

Difficulties in high frequency transformer modelling

Bruno Jurisic, Ivo Uglesic, Alain Xemard, Françoise Paladian and Philippe Guinic

Abstract-- Traditional transformer models available in EMTP-like software packages are not capable of representing transformer behavior during a transient state, which includes high frequencies, since they usually do not adequately take into account the transformer resonant behavior caused by its highly complicated design. Therefore, more complex “Black box” models are developed. Those models can be established without any knowledge on transformer geometry, based on the fitting of the measured admittance matrix of the transformer versus frequency. Unfortunately, the measurement and exploitation of a transformer’s admittance matrix are not straightforward. The existing fitting methods include solving non-convex constrained problem. Hence, it is not always easy to find an optimal solution of the problem. The difficulties, which can arise when building a high frequency “Black box” transformer model, are described in this paper together with a comparison of the performance and fitting accuracy of different numerical packages.

Keywords: “Black box”, fitting, passivity enforcement, Semi-Definite Programming, transformer modelling, transmitted overvoltages, EMTP-type, admittance matrix, FRA.

I. INTRODUCTION

Over several past decades many transformer models were introduced in order to represent transformer behavior at high frequencies, which occur during fast transients i.e. lightning strike or switching of vacuum circuit breakers [1]. Traditional transformer models available in EMTP-like software packages are not capable of representing transformer behavior during a transient state, which includes high frequencies, since they usually do not adequately take into account the transformer resonant behavior caused by its highly complicated design.

In this paper we will concentrate on the “Black box” transformer models. Usage of these models is suggested in IEC 60071-4 standard [2] for insulation coordination studies requiring a higher level of precision. Those models can be determined without any knowledge on transformer geometry, based on the fitting of the measured admittance matrix of the transformer versus frequency [3]-[11]. Therefore, they can only be applicable to evaluate external overvoltages, in order

to analyze the interactions between a transformer and the network and to study the insulation coordination of a power system. These models are widely used within power utility companies since they usually do not have access to the transformer design data, which is the property of a transformer manufacturer.

Unfortunately, the measurement and exploitation of transformer’s admittance matrix are not straightforward. Hence, even if numerical packages are available, the fitting methods do not always fit the measured curves accurately enough. Moreover, since a transformer model has to be both stable and passive, it is not always simple to find an optimal solution of the constrained mathematical problem of minimization, which has to be solved in order to fit the curves. Our experience based on several measurements carried out on real transformers is part of the paper, which also includes a comparison of the performance and fitting accuracy of different numerical packages since the measured curves are not always simple to fit [10], [11].

In the second section of the paper a bibliography on high frequency transformer “Black box” modelling is provided, together with a complete procedure for establishing a model. Additionally results of measurements conducted on a 64 MVA, 24/6,8/6,8 kV, *YNd11d11* transformer are included in this part of the paper. The third section contains an overview of different fitting methods which can be used in order to include a transformer model in an EMTP-type software. A comparison between fitting methods is given in the fourth section. The results are discussed in the next one.

II. “BLACK BOX” TRANSFORMER MODELS

In this section an overview on transformer “Black box” modelling is provided as well as a measurements procedure which was used by the authors to establish such a model. Since the model should be used in an EMTP-type software, the procedure for including the measurements results in such a software is given.

A. Different methodologies

Several measurement techniques can be used in order to establish a “Black box” model. These techniques usually differ regarding the choice of the parameter which will be measured. Scattering (S) parameters, impedance (Z) parameters, admittance (Y) parameters and transfer functions 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 [4], [12], [13]. Pure transfer function does not interact directly with an EMTP-like software. Nevertheless, in software like MATLAB, the practice for the calculation of transmitted overvoltages is to use transfer functions [6]. In the reference

B. Jurisic is with Électricité de France R&D, 92141 Clamart, France (e-mail of corresponding author: bruno.jurisic@edf.fr).

I. Uglesic is with University of Zagreb, Faculty of Electrical Engineering and Computing, 10000 Zagreb, Croatia (e-mail: ivo.uglesic@fer.hr).

A. Xemard is with Électricité de France R&D, 92141 Clamart, France (e-mail: 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).

P. Guinic is with Électricité de France R&D, 92141 Clamart, France (e-mail: philippe.guinic@edf.fr).

[14], it is explained how to calculate Y matrix of the cable from the transfer function measurements. The method on how to calculate Y parameters of the transformer from transfer function measurements is proposed in [15].

Depending on which parameter is measured, different measuring equipment has to be used. To measure S parameters, a network analyzer should be used [16], [18]. To measure Y and Z , current sensors have to be used. Note that according to Gustavsen [19], insertion impedance is added if a vector network analyzer is used in combination with a current sensor. To measure the transfer function of the transformer, the equipment specified in the standard for frequency response analysis (FRA) [20] has to be used. FRA is a standard test done in order to check the transformer condition.

Measurements are usually carried out with low voltage signals 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 the transformer is acting as a linear component.

Three different approaches on how to make a model compatible with the EMTP-like programs from measurement results can be defined: approximation with rational functions [11], [21], [22]; direct construction of an equivalent RLC network; indirect usage of a transfer function (i.e. in MATLAB) [6].

The most used approach is to approximate the admittance curves with rational functions. This approach is based on the method proposed by Levy in [23]. The method is used for the FDBFIT transformer model in EMTP-RV [21]. Recently, the method has been improved. The algorithm for the method, called “Vector fitting”, was implemented in the MATLAB environment by Gustavsen [24], as an open source code which can be found at [25]. Some explanations on the computer code can be found in [26]. After the rational functions approximating each element of the admittance matrix are obtained by using a least squared method, passivity has to be enforced since the transformer is a passive component of the network. This can be done simultaneously during the fitting process or as post processing. Explanations on procedures for enforcing passivity can be found in [10], [27]-[33].

As the final representation of model in EMTP-like software the following representations are adopted: lumped parameters [26], [34], [35]; Norton equivalent (by using recursive convolution) [36], [37]; state space representation [9], [38]. Note that the parameters which are obtained by using these methods are not physical and cannot be brought into relation with the transformer geometry.

“Black box” model cannot be used for frequencies range lower than the frequency of the first maximum of the transformer impedance curve, due to its inability to represent the nonlinear transformer behavior (at these frequencies transformer core influence should also be modeled). Therefore, if we want to represent a transformer for a wide frequency range (including the frequencies lower than a few kHz), a traditional transformer model with parallel connected nonlinear inductances should be used for low frequencies, included the power frequency, instead of a “Black box”

model. This is done in FDBFIT model, already implemented in EMTP-RV [21], [39]-[42].

“Black box” model can also be used for representations of many other components of electrical network (i.e. cables [15], overhead transmission lines [37], grounding systems [9], parts of a grid [43], wind turbine [44]) in transient studies which include wide frequency band.

B. “Black box” model: principle

In this section, a basic approach for deriving the “Black box” model based on state space equations from measurement results is described. More precisely, a procedure for measuring the admittance (Y) matrix elements of a transformer with a FRA equipment and building from these measurements a model compatible with EMTP-RV is presented.

A frequency response analyzer, is only capable of measuring the ratio (H) between the input (V_{in}) and the output (V_{out}) voltages.

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} \quad (1)$$

Since the FRA measurement equipment is not normally used for measuring Y matrix, a procedure for measuring is established.

The measurement method stems from the following expression:

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

Expression (2) is valid for a transformer with N terminals. However, the transformer we consider has 10 terminals: 3 terminals of HV winding, the neutral of HV winding, 6 terminals of two secondary LV windings.

1) Off-diagonal elements

The electric circuit, which represents the frequency network analyzer, is given in the figure 1. The coaxial cables are shown in blue and the flat braids are shown in red.

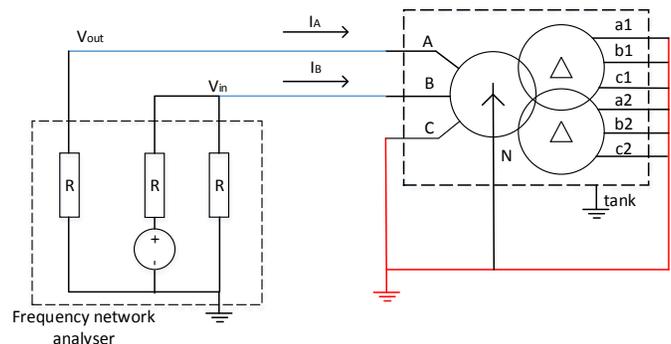


Fig. 1. Electric scheme for measuring off-diagonal Y matrix elements.

In the equipment we used, the source and the reference leads use the same coaxial cable as it is shown in the figure 1. Matching resistance (R) of frequency network analyzer terminals (source, reference and response) should be the same value as the characteristic resistance of the coaxial cables in

order to avoid wave reflections (which can have an effect on the measurement results) at the connection between the network analyzer and the coaxial cables. Therefore, in our calculations we are neglecting the resistance of the coaxial cables. Furthermore, the influence of the connections which are made by straight braids is also neglected.

Note that the measurements of the reference and the response signals are made across the matching resistance of the equipment.

In the figure 1, the measurement configuration for measuring the $Y_{1,2}$ element of the admittance matrix is shown. Since all the terminals which are not under measurement are grounded, their voltages are equal to 0 V (if the effect of the flat braids is neglected). Therefore, from the equation (2), for the connection from the figure 1, the following general expression for calculating the off-diagonal elements of matrix can be deduced:

$$Y_{ij}(s) = -\frac{V_i(s)}{V_j(s)} * \left(Y_{ii}(s) + \frac{1}{R} \right) \quad (3)$$

2) Diagonal elements

For measuring the diagonal elements of the admittance matrix, the matching resistance of the response lead is used as a shunt in order to connect the value of the current flowing through the response lead with its voltage, V_{out} . Therefore, there was no need to use an additional shunt for the measurements.

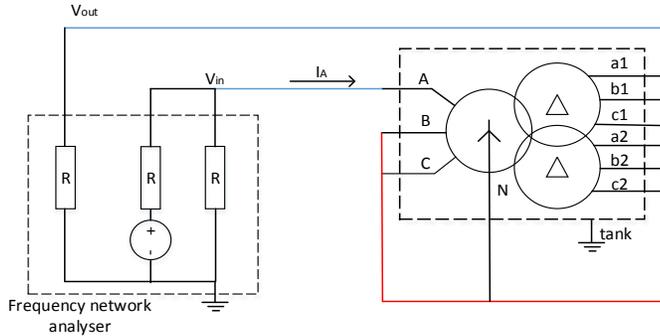


Fig. 2. Electric scheme for measuring diagonal Y matrix elements

For the configuration presented in the figure 2, a general expression for calculating the diagonal elements of matrix can be deduced:

$$Y_{ii}(s) = \frac{I_i(s)}{V_{in}(s) - V_{out}(s)} = \frac{V_{out}(s)}{R * (V_{in}(s) - V_{out}(s))} \quad (4)$$

However, the measurement configuration from the figure 2 could introduce a systematic error (i.e. bad evaluation of the homopolar admittance) to the measurement results due the current return through the ground (i.e. from tank to the grounding point of FRA equipment).

Note that the procedure described in this section of the document is valid for the N terminals admittance matrices.

C. Measurement results

The measurements are done on 64 MVA, 24/6,8/6,8 kV, YNd11d11 transformer unit. The matching resistance of the frequency network analyzer is 50 Ω and the accuracy is better than ± 1 dB in the measurement range 0-75 dB. The frequency

range of the apparatus is 20 Hz-2 MHz.

The measurements are done with the tank grounded during the measurements, as it is normally on site, over the full frequency range of the equipment. Therefore, we model transformer as a 10 terminals system in this case. The number of measurements combinations needed for building such a model is 100. Measured H curves contain 1040 discrete values at particular frequencies for each measurements combination. Calculated admittance matrix elements versus frequency are shown on the figure 3.

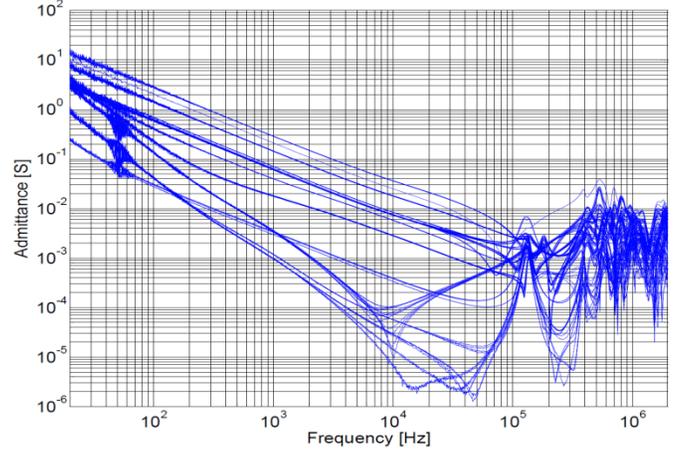


Fig. 3. Y(f) amplitude for transformer with the tank grounded.

Noise which occurs around 50 Hz, from the figure 3, is probably caused by interferences with the power frequency of a power supply of the measurement equipment.

D. EMTP-RV

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 $Y_{ij}(s)$ with a rational expression $Y_{ij,fit}(s)$ [10], [11] of the type given below:

$$Y_{ij}(s) \approx Y_{ij,fit}(s) = \sum_{n=1}^{N_p} \frac{c_{n,ij}}{s - a_{n,ij}} + d_{ij} \quad (5)$$

In the equation (5) $a_{n,ij}$ represents poles which can be either real or complex conjugated pair, $c_{n,ij}$ represents residues which can also be either real or complex conjugated pair, d_{ij} is real values constant. s stands for $j2\pi f$ where f is frequency. N_p 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 [10], [27]-[33]:

$$P = Re\{v^* Y_{fit}(s)v\} > 0 \quad (6)$$

, in which $Y_{fit}(s)$ represents the matrix of fitted rational functions. Expression (6) means that transformer will not produce power for any complex vector v . The expression above will be positive only if all the eigenvalues of real part of $Y_{fit}(s)$ are positive:

$$\text{eig}(\text{Re}(Y_{fit}(s))) > 0 \quad (7)$$

Rational expression (5) allows using state space equations as shown below:

$$sX(s) = A * X(s) + B * U(s) \quad (8)$$

$$I(s) = C * X(s) + D * U(s) \quad (9)$$

Matrices A , B , C and D for state space representation 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 (5) and forming the function given below:

$$I(s) = Y(s) * U(s) = \left[\frac{C * B}{(s[I] - A)} + D \right] * U(s) \quad (10)$$

Expression (10), in which $[I]$ is the identity matrix, can be obtained from equations (8) and (9). It represents the relation between the terminal currents and voltages of the transformer, suitable to represent the rational functions given by expression (5).

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 [30]. 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 main advantage of using these equations is the straightforward conversion from the frequency (measurements) to the time domain (EMTP-type software) without changing the values of the A , B , C and D matrices.

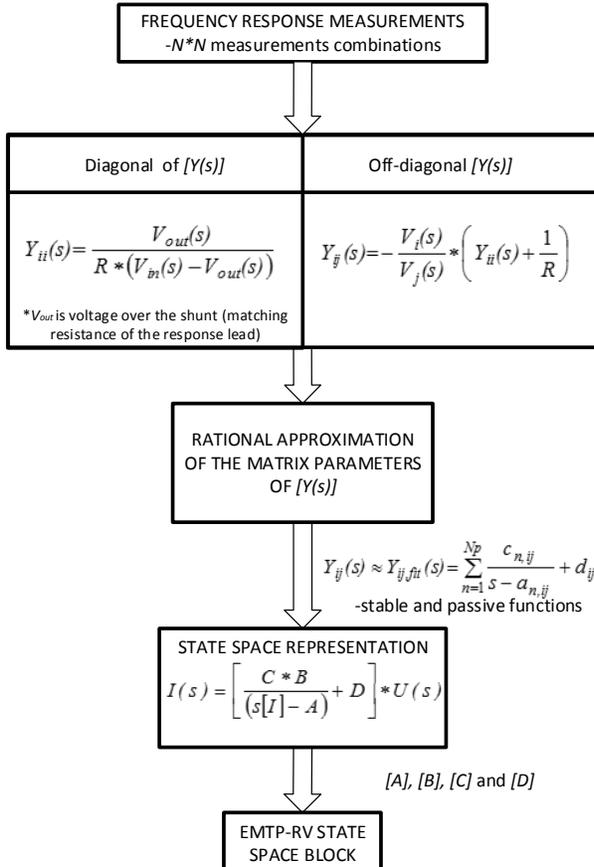


Fig. 4. Procedure for deriving the "Black box" transformer model in EMTP-RV

The complete procedure for building the "Black box" transformer model in EMTP-RV, from the frequency response measurement is shown in the figure 4. Note that the procedure presented above is directly applicable to transformers with N terminals.

III. FITTING METHODS

In this section a short overview of methods for approximating based on rational fitting and passivity enforcement is given.

The task is to approximate the data obtained from the measurements $Y_{ij}(s)$ with low order rational expressions, $Y_{ij,fit}(s)$. This problem can be formulated as minimizing the weighted least square error over frequency [45]:

$$\text{minimize} \sum_i \sum_j w_{ij}(s) \left| Y_{ij}(s) - Y_{ij,fit}(s) \right|^2 \quad (11)$$

$$\text{passive} \quad Y_{fit}(s) \quad (12)$$

, where $w_{ij}(s)$ is weighting factor which is often calculated as:

$$w_{ij}(s) = \frac{1}{\sqrt{|Y_{ij}(s)|}} \quad (13)$$

The problem formulated with (11) and (12) is non-convex (may have multiple feasible regions and multiple locally optimal points within each region) even after neglecting the constraint given in (12).

Therefore, many methods which use unconstrained minimization combined with post processing perturbation to enforce passivity are developed. The example of that approach is "Vector fitting" method (VF) combined with Fast Residue Perturbation (FRP) or Eigenvalue Perturbation Method (EPM) [25], [28], [33]. These methods in the first step identify stable but non-passive rational function (VF algorithm [11]). VF is an iterative process which considers poles identification and residuum identification, in order to fit with the rational expression (5). In the second, post processing step, matrices A , B , C and D calculated with the VF algorithm are used as an input data. Therefore, the non-passive model is checked for passivity violations and those violations are fixed by adjusting the values of the residues of the rational functions.

Another approach is to simultaneously enforce passivity during the fitting process by formulating a convex optimization problem such as semi-definite programming method [46]. These methods are still computationally very expensive, especially for large scale problems such as transformer modelling. Nevertheless, they always generate an optimal solution to the problem formulated with (11) and (12).

A. Unconstrained fitting methods (post processing passivity enforcement)

The following methods are examples of post processing perturbation: Fast Residue Perturbation (FRP); Eigenvalue Perturbation Method (EPM); Local Compensations (LC). All the methods are implemented in Passive macro-modelling (pmm) toolbox in MATLAB environment [10], [47]-[49]. FRP method is also implemented in the SINTEF software [25].

Both pmm and SINTEF software have implemented VF algorithm for calculating matrices A , B , C and D , which are input data for methods for post processing passivity enforcement.

FRP method showed the best results among all the methods for post processing passivity enforcement considered in this paper. Therefore, it will be explained in details. The method strives to enforce passivity by iteratively perturbing the elements value of matrices C and D of the state space model obtained from VF while minimizing the change in $\Delta Y_{fit}(s)$:

$$\text{minimize } \Delta Y_{fit}(s) = \frac{\Delta C * B}{(s[I] - A)} + \Delta D \quad (14)$$

$$\text{subject to } \text{eig}(\text{Re}\{Y_{fit}(s) + \Delta Y_{fit}(s)\}) > 0 \quad (15)$$

$$\text{eig}(D + \Delta D) > 0 \quad (16)$$

Note that (16) enforces matrix D to become positive defined. The problem of the optimization is solved by using the quadratic programming [33]. Due to the non-linear relations between eigenvalues and the matrix perturbations, iterations in the FRP are necessary. The algorithm will stop after the passivity is enforced for all frequencies [25]. Passivity violations are checked with inspection of a Hamiltonian matrix:

$$\begin{bmatrix} A - B(D + D^T)^{-1}C & B(D + D^T)^{-1}B^T \\ -C^T(D + D^T)^{-1}C & -A^T + C^T(D + D^T)^{-1}B^T \end{bmatrix} \quad (17)$$

The state space system described with matrices A , B , C and D is passive if the Hamiltonian matrix has no imaginary eigenvalues [50]. Since it is necessary to detect the frequency bands for which passivity is not enforced, the algorithm searches for purely imaginary eigenvalues of Hamiltonian matrix in order to detect the crossover frequencies for which the eigenvalues of the real part of the admittance matrix are becoming positive or negative (i.e. Y becomes passive or non-passive). Note that in practice a tolerance is accepted for the real part of eigenvalues of the Hamiltonian matrix since we have a finite number of frequency samples. FRP method is a very efficient method but it sometimes encounters convergence issues since the problem which is to be solved is a non-convex problem.

EPM method for enforcing passivity calculates the crossover frequencies (boundaries of the passivity of the system) in the same way as FPR method. After the boundaries are detected, it moves conjugate complex paired eigenvalues towards each other. By doing that EPM is eliminating the regions where the system is non-passive i.e. where the eigenvalues of Hamiltonian matrix are imaginary. During the process EPM can create additional passivity violations and there it may not converge [28].

LC method for enforcing passivity fixes the passivity violations individually by adding new poles and residues [48]. Therefore, the downsides of the LC method are that the resulting state space matrices are bigger than inputted ones and that it will give poor relative accuracy since it preserves absolute one.

Since post processing passivity enforcement methods like FRP, EPM and LC method do not guaranty optimal result, to

find an optimal solution Domain Alternated Optimization (DAO) can be used. This algorithm is implemented in pmm toolbox. It takes the solution of the existing method, which is not optimal and performs local optimization in order to improve accuracy of fitting [10]. Note that DAO is a non-convex method and may have some convergence issues.

B. Constrained fitting methods (enforcing passivity during the fitting)

An example of algorithm which enforces passivity during the fitting is Semi-Definite Programming (SDP) method [46]. The method is implemented in pmm toolbox.

Note that SDP method uses only matrices A and B , calculated with the VF algorithm as an input data. Therefore, SDP is a constrained fitting method for solving a non-convex problem given with equations (11) and (12). The non-convex problem is transformed into a convex problem. Therefore, several elements have to be introduced.

Brune [51] proved that the admittance and impedance matrices of a passive system should be positive real rational functions. The admittance matrix of a linear time invariant system is positive real if its state space formulation $Y_{fit}(s)$ meets Positive Real Lemma [46].

Theorem (Positive Real Lemma) [52]: Let $Y_{fit}(s)$ be a matrix transfer function such that its poles lie either on the left-half plane or on the imaginary axis, in which case they are simple. If there exists a $K=K^T$ such as the linear matrix inequalities,

$$\begin{bmatrix} -A^T K - KA & -KB + C^T \\ -B^T K + C & D + D^T \end{bmatrix} \geq 0 \quad (18)$$

$$K \geq 0 \quad (19)$$

are satisfied, then $Y_{fit}(s)$ is positive real.

Therefore, if equations (18) and (19) are met, function $Y_{fit}(s)$ is passive. Since the positive real constraints are convex in both C and D , matrices A and B will be fixed during the optimization process. Accordingly, the values of the poles should be given as an input data in the algorithm. The poles should be stable with a sufficient level of approximation accuracy (VF method is accurate enough to give a good approximation of the stable poles). With the poles fixed, optimization problem (11) subject to (18) and (19), should be solved. If the poles are fixed in problem (11), it becomes a convex problem. Thus, convex programming method, also called SDP method, is used for calculation. The method will give optimal C and D matrices for given values of A and B matrices. Note that the success of the solution depends on the values of the given fixed matrices A and B .

This method is computationally very inefficient ($O(n^2)$), if n is the number of poles used in approximation functions, but it gives a global optimum for a given case. Comparing to SDP, DAO method (i.e. post processing passivity enforcement with an optimal solution) is potentially more efficient ($O(nm)$), where $m < n$.

IV. FITTING RESULTS

In this section some results of the fitting methods together

with the detailed comparison of their accuracy are given.

From all named methods in the previous section, for the measured data set, the best result is given by the SDP method since it guaranties to calculate an optimal passive solution for the given problem.

To discuss the accuracy of a method, its quantification has to be established. An evaluation of the approximation accuracy was done by calculating the error between measurements and approximations. The error is calculated as the standard deviation or the mean square error, using the following expression:

$$rmserr = \sqrt{\frac{\sum_{j=1}^N \sum_{j=1}^N \sum_{k=1}^{N_k} (|Y_{ij}(f_k) - Y_{ij,fit}(f_k)|)^2}{N^2 * N_k}} \quad (20)$$

, where N represents the number of transformer terminals, f_k represents a particular frequency at which admittance values are measured and N_k represents the number of frequency samples.

The error is also calculated in terms of percentages of the calculated value.

$$rmserr = 100\% \sqrt{\frac{\sum_{j=1}^N \sum_{j=1}^N \sum_{k=1}^{N_k} \left(\frac{|Y_{ij}(f_k) - Y_{ij,fit}(f_k)|}{Y_{ij}(f_k)} \right)^2}{N^2 * N_k}} \quad (21)$$

A comparison of fitting accuracy obtained with the different fitting methods on the data measured in the frequency range 15 kHz-700 kHz is given in table 1. The accuracy is shown for different number of poles used in the rational functions (5) which describe the transformer behavior.

TABLE I

COMPARISON OF ACCURACY OF DIFFERENT FITTING METHODS FOR DIFFERENT NUMBER OF POLES

Number of poles	SDP	FRP	EPM	LC
20	$1,42 * 10^{-3}$	$1,50 * 10^{-3}$	$2,42 * 10^{-3}$	$2,64 * 10^{-3}$
40	$1,29 * 10^{-3}$ (11,67 %)	$1,90 * 10^{-3}$ (28,39 %)	Not succeed	$5,03 * 10^{-3}$
120	Not tested	$1,60 * 10^{-3}$	Not tested	Not tested

In the table 1, accuracy is shown in terms of mean square error. For the most interesting cases, accuracy is also calculated in terms of percentages (given in the brackets). For EPM, the fitting did not succeed in the calculation with 40 poles. Methods EPM and LC were not tested with 120 poles since EPM and LC were not accurate enough. SDP method was not tested for more poles since its time of calculation is very high (40 poles approx. 5 hours) and personal computer can easily run out of memory. Nevertheless, the best result was obtained by the SDP method with only 40 poles.

Following, the comparison between the fitting curves obtained with the SDP and FRP methods is shown for the frequency range 15 kHz-700 kHz. The number of poles used in both cases is 40. The results are compared for amplitude (figures 5 and 7) and for phase (figures 6 and 8) of the admittance curves.

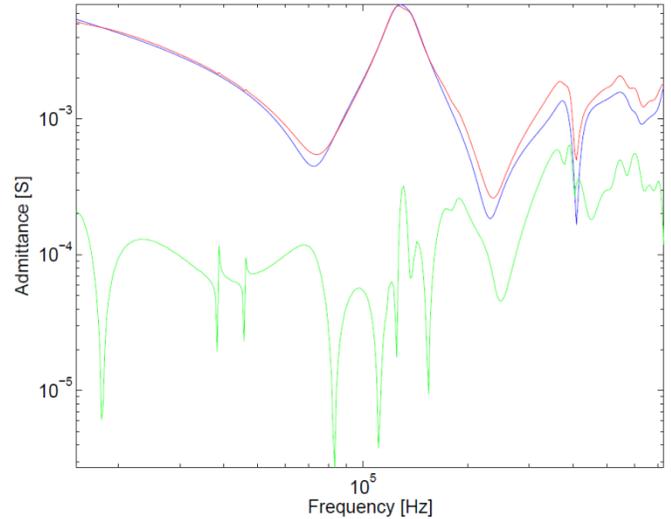


Fig. 5. The fitted admittance matrix element $Y_{1,1}$ using the SDP method for the frequency range 15 kHz – 700 kHz. The measurements are shown in blue; the fitted curve is shown in red; the error is shown in green.

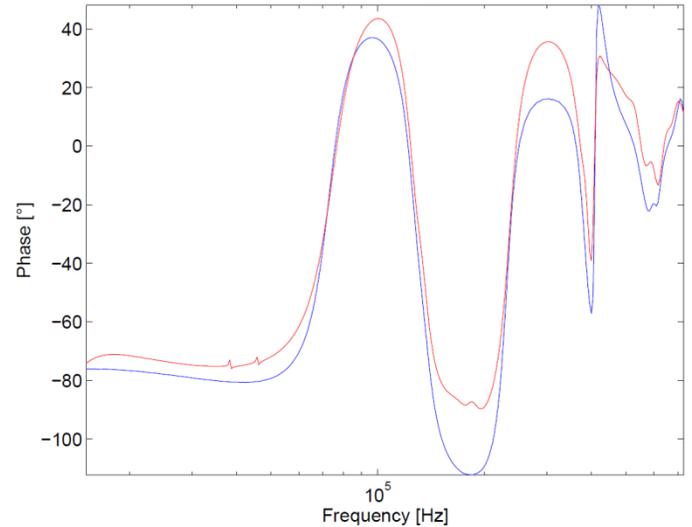


Fig. 6. The fitted phase of admittance matrix element $Y_{1,1}$ using the SDP method for the frequency range 15 kHz – 700 kHz. The measurements are shown in blue; the fitted curve is shown in red.

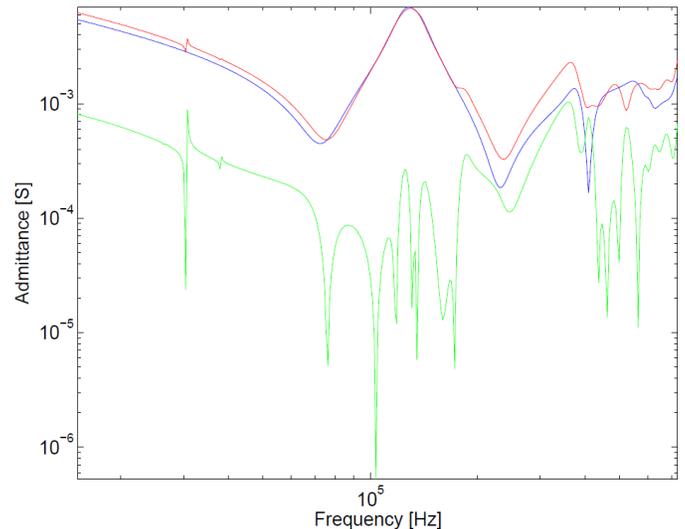


Figure 7 The fitted admittance matrix element $Y_{1,1}$ using the FRP method for the frequency range 15 kHz – 700 kHz. The measurements are shown in blue;

the fitted curve is shown in red; the error is shown in green.

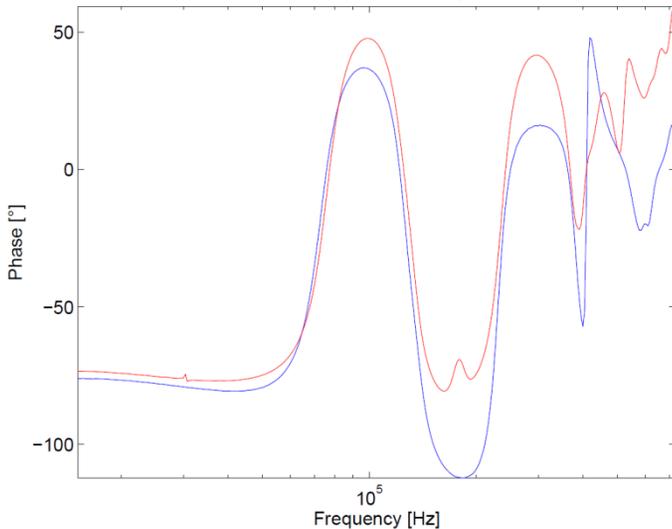


Fig. 8. The fitted phase of the matrix element $Y_{1,1}$ using the FRP method for the frequency range 15 kHz – 700 kHz. The measurements are shown in blue; the fitted curve is shown in red.

V. DISCUSSION

From the figures given above, it can be seen that the approximation results are good, since the order of value of the differences between measurements and approximations is lower than the order of value of measurements or approximations itself.

For fitting the measured transformer admittance matrix elements, two methods should be used: SDP and FRP method. First, the curves should be fitted by using the SDP method (pmm software) with limited number of poles (up to 50). If the fitting achieved with the SDP method is not accurate enough or if it fails, the FRP method (SINTEF software) should be used with a higher number of poles (up to 120). If both methods fail, the curves should be divided into several segments along the frequency range which should be fitted separately. One of the possible ways of merging more segments is to fit once again the response of the functions which are already calculated by fitting different segments of the curves. If the responses do not have similar values on the borders of segments frequency range, filters could be used [27]. Nevertheless, this aspect should be studied in the future.

Note that not all measured data can be fitted accurately with methods like SDP or FRP. Some measurements data can be fitted accurately only if we allow the rational functions, which are obtained from the approximation, to have the poles in the right side of the plane of the coordinate system (these curves are unstable) or if we allow the functions to be non-passive. That is probably due to some error which is introduced by the measurements which changes the measurements data of the passive component to act as non-passive one. Therefore, the stress should be also put on the measurements accuracy and procedure in order to limit the measurements error.

Up to now, the authors experience has shown that a “Black box” model can provide an accurate estimation of the transmitted overvoltages [4]. The next step is to improve the

models in order to calculate the shape of the transmitted overvoltages with a good precision. The improved models will be used to determine whether we need surge arrester or not on the secondary side of the transformer as well as to perform a statistical analysis of lightning impacts to the electrical components situated on the secondary side of the transformer.

VI. CONCLUSIONS

In this paper a bibliography on the field of high frequency transformer “Black box” modelling is given, together with a complete procedure for establishing one, based on FRA measurements, rational approximation and state space equations. A significant advantage of this model is the usage of FRA equipment, which most of transformer producer’s companies already use. Particular emphasis has been placed in the paper on the comparison between several fitting methods. Unconstrained fitting method, Fast Residue Perturbation and constrained fitting method, Semi-Definite Programming, showed the best results on the given set of data. The fundamental point from an industrial perspective is that the model detailed in this paper is able to accurately calculate the amplitude of the overvoltages, which might be transmitted through a 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.

VIII. REFERENCES

- [1] CIGRE Working Group A2/C4.39, “TB577: Electrical transient interaction between transformers and the power systems”, 2013.
- [2] International Standard IEC 60071-4, “Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modelling of electrical networks”, 2004.
- [3] B. Jurisic, A. Xemard, I. Uglesic, F. Paladian and P. Guinic, „Case Study on Transformer Models for Calculation of High Frequency Transmitted Overvoltages”, CIGRE 3rd International Colloquium “Transformer Research and Asset Management”, Split, 2014.
- [4] 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, Lyon, 2014.
- [5] A. Holdyk, B. Gustavsen, I. Arana and J. Holboell, “Wideband Modeling of Power Transformers Using Commercial sFRA Equipment”, IEEE Transactions on Power Delivery, vol.29, no.3, pp.1446,1453, June 2014.
- [6] D. Filipovic-Grcic, B. Filipovic-Grcic and I. Uglesic, “High-Frequency Model of Power Transformer Based on Frequency Response Measurements”, IEEE PES Transaction on Power Delivery, Accepted for publishing, 2013.
- [7] R. Caldecott, Y. Liu, S.A. Sebo, D.G. Kasten and S. E., Wright Sebo, “Measurement of the frequency dependent impedance of major station equipment”, IEEE Transactions on Power Delivery, vol.5, no.1, pp.474,480, Jan 1990.
- [8] 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, Jan 1993.
- [9] X. Legrand, A. Xemard, C.A. Nucci and P. Auriol, “A Method to Interface Electromagnetic Models of Grounding Systems with Transients Programs”, CIGRE C4 Colloquium on Power Quality and Lightning, Sarajevo, May 2012.

- [10] Z. Ye, Y. Li, M. Gao and Z. Yu, "A novel framework for passive macromodeling", 48th ACM/EDAC/IEEE Design Automation Conference, San Diego, USA, June 2011.
- [11] B. Gustavsen, "Wide band modeling of power transformers", IEEE Transactions on Power Delivery, vol. 19, pp. 414-422, 2004.
- [12] D.A. Frickey, "Conversions between S, Z, Y, h, ABCD, and T parameters which are valid for complex source and load impedances". IEEE Trans. Microwave Theory Tech., vol. 42, pp. 205-211, 1994.
- [13] B. Gustavsen, De Silva, H.M.J., "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, April 2013
- [14] M. Heindl, S. Tenbohlen and R. Wimmer, "Transformer Modeling Based on Standard Frequency Response Measurements", International Symposium on High Voltage Engineering, Hannover, Germany, 2011.
- [15] B. Gustavsen, "Study of Transformer Resonant Overvoltages Caused by Cable-Transformer High-Frequency Interaction", IEEE Transactions on Power Delivery, vol.25, no.2, pp.770,779, April 2010.
- [16] Z. Zhongyuan, L. Fangcheng, and C. Yutong, "A High Frequency Circuit Model for Current Transformer Based on the Scattering Parameter", IEEE Asia Pacific Conference on Circuits and Systems, 2006.
- [17] Z. Zhongyuan, L. Fangcheng and L. Guishu, "A High-Frequency Circuit Model of a Potential Transformer for the Very fast Transient Simulation in GIS", IEEE Transactions on Power Delivery, Vol. 25, No. 4, pp. 1995-1999, Oct. 2008.
- [18] Z. Zhongyuan, C. Yutong, L. Yupeng, and L. Fangcheng, "High frequency circuit model of transformer windings based on frequency responses for VFTO studies", Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, China, April 2008.
- [19] B. Gustavsen, "Removing Insertion Impedance Effects From Transformer Admittance Measurements," IEEE Transactions on Power Delivery, vol.27, no.2, pp.1027,1029, April 2012.
- [20] International Standard IEC 60076-18: "Power Transformers – Part 18: Measurement of frequency response", First edition, 2012.
- [21] A. Morched, L. Marti and J. Ottevangers, "A high frequency transformer model for the EMTP", IEEE Transactions on Power Delivery, vol.8, no.3, pp.1615-1626, 1993.
- [22] T. Noda, "Identification of a multiphase network equivalent for electromagnetic transient calculations using partitioned frequency response", IEEE Transactions on Power Delivery, vol.20, no.2, pp.1134, 1142, April 2005.
- [23] E. C. Levy, "Complex-curve fitting", IRE Transaction on Automatic Control, May 1958.
- [24] 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.
- [25] B. Gustavsen, "The vector fitting website" - MATLAB code, <http://www.sintef.no/vectfit>, 21. March 2013.
- [26] B. Gustavsen, "Computer code for rational approximation of frequency dependent admittance matrices", IEEE Transactions on Power Delivery, vol.17, no.4, pp.1093-1098, 2002.
- [27] J. A. Martinez, and Gustavsen, B. "Parameter estimation from frequency response measurements", Power & Energy Society General Meeting, PES '09, pp.1-7, 2009.
- [28] 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.
- [29] B. Gustavsen and A. Semlyen, "Enforcing passivity for admittance matrices approximated by rational functions", IEEE Transactions on Power Delivery, vol. 16, no. 1, pp. 97-104, 2001.
- [30] B. Gustavsen and A. Semlyen, A. "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, 2008.
- [31] 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, February 2010.
- [32] 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.
- [33] 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.
- [34] M. Popov, L. van der Sluis and R.P.P. Smeets, "Evaluation of surge-transferred overvoltages in distribution transformers", Electric Power Systems Research, Volume 78, Issue 3, March 2008.
- [35] B. Gustavsen, "White Box and Black Box Modeling of Power Transformers" - report SINTEF, 2011.
- [36] B. Gustavsen, and O. Mo, "Interfacing Convolution Based Linear Models to an Electromagnetic Transients Program", International Conference on Power Systems Transients (IPST'07) in Lyon, France, June 2007.
- [37] B. Gustavsen, G. Irwin, R. Mangelrød, D. Brandt, and K. Kent, "Transmission line models for the simulation of interaction phenomena between parallel ac and dc overhead lines", International Conference on Power Systems Transients, pp. 61-67., Budapest, Hungary, 1999.
- [38] M. Tiberg et al., "Generic and automated simulation modeling based on measurements", Int. Conf. on Power Systems Transients, 2007.
- [39] H. W. Dommel, "EMTP Theory Book", Microtran Power System Analysis Corporation, second edition, Vancouver, British Columbia, 1992.
- [40] EMTP-RV help file, part of the EMTP-RV 2.4 software documentation
- [41] V. Brandwajn, H. W. Dommel, and I.I. Dommel, "Matrix Representation of Three-Phase N-Winding Transformers for Steady-State and Transient Studies", IEEE Transactions on Power Apparatus and Systems. PAS-101, no. 6. Pp.1369-1378, June 1982.
- [42] A.S. Morched, J. H. Ottevangers and L. Marti, "Multi-port frequency dependent network equivalents for the EMTP", IEEE Transactions on Power Delivery, vol.8, no.3, pp.1402-1412, 1993.
- [43] B. Gustavsen, "Application of Frequency-Dependent Network Equivalents for EMTP Simulation of Transformer Inrush Current in Large Networks", International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada, July, 2013.
- [44] A. Holdyk, I. Arana, and J. Holboell, "Wide band characterization of wind turbine reactors", International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada, July, 2013.
- [45] Z. Mahmood, "Parameterized Modeling of Multiport Passive Circuit blocks", Thesis, Massachusetts Institute of Technology, September 2010.
- [46] C. Coelho, J. Phillips, and L. 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, Feb. 2004.
- [47] Z. Ye, "pmm: A Matlab Toolbox for Passive Macromodeling in RF/mm-wave Circuit Design", IEEE 10th International Conference on ASIC, October 2013.
- [48] T. Wang, Z. Ye and Y. Li, "Robust Passive Macro-Model Generation with Local Compensation", IEEE Trans. on Microwave Theory and Technique, 60(8), 2313-2328, 2012.
- [49] Z. Ye, "Noise Companion State-Space Passive Macromodeling for RF/mm-Wave Circuit Design", IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol.32, no.9, pp.1435,1439, Sept. 2013
- [50] D. Saraswat, R. Achar and M.S. Nakhla, "A fast algorithm and practical considerations for passive macromodeling of measured/simulated data.", IEEE Transactions on Advanced Packaging, vol.27, no.1, pp.57,70, Feb. 2004.
- [51] O. Brune, "Synthesis of a finite two-terminal network whose driving point impedance is a prescribed function of frequency", J. Math. Phys., vol. 10, pp. 191-236, 1931.
- [52] C. Coelho, J. R. Phillips, and L. M. Silveira, "A convex programming approach to positive real rational approximation," in Proc. Int. Conf. Computer Aided-Design, pp. 245-251, Santa Clara, CA, 2001.