Application of wide band transformer models

Bruno Jurisic, Paul Poujade, Alain Xemard, Ivo Uglesic, Françoise Paladian

***Abstract*- The existing wide band transformer models are often too complex or they require confidential information on transformer geometry. Therefore, in this paper two state of the art wide band transformer models derived from accessible information to the transformer purchaser are described: a Black Box model based on sweep frequency response analyser (SFRA) measurements of the transformer's admittance matrix and a Grey Box model based on a finite elements method (FEM) calculation, derived from limited information about the transformer geometry. Furthermore, an application of these transformer models aiming at questioning the measurements performed when purchasing a transformer such as lightning surges transfer and SFRA measurement is presented.**

***Keywords*: Transformer, Black Box, Grey Box, modelling, measurements, wide band, SFRA, FEM, EMTP, rational approximation.**

I. INTRODUCTION

Modelling transformers electromagnetic behaviour during fast front transients' events can often be a critical task. Due to their complex design, transformers can experience resonances along their windings during such events. Nowadays, advanced transformer models exist which are capable of representing transformer's behaviour over a wide frequency band. Unfortunately, many of them are quite complex and not suitable to question the measurements performed when purchasing a transformer, especially for the engineers of the power utilities.

In this paper two wide band transformer models are described [1]: a Black Box model based on sweep frequency response analyser (SFRA) measurements of the transformer's admittance matrix and a Grey Box model based on a finite elements method (FEM) calculation, derived from limited information about the transformer geometry. These models can be constructed from the measurements done with standard high voltage laboratory equipment [2] or from the geometry data accessible to the power utility.

Both models have to be compatible with an EMTP-like software package in order to study the electromagnetic transients in the time domain. The Grey Box model is implemented as a segmented *RLCG* network with frequency dependent parameters [3] forming a frequency dependent admittance matrix similar to the measured one from the Black Box model. To use these models in EMTP-RV, the inclusion of the nodal, frequency dependent admittance matrices is done by using the state space equations. Prior to the construction of the state space equations, the models' measured (in the case of the Black Box model) or calculated (in the case of the Grey Box model) admittance matrix should be fitted with the passive rational expression. The fitting and passivity enforcements are difficult tasks and can be the cause of the models' inaccuracy [4].

An application of these transformer models, in order to question the measurements performed when purchasing a transformer, is presented in the paper. Models' responses are compared with the measurement results of lightning surges transferred from the transformer's HV winding to LV winding and the transformer's frequency response field measurements made on the *64* MVA, *24/6.8/6.8* kV, *YNd11d11* power transformer unit.

Since the models are built primarily to simulate voltage and current at external transformer terminals, the efforts have been focused on the evaluation of transmitted overvoltages wave shapes during the lightning impulses applied to multiple line terminals simultaneously.

II. WIDE BAND TRANSFORMER MODELS

In this section the two wide band transformer models are described [1]: a Black Box model based on SFRA measurements of the transformer's admittance matrix and a Grey Box model based on a FEM calculation, derived from limited information about the transformer geometry.

A. Black Box model

Transformer models that can be classified as Black Box models are usually based on the fitting of the measured frequency dependent admittance matrix of the transformer and can be determined without any prior knowledge on the transformer geometry. Therefore, they can only be applicable to evaluate external overvoltages, in order to analyse the interactions between a transformer and the network and to study the insulation coordination [4]–[14].

For the purpose of this paper, a Black Box model is calculated from the measurements conducted with the SFRA measuring equipment. This is a standard equipment for measuring the frequency response of a transformer as suggested in the IEC 60076-18 Standard [2]. The measurement procedure is similar to the one described in [7]. A frequency response analyzer, is capable of measuring the ratio (*H*) between the input (V_{in}) and the output (V_{out}) voltages:

B. Jurisic and I. Uglesic are with University of Zagreb, Faculty of Electrical Engineering and Computing, 10000 Zagreb, Croatia (e-mail of corresponding author: bruno.jurisic@fer.hr; e-mail: ivo.uglesic@fer.hr).

P. Poujade and A. Xemard are with Électricité de France R&D, 91120 Palaiseau, France (e-mail: paul.poujade@edf.fr; alain.xemard@edf.fr).

F. Paladian is with Clermont Université, Université Blaise Pascal, Institut Pascal, 63177 Aubiere, France (e-mail: francoise.paladian@lasmea.univ-bpclermont.fr).

Paper submitted to the International Conference on Power Systems Transients (IPST2017) in Seoul, Republic of Korea June 26-29, 2017

$$H(f)=\frac{V_{out}(f)}{V_{in}(f)} \tag{1}$$

In (1) f stands for the frequency. Note that the measurements are done at discrete frequency points. Since the SFRA measurement's equipment is not normally used for measuring Y matrix, a specific procedure for measuring is established. The measuring method stems from the following expression:

$$\begin{pmatrix} I_1(f) \\ I_2(f) \\ \vdots \\ I_{N-1}(f) \\ I_N(f) \end{pmatrix} = \begin{pmatrix} Y_{11}(f) & \cdots & Y_{1N}(f) \\ \vdots & \ddots & \vdots \\ Y_{N1}(f) & \cdots & Y_{NN}(f) \end{pmatrix} \begin{pmatrix} U_1(f) \\ U_2(f) \\ \vdots \\ U_{N-1}(f) \\ U_N(f) \end{pmatrix} \tag{2}$$

Expression (2) is valid for a core-type transformer with N terminals. The measuring procedure includes $N*(N+1)/2$ measurements as it is shown in [4] and [5]. The number of measurements can be significantly reduced in the case of shell-type or three single-phase transformers when the admittance matrix has to be measured for only one phase [15]. Note that the measuring methods differ for off-diagonal and diagonal matrix elements. As a results of the measurements one can calculate the transformer frequency dependent admittance matrix, ***Y(f)***.

B. Grey Box model

Transformer models that can be classified as Grey Box models are usually derived from limited information about the transformer geometry. In this section the concept of the Grey Box model presented in [1] is explained.

It is based on a lumped *RLCG* equivalent network and a segmentation of the transformer geometry. Similar models can be found in [3], [16], [17]. 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) 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.

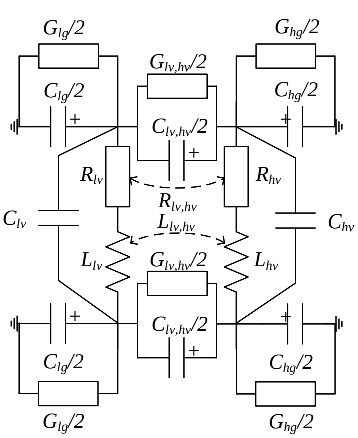

Fig. 1. RLCG network for one phase of a two winding transformer.

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.

Since the model is intended to be used for lightning studies for which the overvoltages have most of their energy stored in the range from tens of kHz up to hundreds of kHz, 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 [18]). Another possibility would be to use analytical expressions. However, it is not always possible to derive analytical expressions for complex structures such as the 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 is implemented. In that way the magnetics FEM problems can be solved more efficiently [18]–[21], which makes the calculation time compatible with the one of an engineering study.

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 [1]. The contribution due to the skin depth has to be added afterwards using analytical formulas [1].

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 the linear approximation of

Buckow's experimental results [22] already used for transformer modelling in [1], [3], [23].

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:

$$\boldsymbol{Z}_{\boldsymbol{RLbranch}}(f) = \boldsymbol{R}(f) + j\omega \boldsymbol{L}(f) \qquad (3)$$

$$\boldsymbol{Y}_{\boldsymbol{CGnodal}}(f) = \boldsymbol{G}(f) + j\omega \boldsymbol{C} \qquad (4)$$

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:

$$\boldsymbol{Y}_{\boldsymbol{RLnodal}}(f) = \boldsymbol{A} * \boldsymbol{Z}_{\boldsymbol{RLbranch}}(f)^{-1} * \boldsymbol{A}^{T} \qquad (5)$$

$\boldsymbol{A}$ is the incidence matrix which contains the relations between the inductive branch currents and the nodal currents [1]. 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:

$$\boldsymbol{Y}_{\boldsymbol{nodal}}(f) = \boldsymbol{Y}_{\boldsymbol{RLnodal}}(f) + \boldsymbol{Y}_{\boldsymbol{CGnodal}}(f) \qquad (6)$$

III. Inclusion of the Model in EMTP-RV

To include the frequency dependent nodal admittance matrix of the Black Box model, $\boldsymbol{Y}(f)$ or the Grey Box model, $\boldsymbol{Y}_{nodal}(f)$ in the EMTP-RV software program, the procedure shown in Fig. 2 is used. It consists of fitting the admittance matrix coefficients using the 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 [24]–[28].

The fitting of the admittance matrix element $Y_{ij}(f)$ is done using a rational expression [12], [29], [30] of the type given below:

$$Y_{ij}(s) \approx Y_{ij,fit}(s) = \sum_{n=1}^{Np} \frac{c_{n,ij}}{s - a_{n,ij}} + d_{ij} \qquad (7)$$

In (7) $a_{n,ij}$ represents the poles which can be either a real or complex conjugated pair, $c_{n,ij}$ represents the residues which can also be either a real or 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 $\boldsymbol{Y}(f)$ or $\boldsymbol{Y}_{nodal}(f)$ should be rewritten to form a function of variable s, $\boldsymbol{Y}(s)$ instead of f.

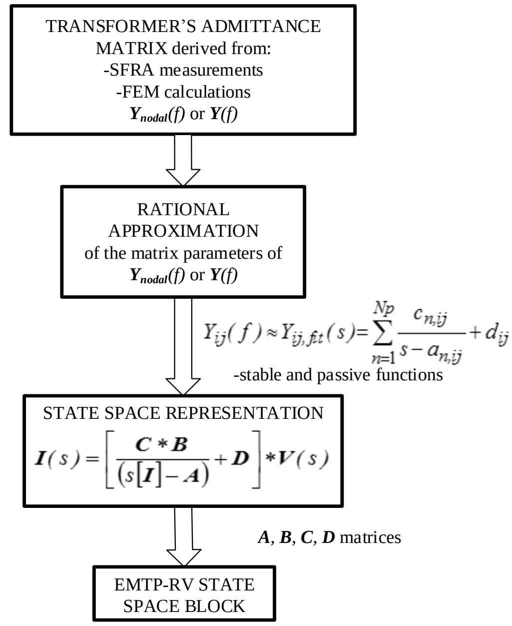

Fig. 2. Procedure for inputting transformer models with frequency dependent parameters in EMTP-RV.

The rational functions have to be both 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 [12], [26], [31]–[36]:

$$\boldsymbol{P} = Re\left\{\boldsymbol{u}^{*} \boldsymbol{Y}_{\boldsymbol{fit}}(s) \boldsymbol{u}\right\} > 0 \qquad (8)$$

In (8), $\boldsymbol{Y}_{fit}(s)$ represents the matrix of the fitted rational functions. Expression (8) 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:

$$eig(Re(\boldsymbol{Y}_{\boldsymbol{fit}}(s))) > 0 \qquad (9)$$

The rational expression (7) enables the use of the state space equations as shown below:

$$s\boldsymbol{X}(s) = \boldsymbol{A} * \boldsymbol{X}(s) + \boldsymbol{B} * \boldsymbol{U}(s) \qquad (10)$$

$$\boldsymbol{I}(s) = \boldsymbol{C} * \boldsymbol{X}(s) + \boldsymbol{D} * \boldsymbol{U}(s) \qquad (11)$$

The matrices $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, and $\boldsymbol{D}$ 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 (7) to form the function given below:

$$\boldsymbol{I}(s) = \boldsymbol{Y}(s) * \boldsymbol{U}(s) = \left[\frac{\boldsymbol{C} * \boldsymbol{B}}{(s[\boldsymbol{I}] - \boldsymbol{A})} + \boldsymbol{D}\right] * \boldsymbol{U}(s) \qquad (12)$$

Expression (12), in which [$\boldsymbol{I}$] is the identity matrix, can be obtained from equations (10) and (11). It represents the relationship between the terminal currents and the voltages of the transformer, suitable to represent the rational functions given by expression (7). 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.

IV. Application of the Wide Band Transformer Models, Comparison of Their Results with Field Measurements

In this section two applications of the wide band transformer models are described. The intention of both applications is to question the measurements results of standard transformer tests done in a high voltage laboratory: lighting impulse test measurements and SFRA measurements.

A. Lightning impulse test measurements

In this section the results of the evaluation of transmitted overvoltages wave shapes during a lightning impulse test are given. The power transformer under study is a *64* MVA, *24/6.8/6.8* kV, *YNd11d11* unit.

The measurement test set-up is shown schematically in Fig. 3.

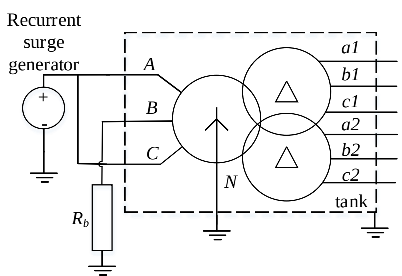

Fig. 3. Measurement test set-up for lightning impulse test.

In Fig. 3, R_b stands for the grounding resistance of the phase B (*400* Ω). A lightning impulse *1.2* µs (±*30*%) / *50* µs (±*20*%), according to the IEC 60060-1 standard [37], is generated with a recurrent surge generator. The amplitude of the applied signal is around *300* V. The lightning impulses are applied simultaneously to multiple line terminals *A* and *C*. The transmitted overvoltages are measured at all the low voltage terminals *a1, b1, c1, a2, b2, c2*.

The measurements set up is simulated in EMTP-RV using both presented wide band transformer models: the Black Box and the Grey Box. The Black Box model, is built from the measured admittance matrix elements for the frequency range from *15-500* kHz. The Grey Box model, is built from the geometry data of the transformer by using the FEM calculations. The transformer geometry is segmented in *38* segments (each LV winding to *6* segments, HV winding to *24* segments and regulatory winding to *2* segments. The model's parameters are calculated for the frequency range from *1-1000* kHz. Measurement cables were not modelled in EMTP-RV.

The comparison between the measurements results and the simulation are given in Fig. 4 and Fig. 5, for the configuration from Fig. 3. It can be seen that both models are very accurate.

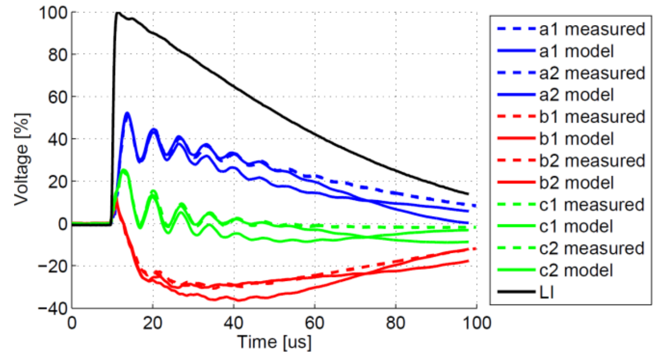

Fig. 4. Comparison of the Black Box simulation results with the measurements.

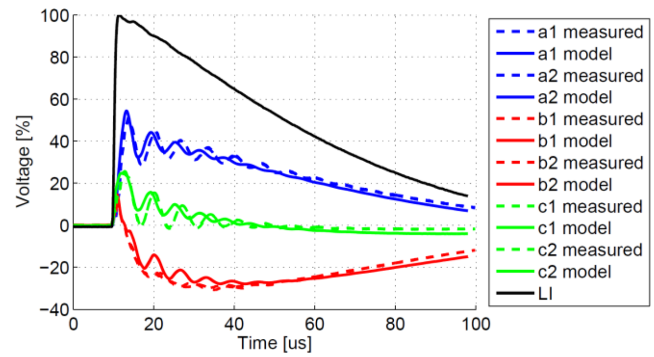

Fig. 5. Comparison of the Grey Box simulation results with the measurements.

B. Frequency response field measurements

In this section the results of the comparison of the model response with the field measurements results of sweep frequency response measurements (SFRA) are given. The transformer unit under study is the same as the one described in the previous section.

The SFRA measurements are conducted for two different configurations: end-to-end *B-N* measurements; end-to-end short circuit *B-N* measurements with *LV2* winding short circuited. In end-to-end measurements the source and the reference leads are connected to one side of the phase winding while the response lead is connected to the other side of the same winding and all the other terminals are open circuited. As an example, the measurement configuration for the end-to-end measurement *B-N* is shown in Fig. 6.

During the SFRA measurements, the tank of the transformer is grounded using a straight braid as indicated in the IEC 60076-18 Standard [2]. In the configuration from Fig. 6, V_{in} is measured at terminal *B*, V_{out} is measured at terminal *N* and all the other terminals are left open circuited. *R* stands for the matching resistance of the frequency network analyser which is equal to *50* Ω. The frequency response analyser measures the ratio *H* between the response signal and the input signal, see (1). The equipment uses only two coaxial cables since the source and the reference terminals share the same cable. The coaxial cables which were used for the measurements are standard *18* m long cables with fixed earth connection (used for grounding the coaxial cables shield). For end-to-end short circuit measurements, it is required to short circuit the other winding of the same phase, as mentioned in the IEC 60076-18 Standard [2]. In the case of the *64* MVA, *24/6.8/6.8* kV, *YNd11d11* transformer unit the *LV2* winding is short circuited during the end-to-end short circuit *B-N* measurements.

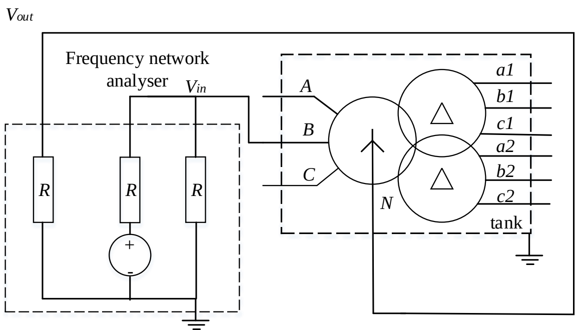

Fig. 6. Measurement configuration for the end-to-end measurements *B-N*.

The measurements set ups are simulated in EMTP-RV using both presented wide band transformer models: the Black Box and Grey Box. The frequency response analyser is modelled together with its matching resistances. The measurement cables were not modelled in EMTP-RV since their influence can be neglected for the SFRA measurements up to *1* MHz due to the perfect cables termination and shielding as reported in [7].

In Fig. 7-Fig. 10, comparisons between the SFRA measurements and the simulation results in terms of amplitude and phase of the voltage ratio (see equation (1)) are given for the two cases observed in the scope of this document.

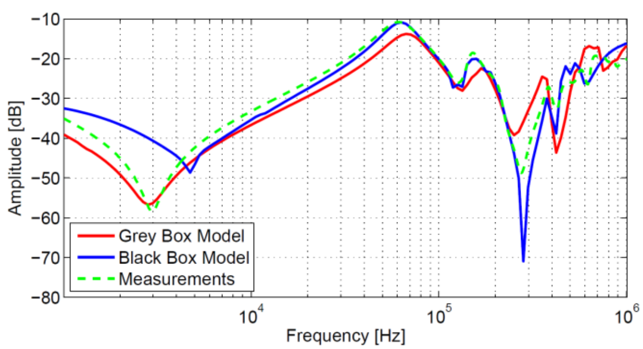

Fig. 7. Comparison of the Grey Box and Black Box simulation results with end-to-end *B-N* measurements (amplitude).

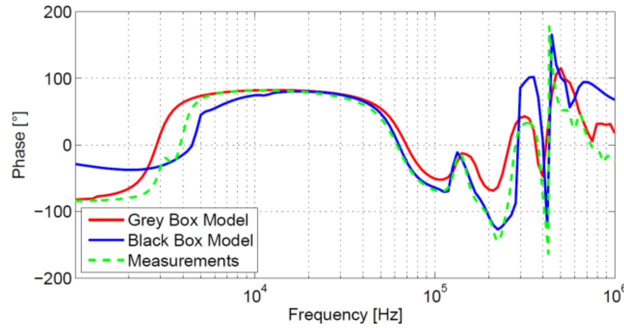

Fig. 8. Comparison of the Grey Box and Black Box simulation results with end-to-end *B-N* measurements (phase).

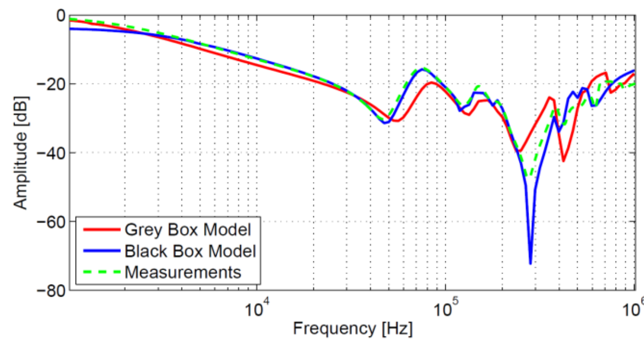

Fig. 9. Comparison of the Grey Box and Black Box simulation results with end-to-end short circuit *B-N* measurements with *LV2* winding short circuited (amplitude).

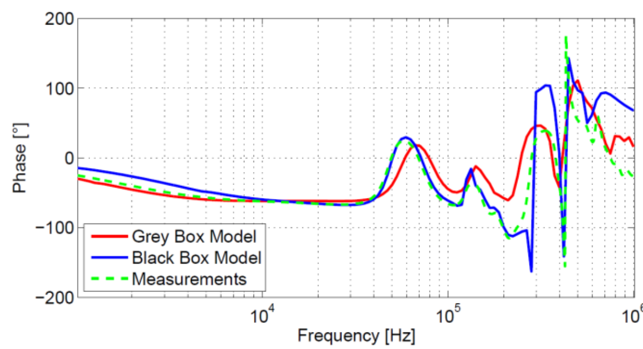

Fig. 10. Comparison of the Grey Box and Black Box simulation results with end-to-end short circuit *B-N* measurements with *LV2* winding short circuited (phase).

From the comparison of the frequency responses, given in Fig. 7-Fig. 10, it can be seen that the models are accurate only for a part of the observed frequency range (from *5* kHz up to *200* kHz). The difference between the models and the measurements could be caused by the errors introduced in the models during the fitting, or due to non-representing the measurements cables in the simulations or the non-linear transformer behaviour at lower frequencies in open circuit conditions, which the models are not intended to represent.

V. Discussion

When observing the comparison between the measurements and the simulations, it can be seen that both presented models can accurately describe transformer electromagnetic behaviour for the transmitted overvoltages and SFRA measurements. However, when it comes to an estimation of the higher frequency components of the transmitted overvoltages or SFRA measurements it is advisable to use the Black Box model while when estimating the lower frequency components it is advisable to use the Grey Box model. That guideline is in accordance with the theory of the models.

A transformer acts nonlinearly versus voltage/current at lower frequencies due to the behaviour of its magnetic core so it is difficult to measure the frequency response of the transformer at these frequencies using the SFRA equipment. Consequently, it is not possible to represent the behaviour of a transformer for the open terminal conditions at low frequency with the Black Box model, which is based exclusively on these measurements.

On the contrary, as the frequency band becomes wider, the geometry of a transformer needs to be segmented in more segments if one wants to represent a transformer with the lumped *RLCG* network. As the Grey Box model is based on this principle, the amount of the geometry details that have effect on the transformer behaviour rise with frequency. This explains why this model becomes less accurate at higher frequencies, as shown in Fig. 7-Fig. 10.

The boundaries of the frequency ranges for which the models will be accurate depends on the transformer's size as well as on its design. It is hard to find a general answer about the frequency range for which the models will be valid. The method used by the authors is to cut the model's geometry so that the biggest wire length is at least ten times smaller than the shortest wavelength of the applied signal for which the model is intended to be used [1].

VI. Conclusions

In this paper two state of the art wide band transformer models are presented. The first one, a Black Box model, is based on sweep frequency response analyser (SFRA) measurements of the transformer's admittance matrix. The second one, a Grey Box model, is based on a finite elements method (FEM) calculation, derived from limited information about the transformer geometry. The comparisons between the measurement results of the standard transformer tests done in high voltage laboratory (such as lighting impulse test and SFRA measurements) and the simulations have shown that both presented models can describe accurately a transformer electromagnetic behaviour over a wide frequency band. Therefore, these models can be used to question measurements results as long as their users are aware of their inherent limitations such as the SFRA measurements accuracy at high frequencies (when constructing the presented Black Box model), the segment length and the amount of details taken into account (when constructing the presented Grey Box model) or linearity of state space representation and fitting accuracy when building both models. These limitations can vary depending on the size and the design of each transformer.

VII. Acknowledgment

The authors express their thanks to Siemens Končar Power Transformers for providing the measurement results which were used for the development and validation of the models presented in this paper.

This work has been supported in part by the Croatian Science Foundation under the project "Development of advanced high voltage systems by application of new information and communication technologies" (DAHVAT).

VIII. References

[1] B. Jurisic, "Methods for Calculations of High Frequency Transmitted Overvoltages through a Power Transformer," Ph.D. dissertation, University of Zagreb, University Blaise Pascal, 2016.

[2] International Electrotechnical Commission, *IEC 60076-18 Power Transformers – Part 18: Measurement of Frequency Response*. 2012.

[3] E. Bjerkan, "High Frequency Modeling of Power Transformers," Ph.D. dissertation, Norwegian University of Science and Technology, 2005.

[4] B. Jurisic, I. Uglesic, A. Xemard, and F. Paladian, "Difficulties in High Frequency Transformer Modelling," *Electric Power Systems Research*, vol. 138, no. Special Issue: 11th International Conference on Power Systems Transients (IPST), pp. 25–32, 2016.

[5] B. Jurisic, A. Xemard, I. Uglešić, F. Paladian, and P. Guuinic, "Case Study on Transformer Models for Calculation of High Frequency Transmitted Overvoltages," in *3rd International Colloquium Transformer Research and Asset Management.*, 2014, pp. 1–10.

[6] B. Jurisic, A. Xemard, I. Uglesic, and F. Paladian, "High Frequency Transformer Model for Calculations of Transferred Overvoltages," *CIGRE International Colloquium on Lightning and Power Systems*, pp. 1–15, 2014.

[7] A. Holdyk, B. Gustavsen, I. Arana, J. Holboell, and S. Member, "Wideband Modeling of Power Transformers Using Commercial sFRA Equipment," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1–8, 2014.

[8] D. Filipovic-Grcic, B. Filipovic-Grcic, and I. Uglesic, "High-Frequency Model of the Power Transformer Based on Frequency-Response Measurements," *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 34–42, 2015.

[9] R. Caldecott, Y. Liu, S. A. Sebo, D. G. Kasten, and S. E. Wright, "Measurement of the Frequency Dependent Impedance of Major Station Equipment," *IEEE Transactions on Power Delivery*, vol. 5, no. 1. pp. 474–480, 1990.

[10] Y. Liu, S. A. Sebo, R. Caldecott, D. G. Kasten, and S. E. Wright, "Modeling of Converter Transformers using Frequency Domain Terminal Impedance Measurements," *IEEE Transactions on Power Delivery*, vol. 8, no. 1. pp. 66–72, 1993.

[11] X. Legrand, A. Xemard, C. A. Nucci, and P. Auriol, "A Method to Interface Electromagnetic Models of Grounding Systems with Transients Programs," in *CIGRE C4 Colloquium on Power Quality and Lightning*, 2012.

[12] Z. Ye, Y. Li, M. Gao, and Z. Yu, "A Novel Framework for Passive Macro-Modeling," *ACM/IEEE 48th Design Automation Conference (DAC-2011)*, pp. 546–551, 2011.

[13] B. Jurisic, "High Frequency Transformer Model for Calculations of Transferred Overvoltages," M.Sc. Thesis, University of Zagreb, 2013.

[14] B. Gustavsen and H. M. J. De Silva, "Inclusion of Rational Models in an Electromagnetic Transients Program: Y-Parameters, Z-Parameters, S-Parameters, Transfer Functions," *IEEE Transactions on Power Delivery*, vol. 28, no. 2. pp. 1164–1174, 2013.

[15] S. Chimklai and J. R. Marti (M), "Simplified Three-Phase Transformer Model for Electromagnetic Transient Studies," *IEEE Transactions on*

Power Delivery, vol. 10, no. 3, pp. 1316–1325, 1995.

[16] E. Bjerkan and H. K. Høidalen, "High Frequency FEM-Based Power Transformer Modeling: Investigation of Internal Stresses due to Network-Initiated Overvoltages," *Electric Power Systems Research*, vol. 77, no. 11, pp. 1483–1489, 2007.

[17] I. Uglešić and M. Lukic, "Calculating Lightning Overvoltages Transferred Through a Transformer," in *1998 International Conference on Lightning Protection (ICLP)*, 1998.

[18] M. David, *Finite Element Method Magnetics - User's Manual Version 4.2*. 2013.

[19] D. Meeker, "Continuum Representation of Wound Coils via an Equivalent Foil Approach," pp. 1–7, 2006.

[20] D. Meeker, "An Improved Continuum Skin and Proximity Effect Model for Hexagonally Packed Wires," *Journal of Computational and Applied Mathematics*, vol. 236, no. 18, pp. 4635–4644, 2012.

[21] O. Moreau, L. Popiel, and J. L. Pages, "Proximity Losses Computation with a 2D Complex Permeability Modelling," *IEEE Transactions on Magnetics*, vol. 34, no. 5, pp. 3612–3615, 1998.

[22] E. Buckow, "Berechnung des verhaltens von leistungs-transformatoren bei resonanzanregung und möglichkeiten des abbaus innerer spannungsberhöhungen [Calculation of Power Transformers' Behavior in the Case of the Resonances and Reduction of the Internal Stresses]," Ph.D. dissertation, Technischen Hochschule Darmstadt, 1986.

[23] E. Rahimpour, "Hochfrequente Modellierung von Transformatoren zur Berechnung der Übertragungsfunktion [High Frequency Modeling of Transformers using the Transfer Function]," Ph.D. dissertation, University of Stuttgart, 2001.

[24] B. Gustavsen, "The Vector Fitting Website-MATLAB Code." [Online]. Available: http://www.sintef.no/vectfit. [Accessed: 21-Mar-2013].

[25] B. Gustavsen, *Matrix Fitting Toolbox, User's Guide and Reference*. Norway, 2009.

[26] S. Grivet-Talocia, "Passivity Enforcement via Perturbation of Hamiltonian Matrices," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 51, no. 9, pp. 1755–1769, 2004.

[27] Z. Ye, "Pmm: A Matlab Toolbox for Passive Macromodeling in RF/mm-Wave Circuit Design," in *2013 IEEE 10th International Conference on ASIC*, 2013, pp. 1–4.

[28] C. P. Coelho, J. Phillips, and L. M. Silveira, "A Convex Programming Approach for Generating Guaranteed Passive Approximations to Tabulated Frequency-Data," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 23, no. 2. pp. 293–301, 2004.

[29] B. Gustavsen and A. Semlyen, "Rational Approximation of Frequency Domain Responses by Vector Fitting," *IEEE Transactions on Power Delivery*, vol. 14, no. 3. pp. 1052–1061, 1999.

[30] B. Gustavsen, "Wide Band Modeling of Power Transformers," *IEEE Transactions on Power Delivery*, vol. 19, no. 1, pp. 414–422, 2004.

[31] J. A. Martinez and B. Gustavsen, "Parameter Estimation from Frequency Response Measurements," *IEEE Power & Energy Society General Meeting*. pp. 1–7, 2009.

[32] B. Gustavsen and A. Semlyen, "Enforcing Passivity for Admittance Matrices Approximated by Rational Functions," *IEEE Transactions on Power Systems*, vol. 16, no. 1. pp. 97–104, 2001.

[33] B. Gustavsen and A. Semlyen, "Fast Passivity Assessment for S-Parameter Rational Models Via a Half-Size Test Matrix," *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 12, pp. 2701–2708, Dec. 2008.

[34] B. Gustavsen, "Fast passivity enforcement for S-parameter models by perturbation of residue matrix eigenvalues," *IEEE Transactions on Advanced Packaging*, vol. 33, no. 1, pp. 257–265, 2010.

[35] A. Semlyen and B. Gustavsen, "A Half-Size Singularity Test Matrix for Fast and Reliable Passivity Assessment of Rational Models," *IEEE Transactions on Power Delivery*, vol. 24, no. 1. pp. 345–351, 2009.

[36] B. Gustavsen, "Fast Passivity Enforcement for Pole-Residue Models by Perturbation of Residue Matrix Eigenvalues," *IEEE Transactions on Power Delivery*, vol. 23, no. 4. pp. 2278–2285, 2008.

[37] International Electrotechnical Commission, *IEC 60060-1 High-Voltage Test Techniques Part 1: General Definitions and Test Requirements*. 2010.