Black box” models) or with a circuit model with physical parameters [21], [22]. For estimation of the “Grey box” model parameters from frequency response measurement results literature [23] proposes an artificial neural network method.

THE “BLACK BOX” MODEL: PRINCIPLE

Since this paper is a part of a research which is being conducted with the support of a power utility company, it is oriented towards the interaction of the transformer with the power grid without requiring a strong knowledge of the detailed inner geometry construction of the transformer. Therefore, the “Black box” model based on state space equations is derived from the measurement of the scattering parameters as it is described in this section.

The scattering or S parameters represent the behavior of the waves which encounter a discontinuity during propagation along a line. Discontinuity means that the travelling wave encounters an impedance which differs from the characteristic impedance of the line. S matrix evaluates the relations between incident and reflected components of the waves as is it shown in the figure 1:

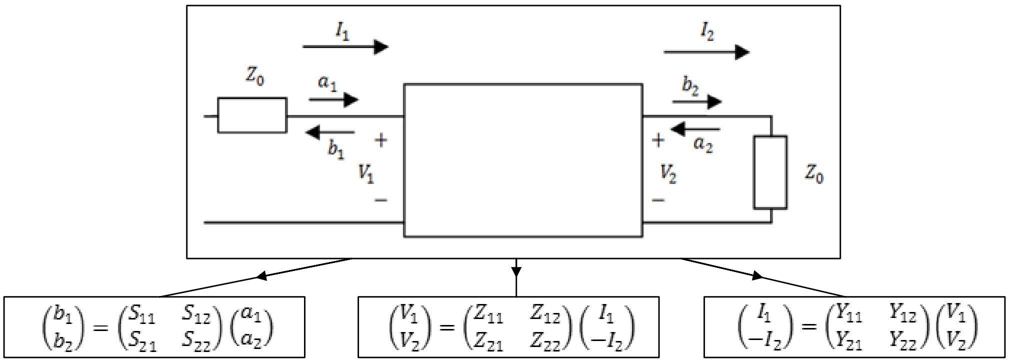

Figure 1: S, Z and Y parameters of a two port network.

Figure 1 shows a two port network connected to a load, whose impedance is equal to the impedance of the network analyzer Z_0. Let’s introduce also Z_{in} and $\mathrm{Z}_{\mathrm{out}}$ which are the characteristic impedances of the network from figure 1. Z_{in} is the impedance of the network observed from port 1 and $\mathrm{Z}_{\mathrm{out}}$ is the impendence of the network observed from the port 2.

The S parameters for the two port network can be derived from the equations shown in the figure 1, in which:
$\mathrm{b_1}$ – represents reflected wave of the $\mathrm{a_1}$ (between $\mathrm{Z_0}$ and $\mathrm{Z_{in}}$) and incident wave of the $\mathrm{a_2}$ (between $\mathrm{Z_0}$ and $\mathrm{Z_{out}}$);
$\mathrm{b_2}$ – represents incident wave of the $\mathrm{a_1}$ (between $\mathrm{Z_0}$ and $\mathrm{Z_{in}}$) and reflected wave of the $\mathrm{a_2}$ (between $\mathrm{Z_0}$ and $\mathrm{Z_{out}}$).

Impedance / admittance parameters of a two port network can be calculated from the S parameters by using the following expressions:

$$\mathrm{Z_{11}} = \left(\frac{(1+\mathrm{S_{11}})(1-\mathrm{S_{22}})+\mathrm{S_{12}S_{21}}}{\Delta_\mathrm{s}}\right)\mathrm{Z_0} \tag{1}$$

$$\mathrm{Z_{12}} = \left(\frac{2\mathrm{S_{12}}}{\Delta_\mathrm{s}}\right)\mathrm{Z_0} \tag{2}$$

$$\mathrm{Z_{21}} = \left(\frac{2\mathrm{S_{21}}}{\Delta_\mathrm{s}}\right)\mathrm{Z_0} \tag{3}$$

$$\mathrm{Z_{22}} = \left(\frac{(1-\mathrm{S_{11}})(1+\mathrm{S_{22}})+\mathrm{S_{12}S_{21}}}{\Delta_\mathrm{s}}\right)\mathrm{Z_0} \tag{4}$$

$$\Delta_\mathrm{s} = (1-\mathrm{S_{11}})(1-\mathrm{S_{22}})-\mathrm{S_{12}S_{21}} \tag{5}$$

These expressions are derived from the relations between voltage, current and a, b parameters for the two port network from the figure 1. The relations are provided in the appendix A.

While measuring S parameters from the transformer terminals, the terminals which are under the measurement are terminated by the 50 **Ω** termination (termination of the equipment). All other terminals, have to be open-circuited. The configuration for the measurement of the S parameters between terminals 1 and 4 of a transformer with 6 terminals is shown in the figure 2 below:

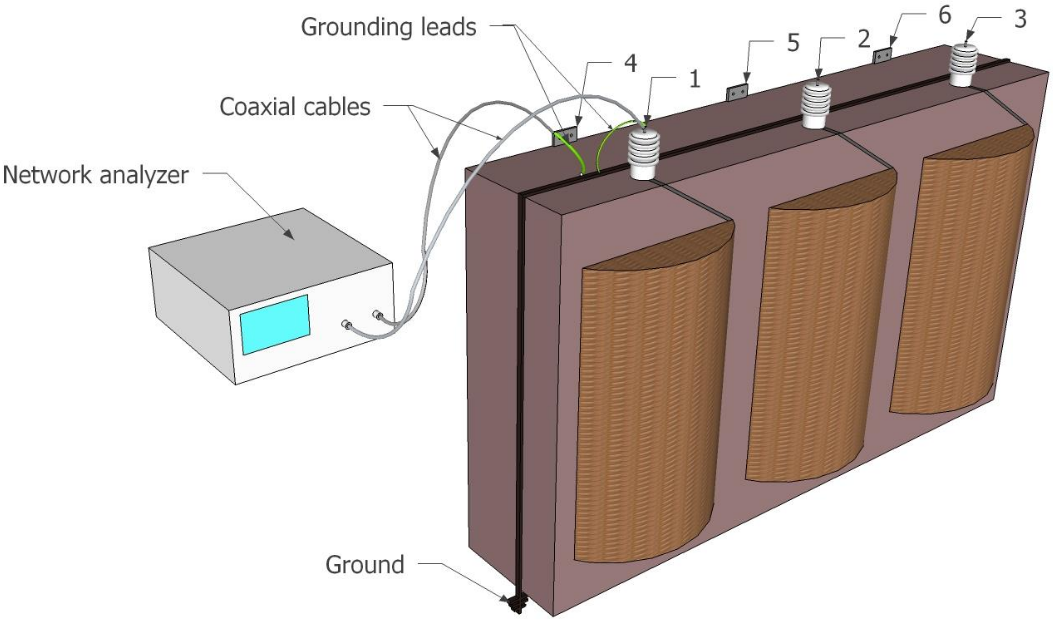

Figure 2: The configuration for the measurement of the S parameters between terminals 1 and 4 (grey cables are coaxial cables, green cables are earth connection of the coaxial cables shields, black line is representing ground).

If the transformer has the wye winding, during the measurement its neutral should be connected as it is usually connected on site. Note that the network analyzer from the figure 2 is capable to measure S parameters as a functions of frequency.

In accordance with the explained procedure for the two port network, from the S(f) parameters measured in the configuration which can be seen in figure 2, following Z(f) matrix elements can be derived:

$$\begin{pmatrix} Z_{11}(f) & Z_{14}(f) \\ Z_{41}(f) & Z_{44}(f) \end{pmatrix} \tag{6}$$

Since the used equipment for measuring is limited to only two ports measurements at once and transformer from the figure 2 has 6 terminals (3 phase, 2 windings), fifteen different measurements have to be done in order to evaluate the whole admittance / impedance matrix of the transformer:

$$\begin{pmatrix} Z_{11}(f) & \cdots & Z_{16}(f) \\ \vdots & \ddots & \vdots \\ Z_{61}(f) & \cdots & Z_{66}(f) \end{pmatrix} \tag{7}$$

Redundant measurements can be found for Z_{ii} element and can be used to control the coherency of values during the measurement. In order to check the Z matrix, some of its elements can be compared because Z matrix has to be a symmetrical matrix.

From Z(f) parameters, Y(f) parameters can be calculated by inverting Z matrices at each frequency:

$$\begin{pmatrix} Y_{11}(f) & \cdots & Y_{16}(f) \\ \vdots & \ddots & \vdots \\ Y_{61}(f) & \cdots & Y_{66}(f) \end{pmatrix} = \begin{pmatrix} Z_{11}(f) & \cdots & Z_{16}(f) \\ \vdots & \ddots & \vdots \\ Z_{61}(f) & \cdots & Z_{66}(f) \end{pmatrix}^{-1} \tag{8}$$

Finally, since the transformer model has to be built in EMTP-RV, The results of the measurement have to be prepared for the input in the computer software. This can be done by using the fitting method to approximate each admittance matrix element $Y_{ij}(f)$ with a rational expression [12], [24], [25] of the type given below:

$$Y_{ij}(s) \approx \sum_{n=1}^{N} \frac{c_{n,ij}}{s - a_{n,ij}} + d_{ij} + s * e_{ij} \tag{9}$$

In the equation (9) $a_{n,ij}$ represents the poles which can be either real or complex conjugated pair, $c_{n,ij}$ represents the residues which can also be either real or complex conjugated pair, d_{ij} and e_{ij} are the real values constant. s stands for $j2\pi f$ where f is frequency. N is number of poles used for approximation of each matrix element.

Rational functions have to be both stable and passive since the transformer is a passive component of the electric grid. Stability is obtained by keeping only the poles which are stable. Passivity is enforced by perturbation of the residues and constants values in order to match the passivity criterion [26]-[29]:

$$P = \mathrm{Re}\{v^{*} Y_{i,fit} v\} > 0 \tag{10}$$

This rational expression allows using state space equations as shown below:

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

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

Matrices A, B, C, D and E for state space representation with real elements can be input directly into the state space block in EMTP-RV. These matrices are obtained by using the values of poles and residues from rational functions and forming the function given below:

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

Expression (13) in which [I] is the identity matrix, can be obtained from equations (11) and (12). It represents the relation between the terminal currents and voltages of the transformer, suitable to represent the rational function given by expression (9).

If some of the matrices elements are complex (as they usually are, since some poles and residues can be complex), a transformation to real values can be done [28]. This transformation does not have any effect on the accuracy of the model.

State space representation is used to describe a linear network. Therefore, it can be used to represent a transformer, since transformer behavior is linear at high frequencies. The advantage of using these equations is the straightforward conversion from the frequency (measurements) to the time domain (EMTP-RV) without changing the values of the A, B, C, D and E matrices.

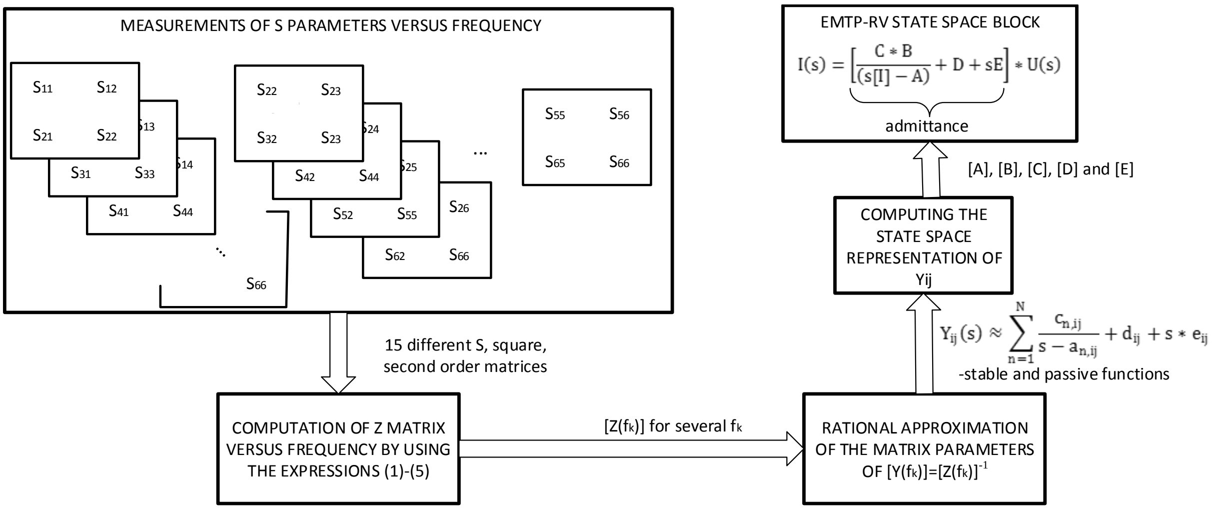

Figure 3: Procedure for deriving the "Black box" transformer model in EMTP-RV.

The complete procedure of building the “Black box” transformer model in EMTP-RV, from the S parameters measurement is shown in the figure 3 above. Note that the procedure given above is directly applicable for transformers with six terminals. Nevertheless, it can be easily adjusted for the representation of transformers with more terminals.

THE “BLACK BOX” MODEL: MEASUREMENTS AND CASE STUDY

Measurements were conducted on the 6,6/0,39 kV, 630 kVA, Dy11, dry-type, distribution transformer, using a network analyzer which can measure the scattering parameters of the two port network only. Therefore, to derive the admittance matrix of the transformer, fifteen different measurement sequences were conducted.

The frequency range used for the measurement was from 10 kHz to 1 MHz. Lower frequency border is determined with the network analyzer frequency range and therefore it can be extended if another network analyzer is used. Upper frequency border is determined with the length of the measurement leads which are used for the measurements. It can be extended by using a flat braid as short as possible, as an earth connections (green connectors from the figure 2), instead of cables [30]. The measurements frequency should not exceed the quarter wave resonance frequency of the measurement cables [3]. [8], standard for frequency response measurements, suggests that results are effected by the measurement set-up above 1 MHz (for >72,5 kV) or above 2 MHz (≤72,5 kV) due to the length of the HV bushings.

One of the Y matrix parameters curve of the transformer, calculated from the measurements results, is shown in the figure 4. Comparison between rational function obtained from MATLAB and its representation in the "Black box" model in EMTP-RV can be seen.

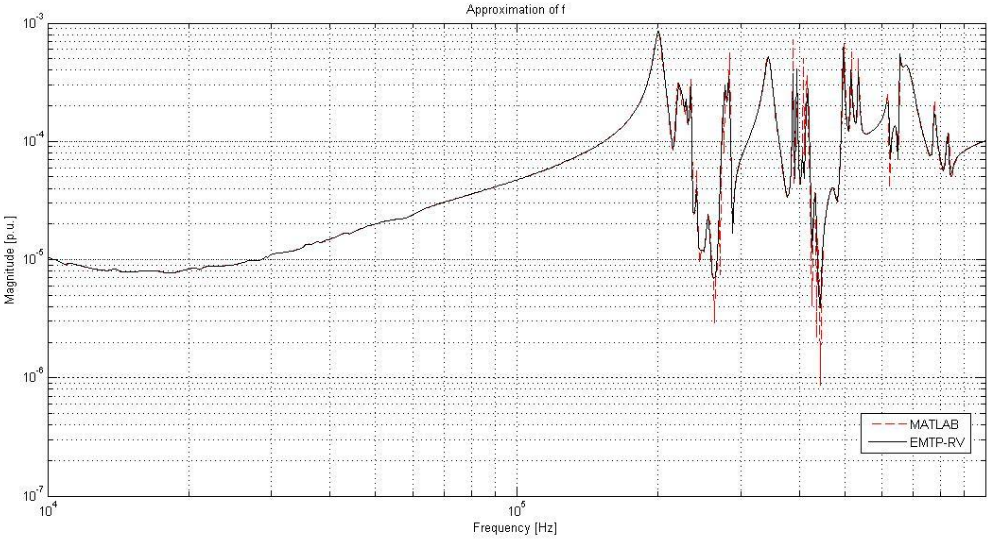

Figure 4: Amplitude of $Y_{11}(f)$ curve calculated in EMTP-RV (black) and approximated in MATLAB.

The good correlation between both curves shows that the state space equation block from EMTP-RV is capable to represents the transformer behavior.

In order to test the model, a case study for the lightning impulse test on a phase A of the HV side of the measured transformer is prepared in EMTP-RV. The lightning impulse 1,2/50 µs is simulated as:

- An ideal lightning impulse by using the point to point voltage source;
- A lightning impulse produced from a lightning impulse generator, as it is explained in standard IEC 60076-4 [31].

The configurations of both test circuits are shown in the figure 5.

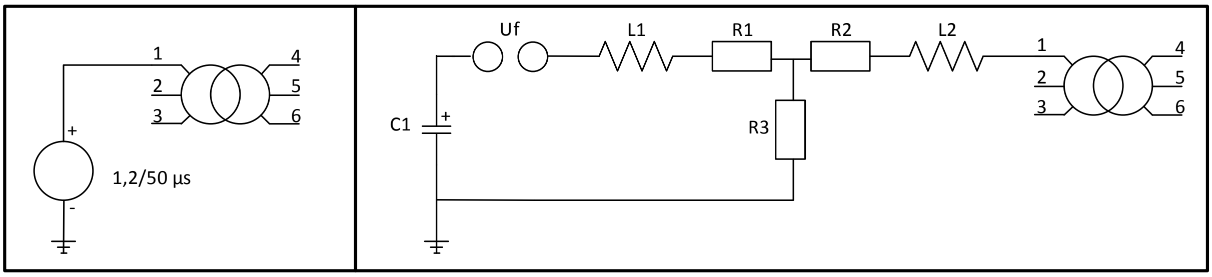

Figure 5: Example case configurations for lightning strike; an ideal lightning impulse (left) and a lightning impulse produced by an impulse generator (right).

A view of the example case configurations in the EMTP-RV is shown in appendix B. A distribution transformer is represented by the state space block in EMTP-RV, using the real measurement data and its rational approximation, in order to form the data file ready for input in EMTP-RV. The transformer is without any load and in open circuit condition.

In order to describe an 1,2/50 µs ideal lighting impulse for the point to point voltage impulse source, discrete points are calculated from the following expression [32]:

$$V(t) = A * V_p(1 - e^{-\frac{t}{T_1}})e^{-\frac{t}{T_2}} \tag{14}$$

, where: $A = 1{,}037$; $T_1 = 0{,}4074\ \mu s$; $T_2 = 68{,}22\ \mu s$; $V_p = 60\ kV$.

The lightning impulse generator equivalent circuit consists of: a polarized capacitor (C1=150 nF), a spark gap with a flashover voltage Uf=85,81 kV, the inductance of the generator itself, resistors and the leads (L1=L2=20 µF), serial resistances (R1=50 Ω and R2=750 Ω) and a parallel resistance (R3=3 kΩ). Parameters values are chosen to be in accordance with the real generators as it can be seen from literature [33].
The amplitude of the lightning impulse is set to 60 kV. Referring to the IEC standard 60076-3 [34], for 6,6 kV nominal voltage there is no test voltage level specified. Therefore, the voltage amplitude is chosen to be the same as for 7,2 kV nominal voltage. However, the lightning impulse amplitude has no further effects on the transmitted overvoltages amplitudes since the transformer is represented as a linear component.

Voltage is considered at each transformer terminal. In the figure 6, 7, 8 and 9 terminals voltages calculated by EMTP-RV are shown separately for both simulation circuits, first at the primary and then at the secondary side of the transformer. Voltages are calculated for the first 100 microseconds. Due to the coupling between phases, lightning impulse in phase A induces voltage in all three phases.

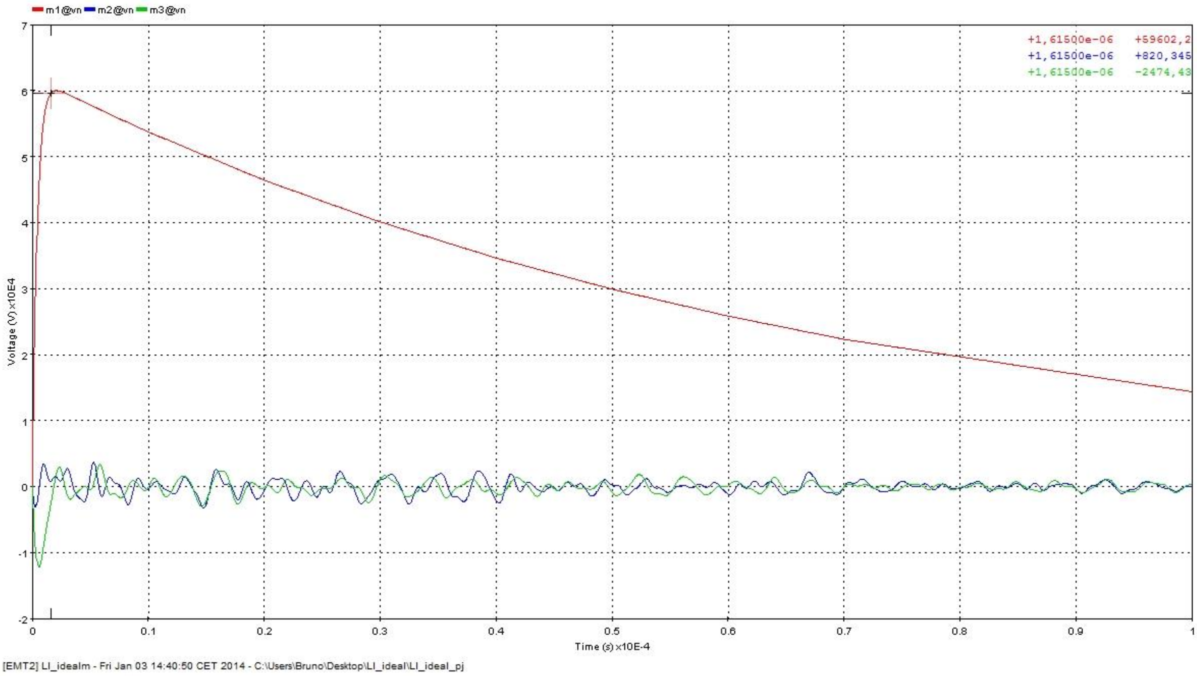

Figure 6: Voltage on the primary side of the transformer: phase A (red), phase B (blue), phase C (green) obtained from EMTP-RV simulation with the ideal lightning impulse.

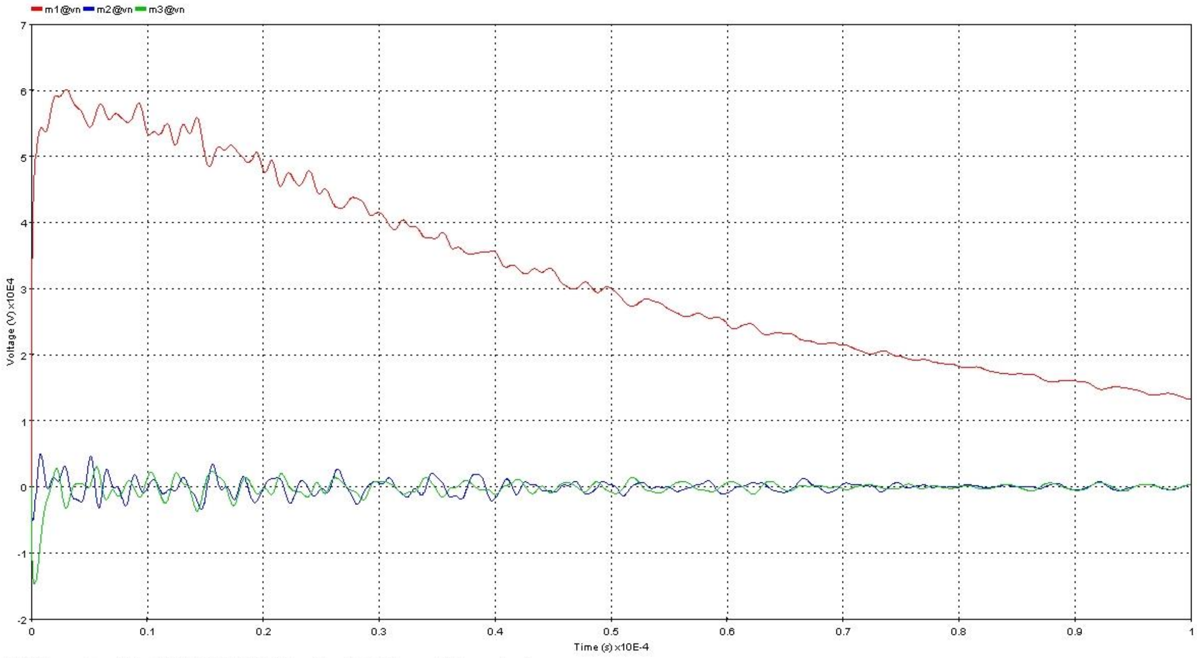

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Figure 7: Voltage on the primary side of the transformer: phase A (red), phase B (blue), phase C (green) obtained from EMTP-RV simulation with the lightning impulse produced by the impulse generator.

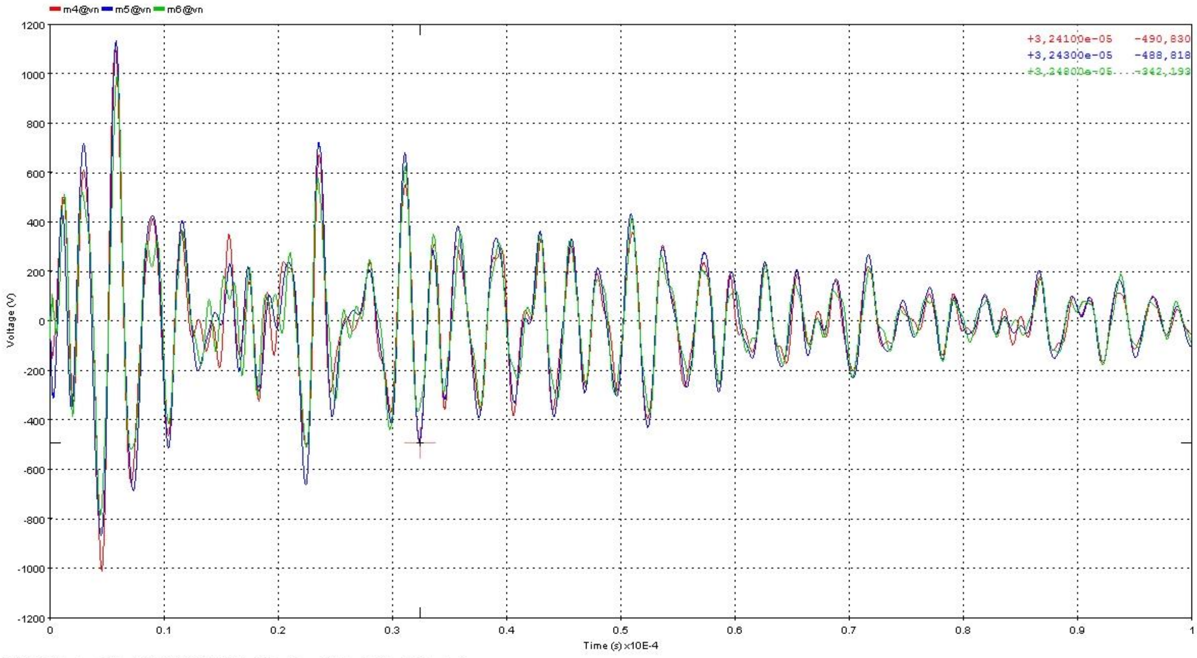

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Figure 8: Voltage on the secondary side of the transformer: phase A (red), phase B (blue), phase C (green) obtained from EMTP-RV simulation with the ideal lightning impulse.

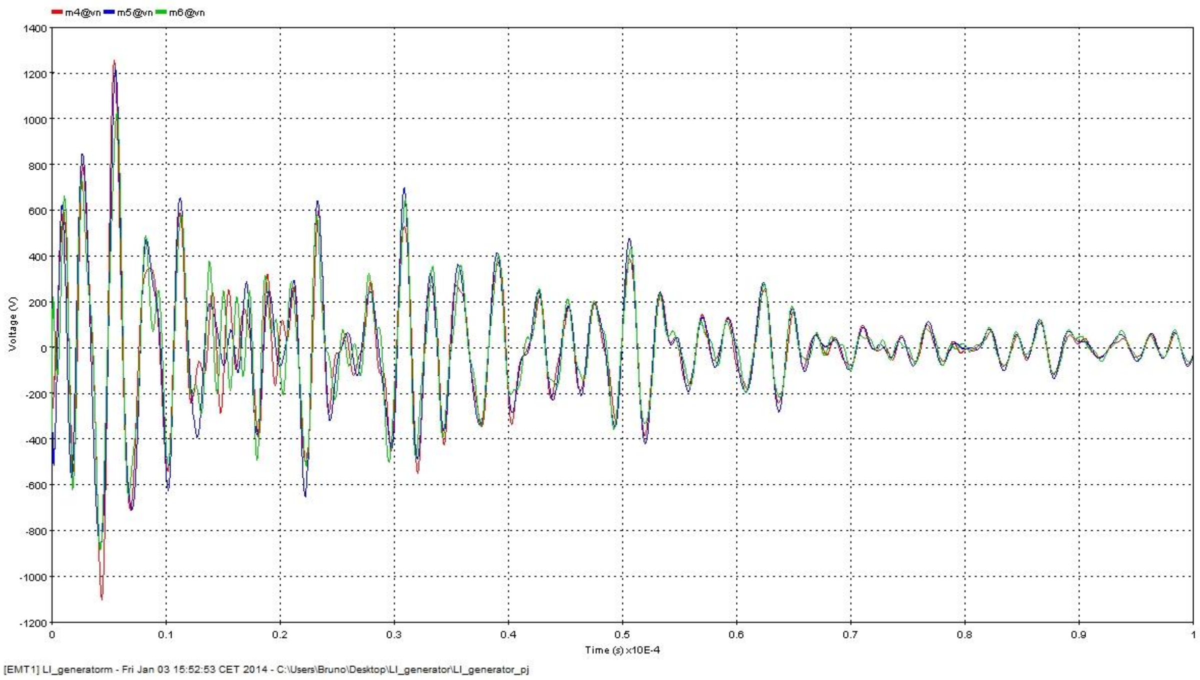

Figure 9: Voltage on the secondary side of the transformer: phase A (red), phase B (blue), phase C (green) obtained from EMTP-RV simulation with the lightning impulse produced by the impulse generator.

DISCUSSION

Frequency components of the overvoltages which are not a part of the frequency range for which the transformer model is established ($10\,\text{kHz} - 1\,\text{MHz}$) are not represented as they should be. It is the reason why the voltage at the phase A transmitted on the secondary side of the transformer is not represented for low frequency.

Overvoltages amplitudes are attenuating since all the losses which occurs inside the transformer are taken into account in the model (i.e. eddy current, proximity effect, dielectric losses). The amplitude (in per unit) of some frequency components of the overvoltages are amplified on the secondary side of the transformer. That can cause damage to the components connected to this side of the transformer and therefore high frequency transformer behavior needs to be studied in details.

As it can be seen from the simulation results, in a case with the lightning impulse produced by the impulse generator, some additional signals are added to the 1,2/50 μs lightning impulse, which cause some voltages to have higher amplitude than the simulation with the ideal lightning impulse. This is due to changes in the frequency spectrum of the input impulse signal caused by the signal reflections between the transformer and the impulse generator.

The second effect which can be seen from the figures is that the damping of the voltages is higher in the case with the lightning impulse produced by the impulse generator. Since the losses in the transformer are taken into account in both cases, this is due to the losses inside the impulse generator and the interaction between the impulse generator circuit and the transformer.

Note also that because of the losses inside the impulse generator the flashover voltage of the spark gap has to be higher than the amplitude of the lightning impulse which occurs on the terminal of the transformer. Therefore, the capacitor of the impulse generator has to be charged to reach a voltage higher or equal to the flashover voltage of the spark gap.

CONCLUSION

This paper has shown a procedure to establish a high frequency transformer model compatible with EMTP-RV. It is based on S parameters' measurements, which have to be done in accordance with the recommendations given in the IEC Standard 60076-18 and the use of the state-space model of EMTP-RV.

The downside of the developed model is that the relation between the model and the physical components of the transformer is not identified yet. Accordingly, the model cannot be constructed or verified directly from the measured electrical values of the transformer, such as capacitance between the windings, between windings and the ground, inductance of the windings, etc.

Therefore, the aim of the further research on high frequency transformer modeling is to develop a physical model of the transformer for high frequency and to identify the minimum level of knowledge on the geometry inside of the transformer, required to get a precise enough model. This approach is in agreement with current exchanges within the CIGRE. The research will consist of defining rules to represent the transformer as simply as possible, but also in an efficient way. Indeed, it will be necessary to take into account the variation versus frequency of the system's parameters, and consequently the inherent physical phenomena (skin and proximity effects). One major issue of the researches will be to identify the dominant parameters (resonances, stray capacitances) of the model. It should be pointed out that most of the studies which were conducted up to now have led to the development of models either extremely complex, or with a narrow frequency range.

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APPENDIX A

The relations between voltage, current and a, b parameters of the two port network shown in the figure 1, are provided below:

$$V_1 = a_1 + b_1 \tag{A.1}$$

$$V_2 = a_2 + b_2 \tag{A.2}$$

$$I_1 = \frac{a_1 - b_1}{Z_0} \tag{A.3}$$

$$I_2 = \frac{b_2 - a_2}{Z_0} \tag{A.4}$$

APPENDIX B

Example case configurations in the EMTP-RV are shown in the figure 10, below:

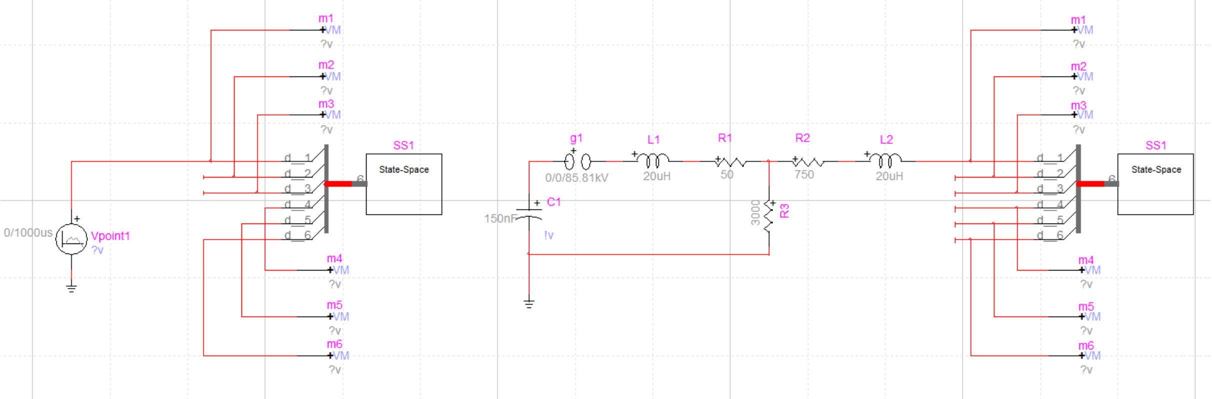

Figure 10: Example case configurations for lightning strike in EMTP-RV; an ideal lightning impulse (left) and an lightning impulse produced by impulse generator (right).

As it can be seen from the figure 10, the transformer in EMTP-RV is represented with the state space block which already exists in the EMTP-RV standard library.