Comparison of Black-Box Modeling Approaches for Transient Analysis: A GIS case study

Gustavo H. C. Oliveira and Steven D. Mitchell

Abstract—**When conducting transient studies on an electrical system, it is important to have an accurate model representation of each of the various system components. This paper compares different methodologies currently used to obtain black box transformer models based on frequency response field measurements. The key point here is to show how good and well implemented black-box modeling procedures can lead to different time-domain results when simulating transient signals. So, this paper presents an comparative study of methods for deriving black-box models aiming transient studies in the power system. It also highlights the need to consider the passivity of the data set and its corresponding model in order to ensure a numerically stable simulation will be obtained. A gas-insulated substation (GIS), with single phase 525/18kV, 256MVA generator transformers, is used as a case study for the analysis. The resulting black box models are then used within an EMTP simulation of a switching event within the substation. The simulation results facilitate an assessment of the relative merits of each of the reviewed modeling methodologies.**

Keywords **- power transformers, black-box modeling, passive circuits, gas-insulated substations.**
[1]

I. Introduction

The rapid growth in energy demand over the past few decades has made the need for an accurate representation of a power system's dynamic behavior critical. During contingencies, the electrical system is subject to oscillations containing a wide range of frequencies. Suitable modeling of electrical equipment within this frequency range allows for the correct analysis and representation of such oscillations. The resulting models are necessary to improve electromagnetic transient program (EMTP) simulations in order to analyze contingencies as well as to check equipment design [1].

Power transformers are a vital asset within any electric power system and represent a considerable portion of the total cost of any substation. In addition, failures must be taken into consideration since their repair or replacement will compromise the power supply continuity required by the quality standards of the electrical energy market.

Over the past few years, statistics related to power transformer performance have shown that some failures could be linked with the voltage transients caused by interactions between transformers and other components of the electrical system [2]. Recent performance studies conducted in Brazil [3] have shown that, for the 20 step-up transformers inspected due to failure, 6 of the failures were associated with very fast transients (VFT) generated on the system. The inclusion of an accurate wideband power transformer model within the system study will improve simulations containing VFT phenomena.

Black-box modelling approaches for power transformers are methods where the model structure and parameters are computed based only on external input and output data. The model structure and realization are chosen from a well known set of models and parameters which have no physical meaning or relationship with the system's electrical principles. Usually the measurement data is in the frequency domain, so such approaches can be considered frequency-domain system identification methods [4]. In this paper, black-box modelling approaches for representing power transformer for very fast transient studies are described and compared.

The key point here is to show how good and well implemented black-box modeling procedures can lead to different results when simulating transient signals. In fact, some of the electrical system transients waves contains frequencies in the range of kilo or mega Hertz. Good measurements for computing black-box models at this range of frequencies are not trivial and sometimes unavailable. On the other hand, passivity issues may also arise in the measurements and in the final model. So, this paper presents an comparative study of methods for deriving black-box models aiming transient studies in the power system. All cases are conducted using data from an actual Gas Insulated Substation (GIS).

The paper is organized as follows. A review on iterative black-box frequency-domain methods for power transformers is presented in Section 2. The passivity assessment is discussed in Section 3. A case study, using transformer measurements and GIS substation data is presented in Section 4. Finally, conclusions are addressed in Section 5.

II. Frequency-Domain Black-box Modelling Approaches

When conducting electromagnetic transient analysis on a power system, its power transformers can be represented by an n terminal admittance matrix $\mathbf{Y}$ where,

$$\mathbf{I} = \mathbf{Y}\,\mathbf{V} \qquad (1)$$

[1]

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or, in terms of its frequency response,

$$\begin{bmatrix} I_1(jw) \\ I_2(jw) \\ \vdots \\ I_n(jw) \end{bmatrix} = \begin{bmatrix} Y_{11}(jw) & Y_{12}(jw) & \cdots & Y_{1n}(jw) \\ & Y_{22}(jw) & \cdots & Y_{2n}(jw) \\ \vdots & \vdots & & \\ & * & & Y_{nn}(jw) \end{bmatrix} \times \begin{bmatrix} V_1(jw) \\ V_2(jw) \\ \vdots \\ V_n(jw) \end{bmatrix}. \quad (2)$$

In this equation, $I_i(jw)$ and $V_l(jw)$ are the frequency responses of the transformer current and voltage at terminals i and l, respectively. $Y_{il}(jw)$ is the frequency response of the element (i,l). The symbol $*$ indicates a symmetric structure.

The calculus of $Y_{il}(jw)$ requires the measurement of $I_i(jw)$ and $V_l(jw)$ for w across a wide band of frequencies. Given these measurements, a transformer MIMO (multi-input-multi-output) non-parametric model in the frequency domain is obtained. The goal is to find a parametric model in the state-space realization ($\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$) of $\mathbf{Y}(s)$. The determination of a parametric model for matrix $\mathbf{Y}(s)$, or for each element of $Y_{i,l}(s)$ from the frequency response measurements, is known as the frequency-domain system identification. Algorithms to solve this problem have been around since the late 1950's (refer [5]). A recent compilation regarding these problem can be found in [4].

Matrices ($\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$) of the model can be estimated directly from a subspace system identification method. However, each element $Y_{i,l}(s)$ of $\mathbf{Y}$ can also be parameterized as a rational transfer function such as:

$$Y_{i,l}(s) = \frac{B_{i,l}(s)}{A_{i,l}(s)}, \quad (3)$$

where $A_{i,l}(s)$ and $B_{i,l}(s)$ are polynomials in s. This model can be expanded as a truncated series of basis functions $\{\phi_{i,l,m}(t)\}_{m=1}^{\infty}$ [6] as follows:

$$Y_{i,l}(s) = \frac{B_{i,l}(s)/F_{i,l}(s)}{A_{i,l}(s)/F_{i,l}(s)} = \frac{\beta_{i,l,0} + \sum_{m=1}^{N} \beta_{i,l,m}\Phi_{i,l,m}(s)}{1 + \sum_{m=1}^{N} \alpha_{i,l,m}\Phi_{i,l,m}(s)} \quad (4)$$

where $\Phi_{i,l,m}(s)$ is the Laplace transform of $\phi_{i,l,m}(t)$. Selections for this basis function can be, for instance, a single-pole partial fraction decomposition, such as:

$$\Phi_{i,l,m}(s) = \frac{1}{s + a_{i,l,m}}, \quad (5)$$

where $a_{i,l,m} \in \mathbb{C}$, for $i, l = 1, ..., n$ and $m = 1, ..., N$ defines the functions dynamic. This is the choice used in [7]. Another option are the Takenaka-Malmquist functions [8], [9], which are given by:

$$\Phi_{i,l,m}(s) = \frac{\sqrt{2\mathfrak{Re}\{a_{i,l,m}\}}}{s + a_{i,l,m}} \prod_{o=1}^{m-1} \frac{s - \bar{a}_{i,l,o}}{s + a_{i,l,o}}. \quad (6)$$

They are orthonormal, complete in the Lebesgue L_2 space (for $n = \infty$) and have continuous-time Laguerre and Kautz basis functions as a special case.

A. Model Parameter Estimation

Once there is a model structure, such as those previously presented, a set of parameters for fitting the model with the measured admittance matrix elements is required. It can be done recursively for models such as (4) using the so-called Sanathanan-Koener iterations [10]. They are compared with a iterative algorithm known as Expectation Maximization for the Maximum Likelihood Estimation [11].

The estimation problem of interest can be stated as the problem of minimizing the following objective function. For the sake of simplicity, lets consider the problem of estimating one element of $\mathbf{Y}(s)$, that is, $Y_{i,l}(s)$.

$$J(\hat{\theta}) = \sum_{k=1}^{K} |\Xi_{i,l}(jw_k)| \left| Y_{i,l}(jw_k) - \hat{Y}_{i,l}(jw_k) \right|^2 \quad (7)$$

where $Y_{i,l}(jw_k)$ is the measured frequency response of an element of (1) at frequencies $\{w_k\}_{k=1}^{K}$, $\hat{Y}_{i,l}(jw_k)$ is the model used to approximate the system dynamics, with parameters $\hat{\theta}_{i,l} = \{\hat{\alpha}_{i,l,1}, ..., \hat{\alpha}_{i,l,N}, \hat{\beta}_{i,l,0}, \hat{\beta}_{i,l,1}, ..., \hat{\beta}_{i,l,N}\}$. $\Xi_{i,l}(jw_k)$ is a weighting function.

The problem of estimating the parameters of $\hat{Y}_{i,l}(s)$, that is, to compute

$$\hat{\theta}_{i,l} \;=\; \text{argmin } J(\hat{\theta}_{i,l}), \quad (8)$$

has been studied by several authors in relation to power transformer frequency domain data [12], [13], [14]. An issue related to the approach taken by (7) and (8) is the selection of the dynamics of the basis functions (or poles of $\hat{F}_{i,l}(s)$). This is frequently called basis function pole selection (refer, for instance [15]). Such problems are non-linear and may converge to local minima.

Another approach is to rewrite the objective function using a fixed-denominator structure such as:

$$J(\hat{\theta}_{i,l}) = \sum_{k=1}^{K} |\Xi_{i,l}(jw_k)| \left| \hat{A}_{i,l}(jw_k)Y_{i,l}(jw_k) - \hat{B}_{i,l}(jw_k) \right|^2 \times \frac{1}{|\hat{F}_{i,l}(jw_k)|^2} \quad (9)$$

When $\hat{F}_{i,l}(jw_k)$ is known, (9) is linear in relation to $\hat{\theta}_{i,l}$ and can be solved using a standard linear least square procedure. However, since the best $\hat{F}_{i,l}(jw_k)$ for the model has to be determined, an iterative procedure for $\hat{F}_{i,l}(jw_k)$ and $\hat{\theta}_{i,l}$ based on (9) is as follows,

$$J^c(\hat{\theta}_{i,l}) = \sum_{k=1}^{K} |\Xi_{i,l}(jw_k)| \left| \hat{A}^c_{i,l}(jw_k) Y_{i,l}(jw_k) - \hat{B}^c_{i,l}(jw_k) \right|^2 \times \frac{1}{|\hat{F}^{c-1}_{i,l}(jw_k)|^2}. \quad (10)$$

Starting with $\hat{F}^0(s) = 1$, estimate $\hat{\theta}$ at iteration c using

$$\hat{\theta}^c_{i,l} \ = \ \text{argmin} \ J^c(\hat{\theta}_{i,l}) \quad (11)$$

$\hat{F}^c_{i,l}(s)$ is then made equal to $\hat{A}^c_{i,l}(s)$ and the procedure is repeated until the difference between the parameters of the estimated $\hat{A}^c_{i,l}(s)$ and the parameters of $\hat{F}^{c-1}_{i,l}(s)$ are sufficiently small. This is equivalent to $\beta_{i,l,m}$ tending to zero. This algorithm, when the basis functions are of the form (5), is known as Vector Fitting [16] and, when the basis functions are of the form (6), is known as Orthonormal Vector Fitting [17].

III. Passive Measurements and Networks

Whilst power transformers are comprised of passive elements, there are frequently two problems which can arise when modeling power transformers for electromagnetic simulation studies. The first issue is to get disturbed measurements of $Y_{i,l}(jw_k)$ in such way that they do not correspond to a passive element. The second issue is to identify models $\hat{Y}_{i,l}(s)$ that are not passive or representative of any passive electrical network. The use of non-passive models for representing power transformers in EMTP studies usually degenerates into unstable simulations.

A criterion for assessing the passivity of an electrical element $\mathbf{Y}$ is to compute its conductance G and the eigenvalues of the conductances [18]. $\mathbf{Y}$ is passive only if

$$G = \mathfrak{Re}\{\mathbf{Y}(jw)\} \quad (12)$$

is positive-definite for all w.

IV. Case Study: A Step-up Transformer on a Gas-Insulated Substation

A. Problem statement

The present case is based on an actual Gas-Insulated Substation (GIS). It considers the influence of transformer modeling approaches on the propagation of system transient voltages. The transient voltages are generated by switching circuit breakers and/or disconnectors on systems connected to the step-up transformers. The transformer under consideration is a single-phase 525/18 kV, 256 MVA step-up transformer. In order to study such a problem and to simulate the above mentioned phenomena, a section (containing disconnectors, circuit breakers and transmission lines) of the actual substation is modeled using a EMTP software. This part is illustrated in Figure 1.

The transient signal analyzed here is generated by closing the disconnector 95U03 (see Figure 1) assuming: circuit breakers 05U03 and 45U34 are open; the disconnectors between Bus A and node PM2 and between nodes PM2 and PM3 are closed; Bus A and node PM3 are energized. Although, due to security issues, the standard procedure is different, the idea here is to study an operating procedure related to connecting generator U3 to the system and to determine the impact of switching of 95U03 at the high voltage terminal of the transformer.

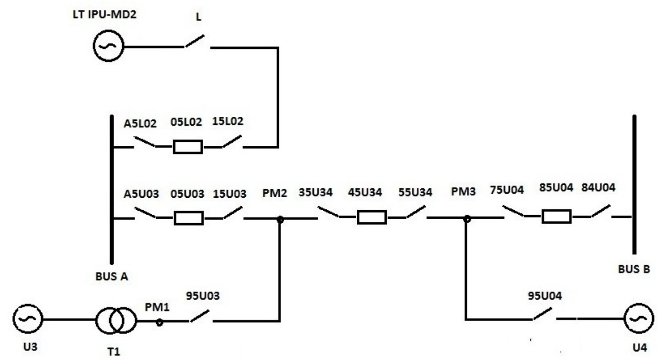

Fig. 1. Unifilar representation of the GIS substation model.

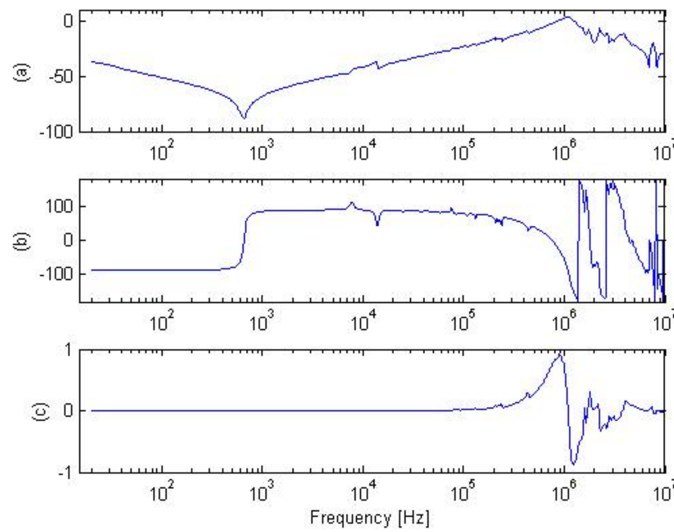

Fig. 2. Admittance of the high voltage terminal: magnitude [dB] (a) and angle [degrees] (b); and, Conductance [S] (c).

Black box models have been developed using frequency response admittance data (see Figure 2) for the single-phase 525/18 kV, 256 MVA generator transformer under consideration. Only the high voltage winding open circuit admittance data is used since the present study is concentrated on this terminal of the transformer.

Figure 2 also contains the eigenvalues of the measured conductance (see (12)). The transformer measurements presents a passivity violation between 1 and 10 MHz. Therefore only the frequency response measurements from 10 Hz to 1 MHz will be used. With this data, different black box modeling procedures will be analyzed and discussed.

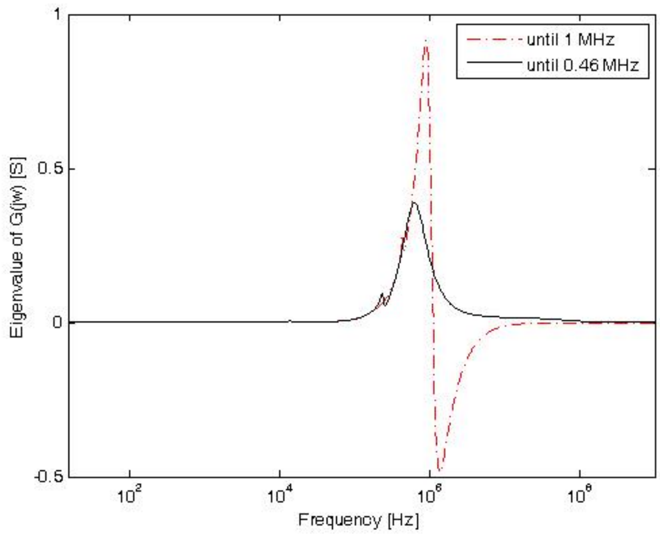

Fig. 3. Conductance of models computed using data up to 1 MHz and 0.46 MHz respectively.

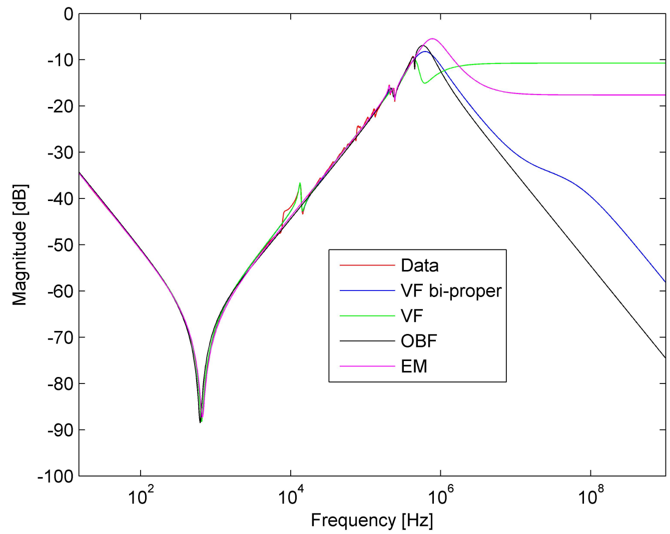

Fig. 4. Magnitude of the models in comparison with the measured data.

The small propagation delays associated with the substation sections involved in the simulation will require the EMTP simulation to run with small time steps. In the present case, the simulation time step is made equal to 1 nanosecond. This results in high frequency modes (up to 0.5 GHz) of the identified black box models being relevant during the simulation despite the model having been computed from data with an upper limit of 1 MHz. Therefore we must also ensure that there are no passivity issues associated with the models for the frequency range above 1 MHz.

Figure 3 illustrates this issue. By using the iterative identification method described in Section II-A, with the basis given by (5), $N = 8$ and a strictly proper model, two models were identified. One based on data measured up to 1 MHz and other based on data measured up to 0.46 MHz. It can be noted that, even though both used data that are consistent with a passive circuit, one model is passive and the other one isn't passive when the larger band is considered. Therefore the data range used in the system identification will be limited to 0.46 MHz.

B. Transformer Modelling

Four procedures will now be tested: a) The iterative identification method described in Section II-A, with the basis given by (5), $N = 8$ and bi-proper model; b) The iterative identification method described in Section II-A, with the basis given by (5), $N = 8$ and strictly proper model; c) The iterative identification method described in Section II-A, with the basis given by (6), $N = 8$ and strictly proper model; d) The iterative identification method based on expectation maximization algorithm [11], with 8-th order and $N = 8$ and bi-proper model;

Figures 4, 5 and 6 contain the frequency response and conductance of the four models. It can be noted that all of the models are able to reproduce the data quite well in the band from DC to 0.46 MHz, since this is the data used to compute the model parameters. This is reinforced by Table I. In this table, it can be noted that although all approximations are good, the model with basis (6) is the one with the better approximation. It is important to remark that the EM method ([11]) is also capable to estimate the covariance of the measurement noise.

Model	MSE ($\times 10^{-4}$)
VF bi-proper	1.1048
VF	1.1429
OVF	0.7164
EM	1.4367

TABLE I
MEAN SQUARE ERROR OF THE MODELS FITNESS.

In the band from MHz to GHz, each model presented a different behavior. The high frequency asymptotes of models with strictly proper structure are decreasing, reproducing the behavior of the data (see Figure 2). The model computed using the EM method presented passive violation in high frequencies, as it is shown by Figure 6. The passivity issue appeared in a band that was not used in the system identification procedure, but is important in the final application of the model.

C. Simulation study

As described in the beginning of this section, the transient signal analyzed here is generated by closing the disconnector 95U03 and then energizing PM1, at the high voltage side of the transformer.

The simulation is reproduced using the models obtained in Section II, that is: the model with the basis given by (6), denoted here by model OBF; model with the basis given by

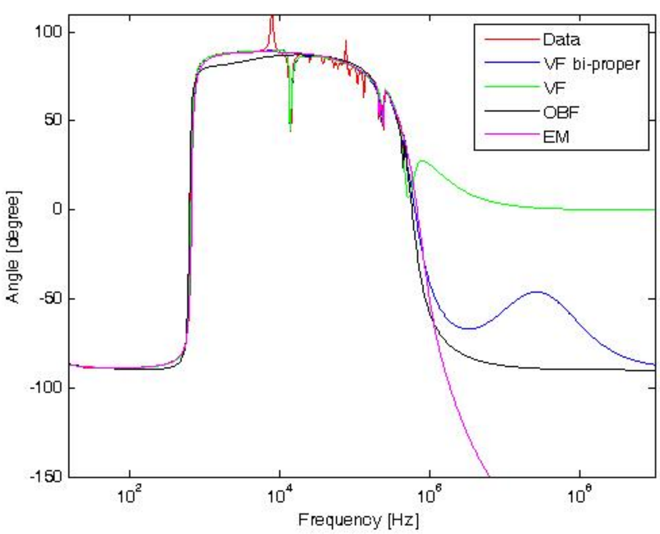

Fig. 5. Angle of the models in comparison with the measured data.

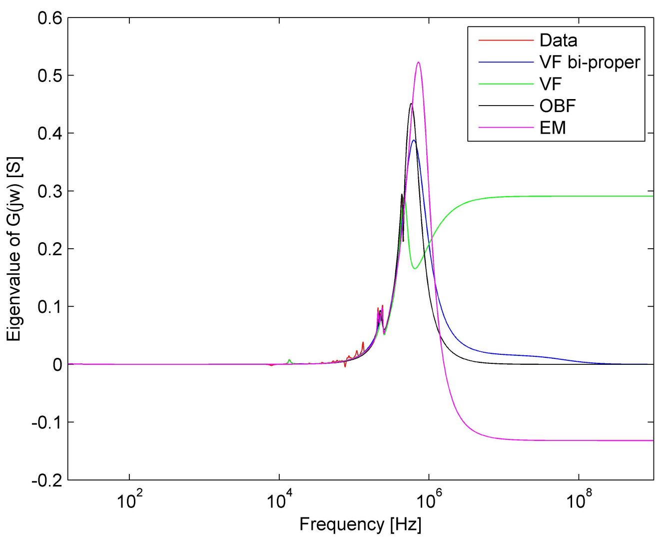

Fig. 6. Conductance of models in comparison with the measured data.

(5) and strictly proper model, denoted here by model VF1; the model with the basis given by (5) and bi-proper model, denoted here by model VF2. The model computed using the EM method will not be used because it is non-passive.

Figure 7 shows the simulation from time zero to time 0.02×10^{-3} seconds and Figure 8 shows the same simulation, but from time 0.01 to 0.02×10^{-3} seconds. It can be noted that, although the models are quite accurate within the band provided by the measurements, the fast transients stimulated by this switching generated resonances above this band, where the three models are different, so the results are different in the time domain. The transient obtained with the three models,

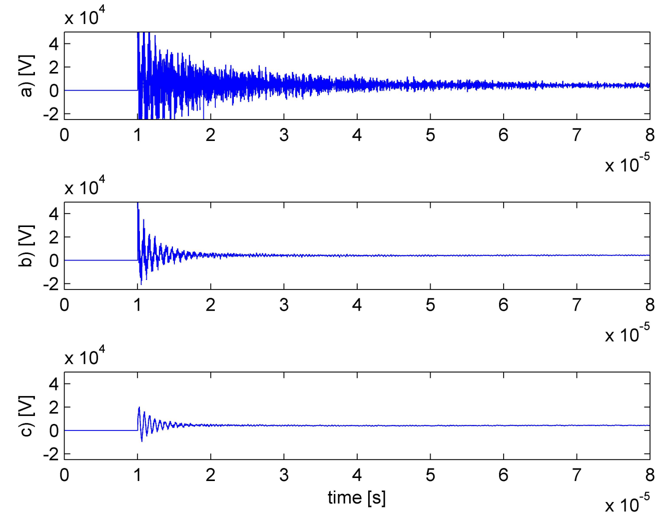

Fig. 7. Comparison between time domain responses: a) model OBF; b) model VF1; c) model VF2.

when interacting with the system, have similar fundamental frequencies (around 1.3 MHz, which is above the measured band), however the transient generated with model OBF has higher energy and higher frequencies than the ones generated by the other models. As far as the VF1 and VF2 models are concerned, the strictly proper model presented transients with higher frequencies and higher energy.

Unfortunately, the authors have no field measurements neither a reliable wide-band white-box model of this transformer in other to validate the time-domain results presented here. However, as a matter of fact, such information aren't always available in general transient studies and, in interesting issue arisen with the present paper is how simulations can be different due to the use of different modelling procedures although all of them provided models with similar approximation quality in relation to the available measurements. Once it could be possible to enlarge the band of the reliable measurements, such effect will tends to fade.

V. Conclusion

This work described and compared methods for obtaining power transformer models based on frequency response field measurements for use in transient studies. The importance of analyzing the passivity of the measured data and the passivity of the identified model for obtaining numerically stable simulations, has been demonstrated. One method that used the conductance matrix was described in detail.

A case study based on an actual GIS substation is presented for comparing the modeling approaches. Measurements from the field transformer are used in the system identification procedures.

All models presented quite good agreement with the measurements. However, above the measurement frequency band,

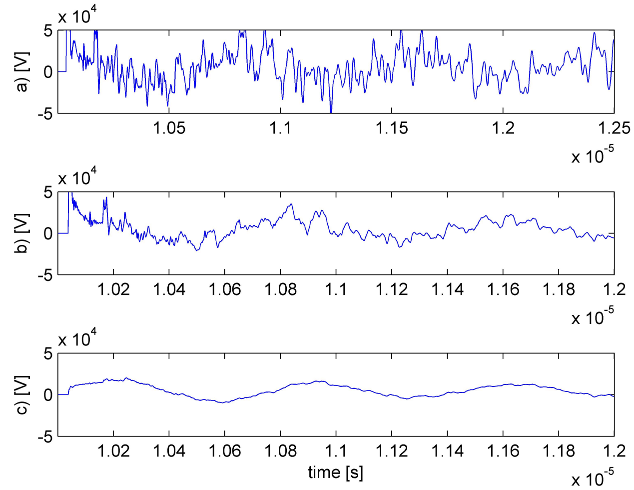

Fig. 8. Comparison between time domain responses (zoom): a) model OBF; b) model VF1; c) model VF2.

each model had its own properties. The difference between the models leads to an important impact in the time domain simulations, since the very fast transients generated have frequencies above the measurement band, where the differences between models are higher.

This study highlight that, although a good system identification method is fundamental for transient studies, it is also important to have wide band accurate measurements in order to provide accurate time domain very fast transients analysis.

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