High-frequency Transformer Modeling for Transient Overvoltage Studies

G. Marchesan, A. P. Morais, L. Mariotto, M. C. Camargo, A. C. Marchesan

***Abstract*-This paper presents the development of high frequency transformers models for electromagnetic transient studies. The Vector Fitting algorithm based on the short circuit admittance matrix has been used to achieving this goal. It was employed two approaches; the first uses a set oscilloscope and function generator, while the second utilizes a Sweep Frequency Response Analyzer (SFRA) through a special connection. The results showed that both methodologies may be used to assemble the admittance matrix. However, SFRA does not suffer noise and harmonics influence, and therefore, presented better results.**

***Keywords*: Transformer modeling, Transient Overvoltage, High frequency, Vector fitting, Sweep Frequency Response Analyzer.**

I. INTRODUCTION

THE majority of components which constitute a modern electrical power system have been successfully modeled for transients studies. The transformer is one exception to this rule.

Modeling transformers for electromagnetic transient studies is very complex, since there is no general consensus about a model that can represent the transformer for all types of events. The complexity is due to each phenomena is characterized by a distinct frequency range. For instance, elements such as capacitances can be neglected in low frequency; however are essential in high frequency transients studies.

Most transformers models available in computer simulation programs for electromagnetic transient analyzes are suitable only for studies of mid and low frequencies. The use of conventional models and simplified approaches, such as the addition of typical capacitors, for fast and very fast transient studies result in a completely lacking analysis. Thus, for these applications, the transformer needs to be properly modeled considering their behavior at high frequencies.

The models shown so far in the literature are not consolidated and they are divided into three groups: Black, White and Gray box models. The White box models, consider the modeling of the internal elements of the transformer and its geometrical arrangement. The Gray box models take into account also the internal geometry of the transformer. However, the determination of the elements values is made through external measurements [1], [2].

The Black box models do not take into account the internal geometry, and they are based on time or frequency domain measurements. The Vector Fitting is one of the most recognized methods to find Black box models. Therefore, this paper reports the experience in high frequencies modeling of transformers using Vector Fitting [3].

II. VECTOR FITTING ALGORITHM (VF)

The terminal behavior of linear component can be characterized by its voltage/current relationship, defined by the admittance matrix, *Y:*

$$I(s) = Y(s).V(s) \qquad (1)$$

The Y matrix can be represented by a rational function; and a suitable model for EMTP-type programs can be obtained. In [3] the authors proposed to solve this nonlinear least square problem with VF. This approach produces an approximation in the form of residue matrices and common set of guaranteed stable poles, which are real or come in complex conjugate pairs. The realization is on the form:

$$Y(s) = \sum_{m=1}^{N} R_m \cdot \frac{1}{s-a_m} + D + sE \qquad (2)$$

Passivity must be enforced; the procedure for passivity enforcement is shown in [4]. From the state space equations, a RLC equivalent is obtained as shown in [5].

III. METHODS OF MEASUREMENTS THE ADMITTANCE MATRIX

Measuring the admittance matrix Y(s) concerning transformer terminals is an alternative procedure to modeling transformers. This approach gives a terminal equivalent only. It means that internal overvoltages cannot be computed with this methodology.

The element Yjj can be measured applying a voltage of 1 V in a terminal j with the remaining terminals grounded. Element Yij equals the current flowing from ground into terminal i. Fig. 1 shows how to obtain each element of matrix.

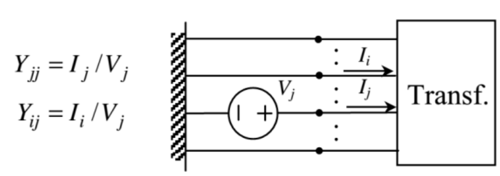

Fig. 1. Simplified representation of electric connections [6].

The admittance matrix can be obtained using Sweep

This work was supported by the State Company of Generation and Transmission of Electricity (CEEE-GT), Brazil.

G. Marchesan, A. P. Morais, L. Mariotto, M. C. Camargo, G. Cardoso Junior, A.C. Marchesan are with Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brazil (e-mail: gustavomarchesan@gmail.com; adriano@ctism.ufsm.br; mariotto@ufsm.br; matheuskmargo@gmail.com; adriano.marchesan@gmail.com).

Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

Frequency Response Analyzer. This equipment has been designed to carry out studies of transfer voltage in transformers and to identify transformers mechanical deformation or internal defects. The data obtained from the measurements can be used for assembling the admittance matrix. However, in order to properly represent the values of their admittances matrix, it is necessary to calculate and correct these data by external equations.

Another approach to obtain the admittance matrix employs the set oscilloscope and a function generator. Both methods are evaluated in this paper as follows:

A. Using the set oscilloscope and function generator(OSCFG)

In this methodology, each frequency has been set on the function generator and then currents and voltages responses in each terminals of the transformer have been analyzed on oscilloscope. The equipment to measuring the voltage and current were a Tektronix MSO4104B oscilloscope, Rigol DG1022 function generator, and TCPA300 current probe.

B. Using Sweep Frequency Response Analyzer (SFRA)

SFRA injects a sinusoidal excitation voltage with a continuously increasing frequency into one terminal of the transformer winding and measures the signal returning from the other terminal. The comparison of input and output signals generates a unique frequency response which can be compared to reference data. The SFRA procedure has been done according to [7].

IV. RESULTS

A. Single phase transformer

The single phase transformer model has been accomplished using the admittance matrix obtained by the two ways recently described. Both results have been fitted by VF approach and have been compared.

The first test was carried out for a single phase, 220 V / 127 V, 1 kVA transformer.

A sinusoidal voltage signal with variable frequency was applied to one terminal and all others were grounded. In the tests have been used 53frequencies logarithmically distributed between 20 Hz and 3.16 MHz. The equipment used for the test and the transformer are shown in Fig. 2.

After finishing all measurements and build the admittance matrix, the fitting has been accomplished by means of the VF algorithm [3], [8] and [9]. Fig. 3 shows the admittances obtained by OSCFG, the rational approximation obtained by the VF and the fitting error. In the Fig. 4 53 samples frequencies logarithmically distributed between 20 Hz and 3.16 MHz obtained by SFRA measurements are shown. It can be noticed that both frequency responses are very close one to each other. The frequency responses obtained by SFRA suffer much less influence of noise and harmonics. Furthermore, the procedure using SFRA is much faster and is less susceptive to human mistakes and it is possible make the test with a highest sampling frequency.

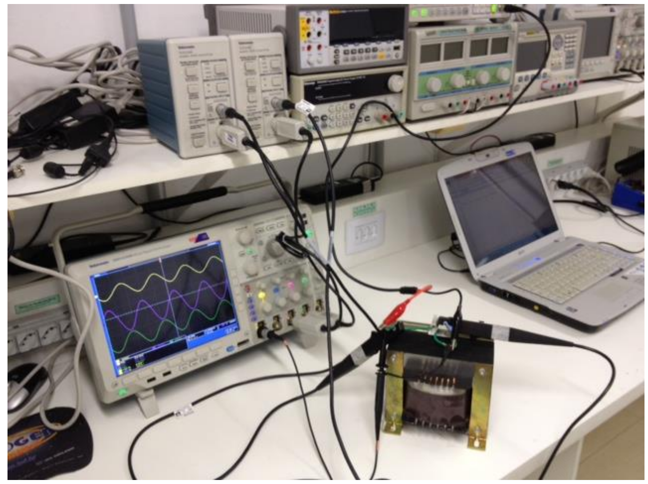

Fig. 2– Equipment used in the test and the transformer

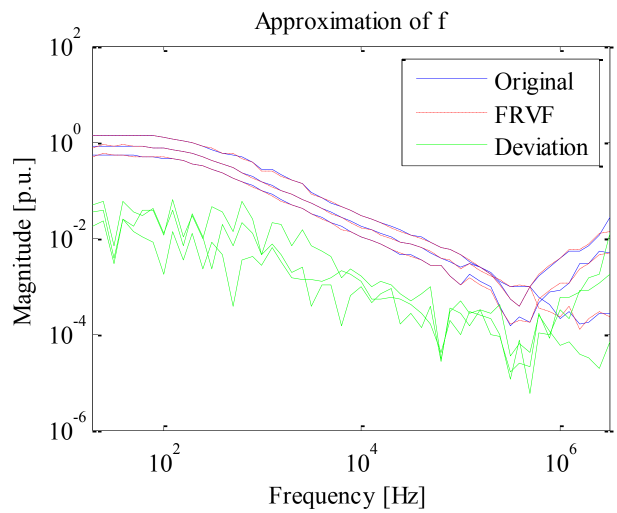

Fig. 3 – Measurement by OCSFG and its rational approximation

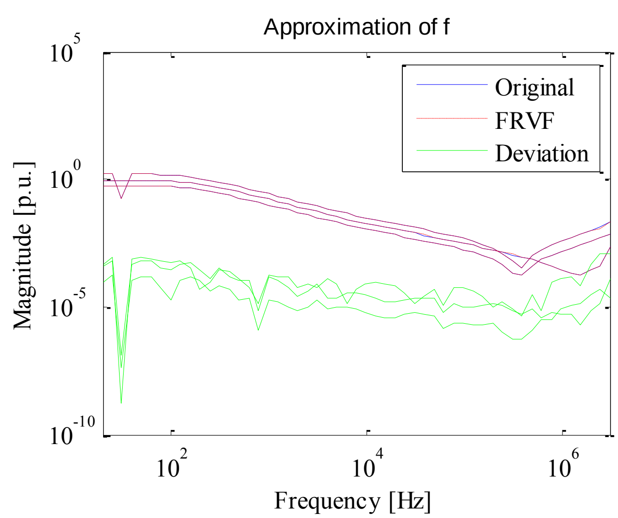

Fig. 4 – Measurement by SFRA and its rational approximation

Two RLCs models have been generated from the two frequency responses. In order to evaluate them, a step response has been applied in the models and in the transformer.

Fig. 5 shows the responses for a voltage step applied in the primary of the transformer. Fig. 6 shows the responses for a voltage step applied in the models (OSCFG and SFRA). Comparing the models responses with the transformer response, it can be observed that the model generated by SFRA presents results more precise than OSCFG. The main problem in the model obtained by OSCFG is that the response has low damping resulting in errors after 5µs.

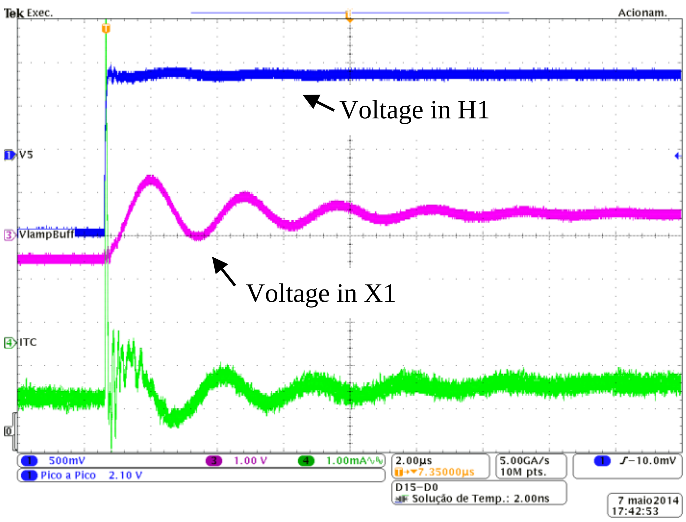

Fig. 5 – Transformer step response applied in H1

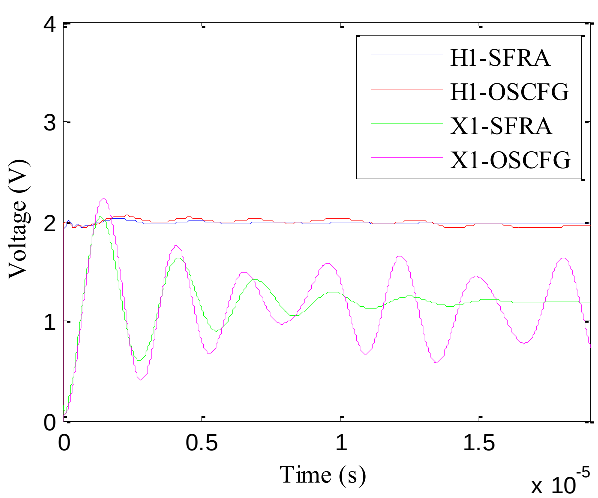

Fig. 6 – Model response for step applied in H1 of the models (OSCFG and SFRA)

Fig. 7 shows the responses for a voltage step applied in the secondary of the transformer. Fig. 8 shows the responses for a voltage step applied in the secondary of the models (OSCFG and SFRA). Analyzing the three responses it can be noticed that the SFRA procedure gives much precise responses.

Even though SFRA procedure utilizes indirect measurements, it is more accurate than the procedure using current probes and oscilloscope. However, it can be noticed that both ways can generate true models. So, the set OSCFG may be an alternative procedure when the SFRA is not available.

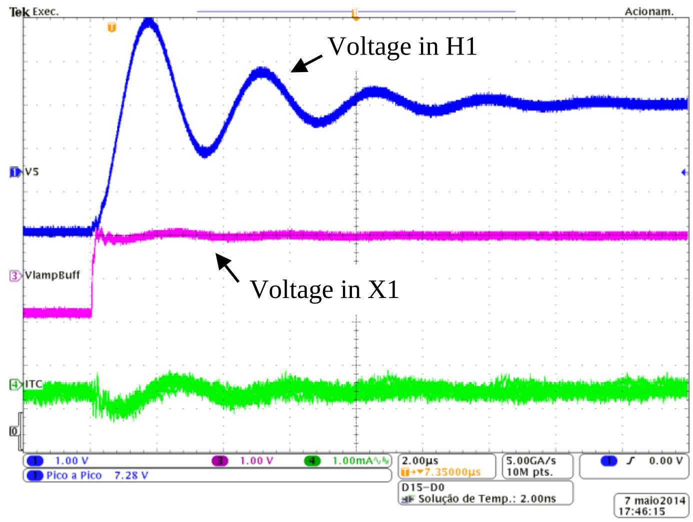

Fig. 7 – Transformer step response applied in X1

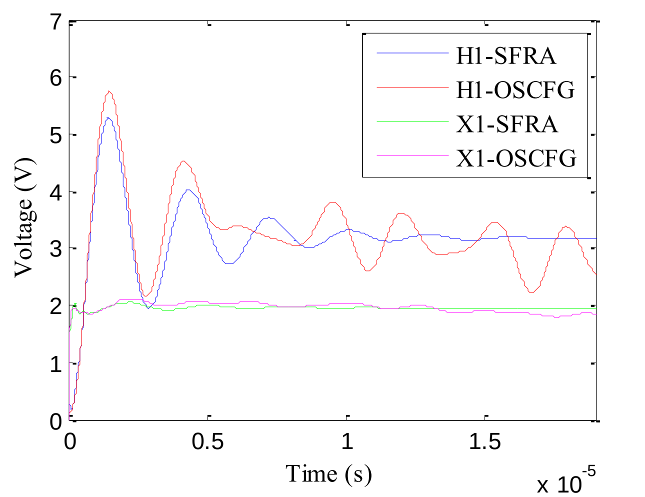

Fig.8 – Model response for step applied in terminal X1 of the models (OSCFG and SFRA)

B. Three Phase Transformer

The second test was performed in a three-phase 1kVA, 0.38/0.76 kV Yg-Yg transformer. Due to a large number of measures, this transformer has been tested only with SFRA procedure. Fig. 9 shows the equipment used and the transformer tested. The admittances obtained in the test, its rational approximation and the deviation between both, are presented in the Fig. 10. The measurements have been made logarithmically spaced frequencies between 20 and 2 MHz. Its rational approximation showed very low error in all frequency spectrum.

The rational transformer approximation is represented by RLC network and it is suitable model for EMTP-type programs.

Fig. 9 – Equipment used and the transformer tested

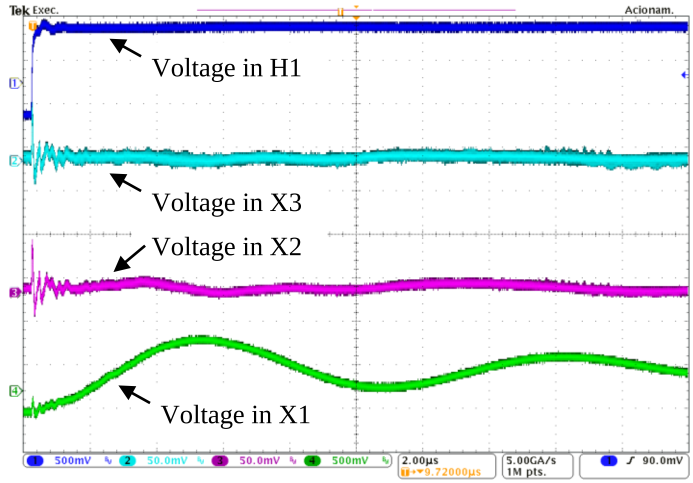

Fig. 11 – Transformer response for voltage step applied in terminal H1

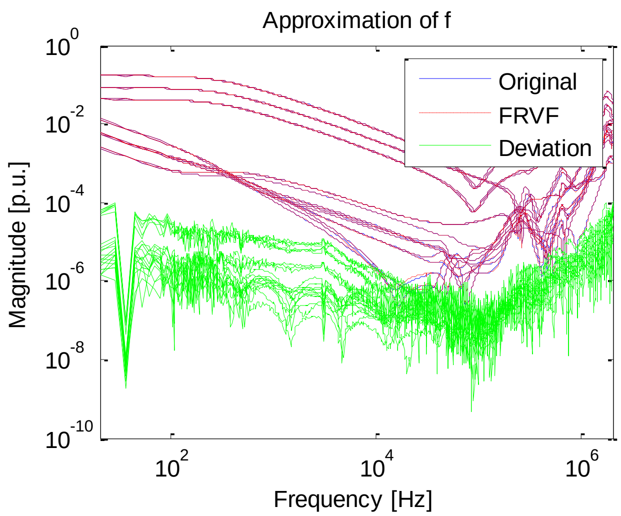

Fig. 10 – Elements of admittance matrix Y measured by SFRA and its rational approximation

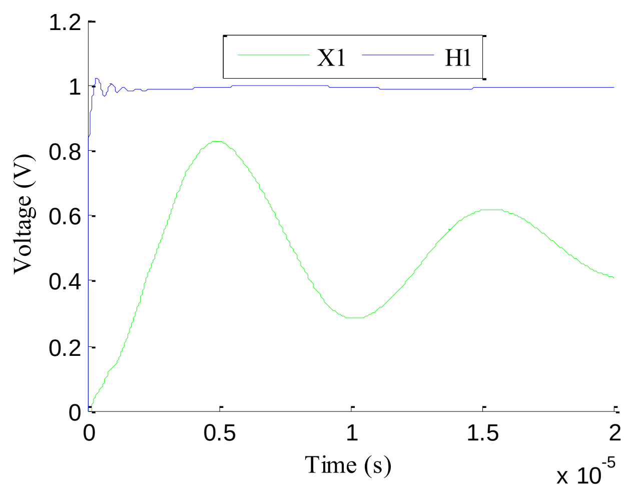

Fig. 12 – Model response for voltage step Applied in terminal H1

In order to validate the model obtained, a voltage step has been applied on the terminal H1.The terminals H2 and H3 were grounded and X1, X2 and X3 were connected to ground through a 3kΩ resistor. Fig. 11 shows the voltages in the transformer and Fig. 12shows the voltage in model.

Comparing the transformer and model responses it can be noticed that both are very close. The voltage in the terminal H1 of the transformer and the model are almost the same.

The frequency measurement has performed up to 2MHz, in this way; the higher frequency oscillations are not properly represented.

When the terminals X1, X2 and X3 are connected to ground with 5 kΩ resistors, the model has shown to be unstable. More studies are being conducing to identifying why the model did not converge with some loads.

The model was also tested for voltage step at the terminal X1. The terminals X2 and X3 were grounded and the terminals H1, H2, andH3 were connected to ground using three resistors. The resistances have been varied and all simulations converged using this connection. In the Fig. 13 and Fig. 14 are shown the transformer and the model responses with the transformer secondary opened, respectively. Comparing both figures is possible to see that the transformer and the model have shown a very similar response.

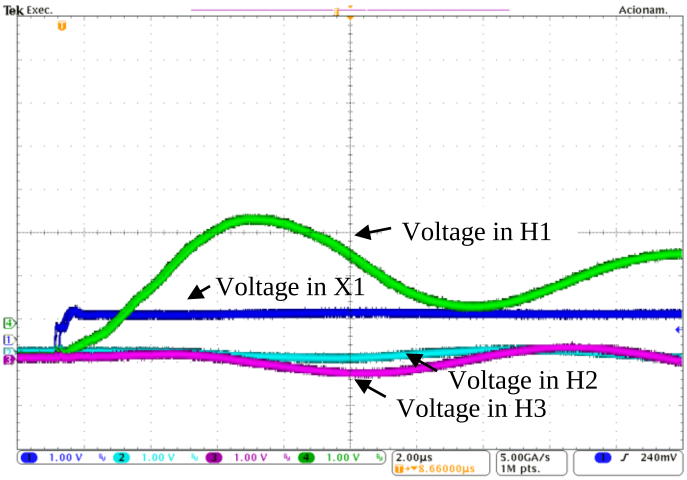

Fig. 13 – Transformer response for voltage step applied in terminal X1

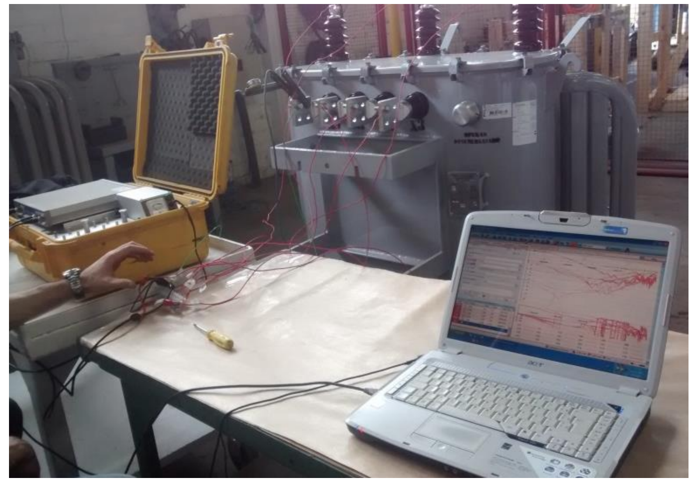

Fig. 15 – Equipment used and the transformer tested

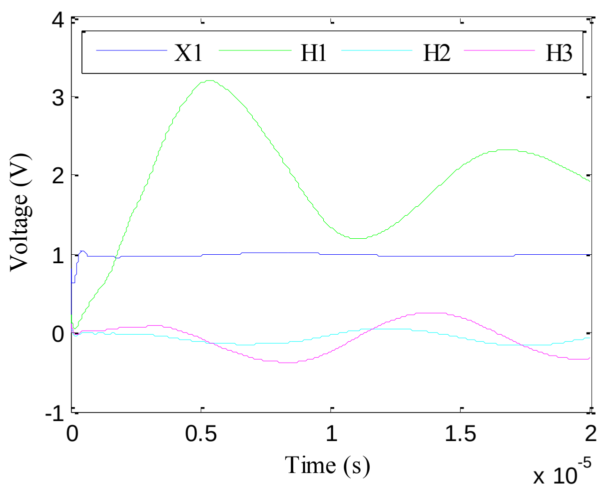

Fig. 14 – Model response for voltage step Applied in terminal X1

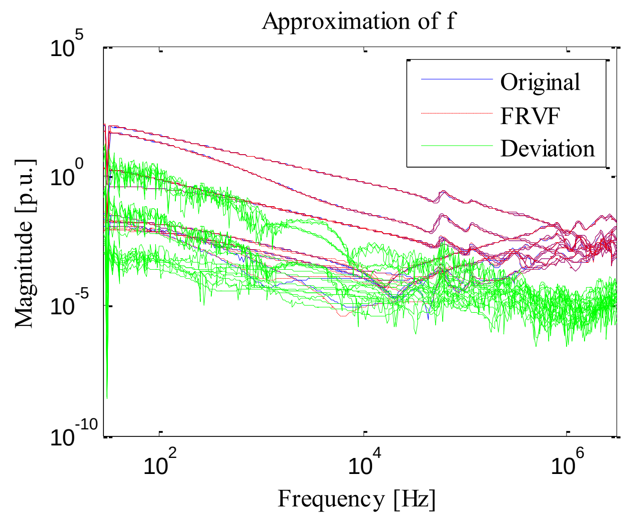

Fig. 16 – Elements of admittance matrix Y measured by SFRA and its rational approximation

C. *Three-phase Distribution Transformer Modeling*

The third model was generated from a three-phase 300 kVA, 13.8 / 0.38 kV Yg-D distribution transformer. The Fig. 15 shows the equipment used for this test. The admittances obtained in the test, its rational approximation and the deviation between both, are presented in the Fig. 16. Four hundred measurements have been made logarithmically spaced frequencies between 20 and 3MHz. Its rational approximation has shown small errors in all frequency spectrum.

The transformer and the RLC model were also tested with a step in the terminal H1. The voltages in the transformer are shown in the Fig. 17.Fig. 18-A shows the voltages applied in the terminal H1, Fig. 18-B,C and D show respectively the voltages in the terminals X1, X3, and X2. Comparing Fig. 17 and Fig. 18 is possible to notice that the model correctly represents the transformer in general aspects. When a voltage step is applied in the secondary of the transformer the model becomes unstable.

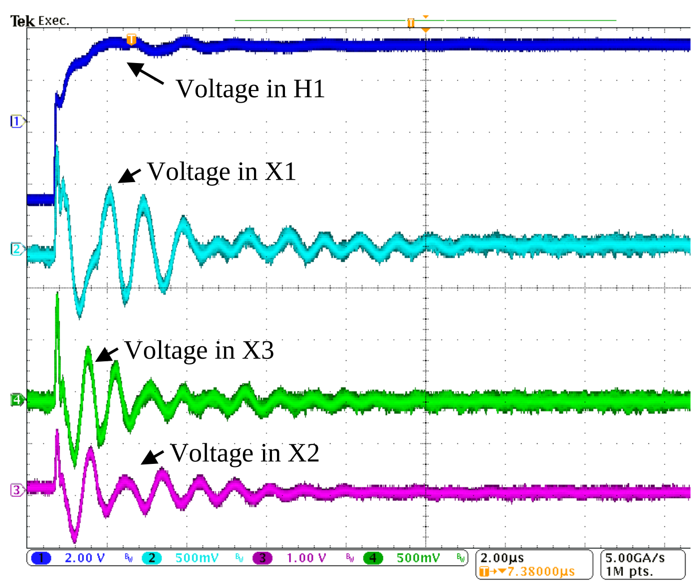

Fig. 17 – Transformer response for voltage step applied in terminal H1

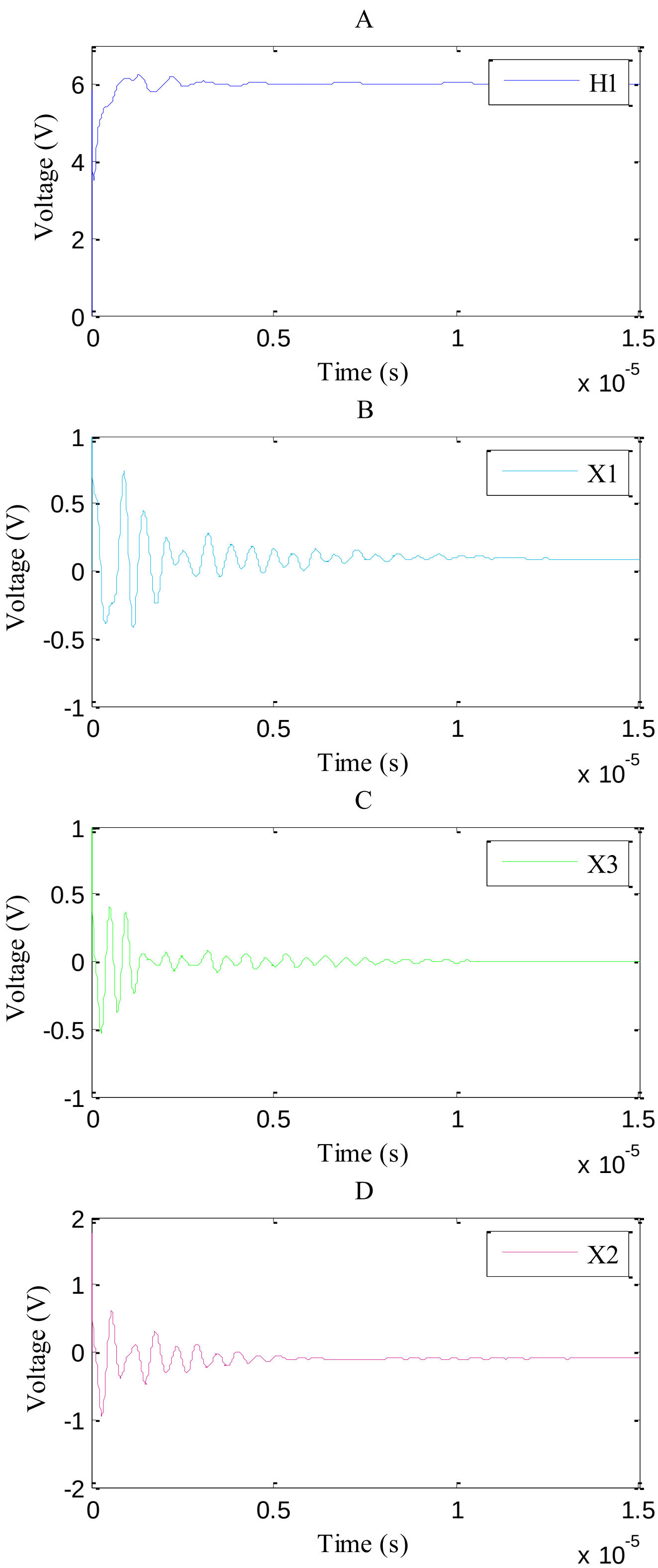

Fig. 18 – Model response for voltage step applied in the terminal H1

V. Conclusions

This paper has reported the experience in high frequencies transformers modeling using Vector Fitting. Two different approaches in the assembly of the admittance matrix have been performed by using the OSCFG for a single phase transformer and with SFRA for single and three phase transformers. Although much more laborious and less accurate, has been shown that it is possible to get transformers models using OSCFG. The paper also presents a high frequency three-phase transformer model. The model is very accurate in most of the simulated cases, but, when the load is varied, it becomes unstable for some of these load values. A distribution power transformer was also modeled with SFRA and Vector Fitting algorithm, the result shows that the method is accurate, but some instability in the model can occur.

VI. Acknowledgment

This work is receiving financial resources from the State Company of Generation and Transmission of Electricity (CEEE-GT), within the Project of Research and Development 9947883.The authors gratefully acknowledge CEEE-GT for providing the SFRA equipment, and Polo Electro, for providing the Distribution Transformer.

VII. References

[1] P. I. Fergestad and T. Henriksen, "Transient oscillations in multi-winding transformers", *IEEE Trans. Power Apparatus and Systems*, vol. 93, pp. 500-509, 1974.

[2] R. C. Degeneff, A general method for determining resonances in transformer windings", *IEEE Trans. Power Apparatus and Systems*, vol. 96, no. 2, pp. 423-430, March/april 1977.

[3] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by Vector Fitting", *IEEE Trans. Power Delivery*, vol. 14, no. 3, pp. 1052-1061, July 1999.

[4] B. Gustavsen and A. Semlyen, "Enforcing Passivity for Admittance Matrices Approximated by Rational Functions", *IEEE Trans. Power Systems*, vol. 16, no. 1, pp. 97-104, February2001.

[5] Gustavsen, B., "Computer code for rational approximation of frequency dependent admittance matrices," Power Delivery, IEEE Transactions on , vol.17, no.4, pp.1093,1098, Oct 2002

[6] Gustavsen, B., "Wide band modeling of power transformers," *Power Delivery, IEEE Transactions on* , vol.19, no.1, pp.414,422, Jan. 2004

[7] Holdyk, A.; Gustavsen, B.; Arana, I.; Holboell, J., "Wideband Modeling of Power Transformers Using Commercial sFRA Equipment," *Power Delivery, IEEE Transactions on* , vol.29, no.3, pp.1446,1453, June 2014 doi: 10.1109/TPWRD.2014.2303174

[8] B. Gustavsen, "Improving the pole relocating properties of vector fitting", *IEEE Trans. Power Delivery*, vol. 21, no. 3, pp. 1587-1592, July 2006

[9] D. Deschrijver, M. Mrozowski, T. Dhaene, and D. De Zutter, "Macromodeling of Multiport Systems Using a Fast Implementation of the Vector Fitting Method", *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 6, pp. 383-385, June 2008