Black-Box Modeling of Power Transformers at High Frequencies

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Abstract - **In some studies of electromagnetic transients it is necessary to use a model that represents the power transformer at high frequencies. The transformer was modeled in this case by its impedance seen from the high voltage terminal. It is a single-phase power transformer of 200 MVA, 500 / √3 / 138 / √3 / 13.8 kV installed in a substation. The black-box methodology was used, which was based on field measurements of the terminal impedance in a frequency range, through access to the external terminals of the transformer. Two models of the power transformer in the range of 20 Hz to 2.5 MHz were used and a comparative analysis was carried out. The simulation of switching operations was done using the ATPDraw / ATP – Alternative Transients Program – and the validation of the power transformer models in the frequency range of 20 kHz to 2.5 MHz was done through field measurement of voltage transients.**

Keywords: **Power Transformers Modeling; High Frequencies; Electromagnetic Transients; Black-Box Modeling; Frequency Response; Terminal Impedance; Field Measurements; ATPDraw/ATP.**

I. INTRODUCTION

The electrical system is subject to disturbances that can put at risk the equipment connected to it, compromising their useful life and, consequently, the reliability and quality of the electric power supply. Therefore, it is necessary to study the interaction between the equipment and the system and analyze the electrical stress imposed on the high voltage equipment.

Approximately 35 years ago, in a substation of the Brazilian Interconnected System, three power transformer units and one high voltage bushing have failed. In addition to that, the values of partial discharges in several bushings of the same type increased. It is a 500/√3 / 138/√3kV shielded substation isolated by SF6, and of great importance for the supply of electric energy to a certain region. The analyzes at that time indicated the occurrence of high frequency transients related to some switching operations on the 500 kV side as a possible cause of the failures. This way, it was determined the restriction of operation of these switches which, since then, are not operated when one of their terminals is with voltage [1].

More recently, these restrictions have in some cases resulted in penalties and financial charges to the power transmission company responsible for the substation. In addition, some additional circuit breaker operations and sometimes the inconvenient disconnection of the synchronous compensator are required. In an attempt to eliminate this operational constraint, an investigation was initiated to evaluate the electric transients originated from the switching operations on the 500 kV side and the interaction of these with the new transforming units.

For the analysis of the interaction between the electromagnetic transients stress generated from the switching operations and the power transformer, it is necessary to represent the equipment at high frequencies. The aim of this paper is to present the development of high frequencies models of this power transformer from its terminal measurements for electromagnetic transient studies, and discuss a comparative analysis between these models. The measurements were performed by LabDig – Laboratory of Diagnostic of Electrical Equipment and Installations – of Cepel – Research Center in Electrical Energy, in Brazil.

II. METHODOLOGY

In order to provide to transformer manufacturers requests for switching operations, good modeling is required. Based on a literature review, it was verified that, for studies of the interaction of high frequency transient requests and the power transformer, among others an appropriate methodology is the black-box. For this, the behavior of the transformer in the frequency must be analyzed [2-8].

According to this methodology, the impedance from phase-to-ground seen in the high voltage terminal of the power transformer being studied in the range of 20 Hz to 10 MHz was measured in the field. It is a single-phase transformer of 200 MVA, 500 / √3 / 138 / √ 3 / 13.8 kV shown in Fig. 1. The other terminals were opened. The tests were performed with the taps in 525 / √3 kV and 138 / √3 kV and with the equipment disconnected from the electrical network, that is, the measurement of the terminal impedance in the frequency range was performed offline.

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Fig. 1. Single-phase power transformer 200MVA, 500 / √3 / 138/√3 / 13.8 kV installed closed to a GIS substation.

For the impedance measurements two RLC meters were used. A voltage signal is applied and the resulting current and voltage are measured. From the relationship between measured voltage and current, the desired impedance is obtained in modulus and angle for a frequency range.

From 20 Hz to 100 kHz the QuadTech7600 measurement equipment was used with 5V of input voltage, and from 100 kHz to 10 MHz, the HP 4285A measurement equipment was used with 2V applied at the entrance. A total of 346 points were acquired.

Copper strips were used from the instrumentation to the bushing terminal in order to reduce the inductance. However, repeatability is lost in the test since, depending on the physical displacement of the tapes, the measuring arrangement is changed. As the frequency increases, there is a greater influence of the measurement arrangement, since the inductive reactance of the conductors and connections increases considerably, and the capacitive reactance has a very low value, which means an increased capacitance to ground.

There are ongoing studies in CEPEL regarding the use of coaxial cables for the measurement of frequency response of power transformers associated with possible techniques for elimination of cable effects by using transmission-line representation of the measurement cables with parameters obtained from standard cable data [8].

Fig. 2 shows the result of impedance measurement along the frequency range, in module and angle, seen at the high voltage terminal.

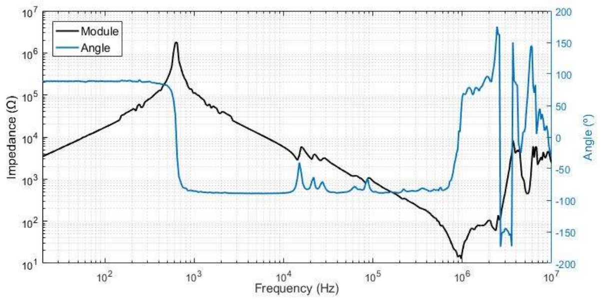

Fig. 2. Measurement of impedance along the frequency range seen at the high voltage terminal.

Fig. 2 reveals that there is an inductive behavior up to approximately 650 Hz and a capacitive effect up to approximately 1 MHz. From 1 MHz to 10 MHz the predominance of the inductive behavior is noted again, with some variations to capacitive behavior.

The frequencies at which the inductive and capacitive reactances are equals (maximum energy exchange between capacitor and inductor) are called resonant frequencies. In these points the impedance value is equal to the resistive parcel. The maximum points are called parallel resonances and the minimum points will be named in this work as series resonances.

Interference at the end of the spectrum is noticed. Phase angle measurement is more susceptible to interference. From approximately 2 MHz, the angle values exceed the range between -90º and 90º which configures an error in the terminal impedance measurement. This way, it was chosen to model the transformer only up to 2.5 MHz.

III. Power Transformer Modeling

The terminal impedance curve is analyzed in the frequency range and it is aimed to derive a synthesis that represents the transformer in high frequencies. The stray capacitance is considered.

Any system is modeled using a methodology and from a point of view. Two models of the power transformer were achieved using the black-box methodology: 1) the approximation through Vector Fitting and 2) terminal impedance analysis relating the resonance points fitting through the quality factor. The last one is the lightweight model. Both have, as their point of view, the impedance of the high voltage terminal.

To simplify, the aforementioned models will be defined in this work, such as Vector Fitting model and Terminal Impedance model, respectively.

A. Vector Fitting Model

Vector Fitting generates, in an iterative way, an approximate rational function of the measured curve. Gustavsen has several publications about the method, implementations and applications [3-4], [9-12]. A set of poles and zeros that have behavior at the frequency close to the measurement is achieved. In order to do this, a number of poles and iterations are determined and the weight given to each frequency band. This is a well-established method and routines are in the public domain, available through the Matrix Fitting Toolbox. The VFdriver and vectfit3 routines make the rational adjustment through the reallocation of the poles. The RPdriver routine is responsible for the application of passivity [11].

There is the possibility of generating a RLC circuit that represents the function for implementation in programs based on the EMTP, through the Netgen_ATP routine. Fig. 3 shows the synthesized circuit of the approximate rational function using Vector Fitting. The RL branches represent the real poles and the RLC branches are equivalent to the conjugated complex poles [12].

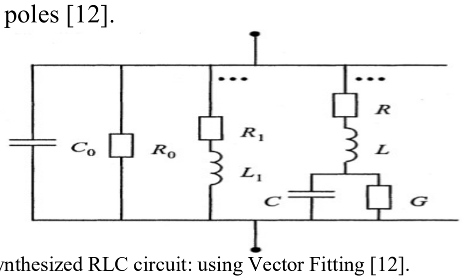

Fig. 3. Synthesized RLC circuit: using Vector Fitting [12].

The software MatLab was used to implement the Vector Fitting routines. Admittance is used as data input. Thus, for the modeling of the transformer by its impedance seen from the high-voltage side, element-by-element of the impedance vector was inverted.

The fitting was performed with 15 poles – 1 real pole and 7 conjugated complex poles. The result of the approximation is shown in Fig. 4. The absolute error is the difference between the non-passivity approach and the passivity application. Fig. 5 shows the result of the sweep in frequency of the model compared to the measurement in module and angle.

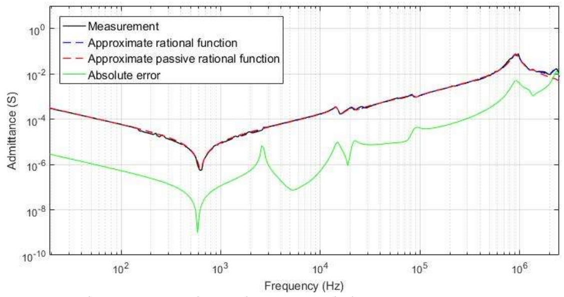

Fig. 4. Approximate curve through Vector Fitting.

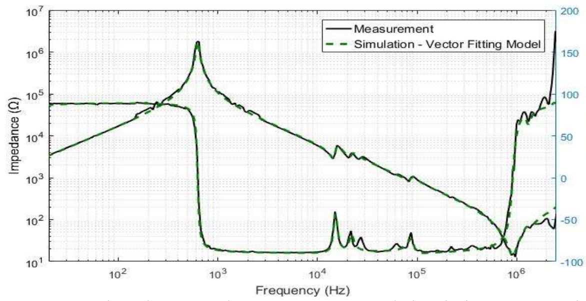

Fig. 5. Comparison between the measurement and simulation: Vector Fitting model.

B. Terminal Impedance Model

Azevedo, Rodrigues and Cerqueira propose in [2] a modeling based on the measurement of terminal impedance in the frequency range, relating the capacitance and inductance values of the resonant points through the quality factor. It is a practical, simplified method that allows to reach the model based on only one terminal. Fig. 6 highlights the frequency points considered in the modeling. The parallel resonance frequency (f_1), the series resonance (f_2) with a difference greater than 3 dB in relation to the central frequency and the series resonance (f_3) between the surge capacitance (Cs) and the inductance of the connections are considered.

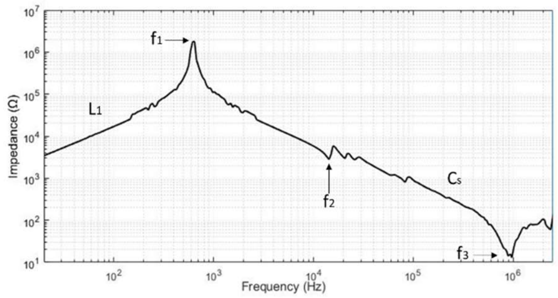

Fig. 6. Measurement of the impedance module in the frequency range seen from the high voltage terminal – Highlight for the points considered in the modeling.

The modeling starts taking into consideration f1 and Cs, the resistance value of the first circuit of the synthesis is identified and the inductance (L1) values – relative to the nominal frequency – and capacitance are calculated. Then, the resistance value related to f2 is verified and the capacitance and inductance values are associated through two definitions of quality factor shown in (1) and (2) [2].

$$Q = \frac{2\pi f_0 L_0}{R_0} \tag{1}$$

$$Q = \frac{f_0}{df} \tag{2}$$

The bandwidth df (Fig. 7) is defined as the range of frequencies in which the signal's spectral density is above (below) a certain threshold relative to its maximum (minimum). Most commonly, the threshold refers to 3 dB. The impedance related to the bandwidth df is determined by (3) [2].

$$Z_{dB} = 20 \log\left(\frac{Z_{df}}{R_0}\right) \tag{3}$$

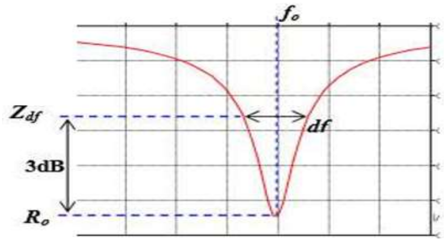

Fig. 7. Bandwidth relative to its center frequency.

By combining the two definitions of quality factor (equations (1) and (2)) gives the inductance and capacitance values determined by (4) and (5), respectively [2].

$$L_0 = \frac{R_0}{2\pi df} \tag{4}$$

$$C_0 = \frac{1}{L_0(2\pi f_0)^2} \tag{5}$$

The final step of the synthesis process is the modeling of the f_3 series resonance, between the Cs and the inductance of the connections [2].

The parameters resulting from the modeling are shown in Table I. The resulting synthesis circuit assembled in the ATPDraw is shown in Fig. 8, and Fig. 9 shows the modeling results compared to the module and angle measurements.

TABLE I
PARAMETERS OF THE MODEL FROM THE ANALYSIS OF RESONANT POINTS OF THE TERMINAL IMPEDANCE AT THE FREQUENCY RANGE.

Frequency (Hz)		R (Ω)	L (H)	C (F)
f_1	644.20	1.784 M	-	-
	60.80	-	26.66	-
	287 k	-	-	1.83 n
f_2	14.31 k	2.81 k	176.54 m	701.39 p
f_3	969 k	12.80	17 μ	-

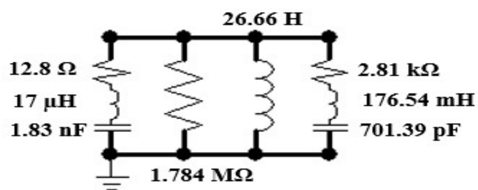

Fig. 8. Synthesized circuit: Terminal Impedance model.

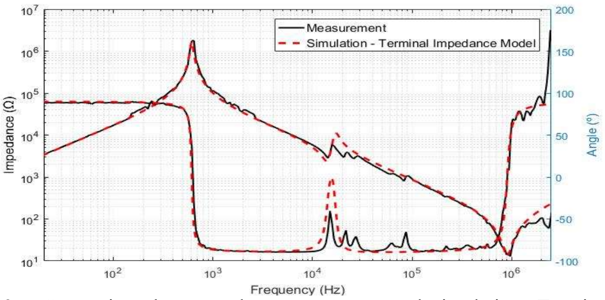

Fig. 9. Comparison between the measurement and simulation: Terminal Impedance model.

IV. RESULTS

For the investigation of a problem in the electrical system, the simulation and measurement steps, for being complementary, must be associated. The results of the simulations are also of great importance for the specification and design of the appropriate instrumentation for the measurement of voltage transients in the field, besides allowing the definition of a sequence of switching operations. On the other side, the frequency response measurement of the transformer allows the development of a model that enables simulations to be closer to reality.

Transient measurements in the field are of fundamental importance to validate the modeling of the phenomenon analyzed in the simulations [2]. With the results of the transient measurement it is possible to validate the models used, and with this, validate the model of the equipment under analysis, in this case, the power transformer.

Simulation of the switching operations was performed and the results of the simulations were compared with the voltage transient measurements made in the field. The operational restriction is in the 500 kV substation, so the results presented, both simulation and measurement, refer to the transient voltage that arrives at the high voltage terminal of the transformer from the switching operation. The results of the simulations and the field measurements are presented, considering a time window of 50 µs (frequency range between 20 kHz and 10 MHz) of the switch operation 9437. The time signal will be shown up to 15 µs for better visualization.

Fig. 10 shows the diagram of the section of the substation. The switch operation is realized with the disconnect switches 9435, 9447, 9445 and 931 closed and circuit breakers 9432 and 9442 open.

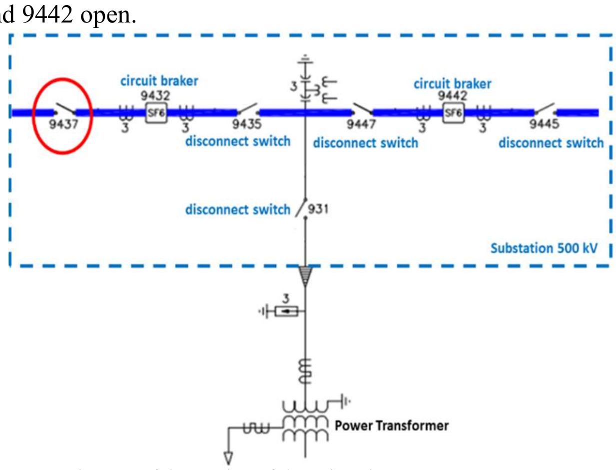

Fig. 10. Diagram of the section of the substation.

A. Simulation

In the ATPDraw / ATP, simulations were performed in the time domain of the switching operations, which are currently restricted. The 500 kV GIS substation was represented by the JMarti model, which takes into account the variation of the parameters with the frequency, but the aerial section (output of the substation of 500 kV to the transformers) was modeled by a transmission line with distributed and constant parameters.

For the disconnecting switches and the circuit breakers, the time controlled switch model was used. In the circuit breaker model, there is a series capacitance representing the equalization capacitor. A maximum voltage difference was represented between the disconnecting switch contacts by charging the de-energizing section with the same amplitude and polarity opposite to that of the system associated with the last reignition of the opening operation. A time step (Δt) of 1 ns was used in the simulations.

Fig. 11 shows the results of the simulation of the transient voltage from the switching operation in time using the Terminal Impedance and Vector Fitting models.

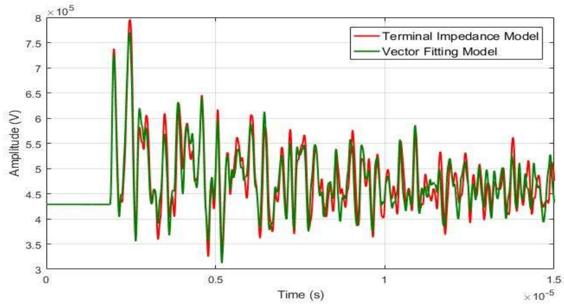

Fig. 11. Transient voltage from the switching operation – Simulation: Terminal Impedance model and Vector Fitting model.

In order to determine the frequency components of the transient voltage signal, the FFT – Fast Fourier Transform was performed. The result is shown in Fig. 12. With the purpose of making the relation with the nominal voltage, the vertical axis shows the amplitude in pu (ratio between the measured voltage and a base voltage), using as base value the nominal phase-to-ground peak voltage taking into account the position of the tap – 525 kV / √3 * √2. Using the 50 µs time window, frequencies from 20 kHz are reached. The frequency range was started at 300 kHz, since the first component with the greatest amplitude (in the range of 20 kHz) is approximately 560 kHz.

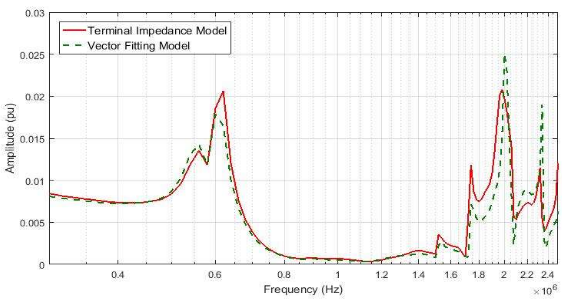

Fig. 12. FFT of the transient voltage from the switching operation– Simulation.

The models present very close results. The amplitude frequency components are at approximately 560 kHz, 600 kHz, 1.53 MHz, 1.74 MHz, 2 MHz, 2.33 MHz and 2.5 MHz and are practically coincident using the two models. The Vector Fitting model presents the highest amplitudes in the frequency components 2 MHz and 2.33 MHz, and in the other components the results with the Terminal Impedance model have larger amplitudes. The highest amplitude component is at approximately 2 MHz and has 0.02507 pu (2.51% of nominal phase-to-ground peak voltage) with the Vector Fitting model and 0.02079 pu (2.08% of nominal phase-to-ground peak voltage) with the Terminal Impedance model.

B. Voltage Transient Field Measurements

One of the great challenges of the Electric Power System is the measurement of high voltage values in the field, and in the case of high frequencies, the measurement becomes even more difficult. Due to the difficulties of measuring high frequency overvoltages in the field, many of the electromagnetic transient studies have their simulations based mainly in mathematical calculations.

CEPEL performed the transient voltage measurements up to 10 MHz through the capacitive tap of the high voltage bushing of the transformer. Since the voltage levels of the bushing tap are not yet compatible with the measuring system, for attenuation of the signal, it was used a low voltage unit (connected to the bushing tap) and an attenuator (connected to the output of the low voltage unit). To transmit the signal it was used optical fiber, seeking to immunize it from electromagnetic interference.

After the fiber optic receiver, a high pass filter was used in order to remove the operating frequency to increase the resolution of the measured signal. Finally, there is an oscilloscope and a notebook for recording, viewing and analyzing the measured signal. The measured signal was attenuated approximately 377,000 times. Therefore, the measurement results had to be multiplied by this scale factor.

The characteristics of the measuring system and the conditioning for the measurements involve correcting the recorded signals to better infer the signal arriving at the high voltage bushing. Since the measuring system does not remain constant over the entire frequency range, the characterization in the frequency of the attenuator, the filter and the tap assembly, low voltage unit and optical fiber were made. There are ongoing studies in CEPEL that aim for greater reliability in measuring the frequency response of the voltage transient measurement system at the end of the spectrum. Fig. 13 shows the measuring system used.

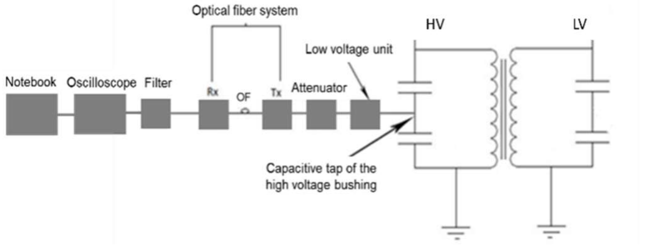

Fig. 13. Transient voltage measurement system integrated into the capacitive tap of the high voltage bushing of the power transformer.

In the simulation it was shown the maximum voltage impulse associated with the last reignition of the opening operation. The maximum voltage impulse measured is shown in Figs. 14 and 15 in time and frequency, respectively.

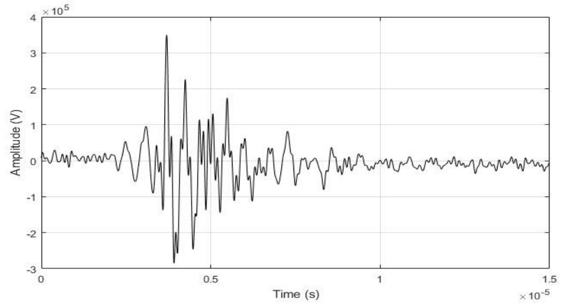

Fig. 14. Maximum voltage impulse from the switching operation– Measurement.

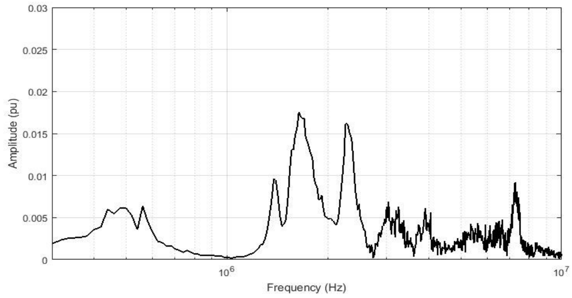

Fig. 15. FFT of the maximum voltage impulse from the switching operation– Measurement.

Interference in the frequency spectrum is observed mainly from above 2.5 MHz. CEPEL believes that by shielding the secondary unit, the attenuator and the fiber optic transmitter – instruments of the measurement system which are most susceptible to interference – will significantly reduce electromagnetic interference in the measured signal. The next field measurements will already be carried out with these shielded instruments.

The highest amplitude components of the measurement, up to 2.5 MHz, are at approximately 480 kHz, 560 kHz, 1.38 MHz, 1.64 MHz and 2.28 MHz. The largest amplitude component is at 1.64 MHz and has 0.01752 pu (1.75% of nominal phase-to-groung peak voltage).

C. Validation of Power Transformer Models at High Frequencies

For the validation of the models, the results of the simulations were compared with the field voltage transient measurements. Although the field measurements of both the terminal impedance at the frequency range and the voltage transients were made up to 10 MHz, it was decided to use them up to 2.5 MHz taking into account the greater reliability in the measurement up to that frequency and the interference in the end of the spectrum – from 2.5 MHz to 10 MHz – in both measurements. Figs. 16 and 17 show the comparison of the results of the measurement and simulation of the transient voltage from the switching operation in time and frequency using the two models. The 60 Hz component was not measured. Thus, in order to be possible to compare measurement and simulation in the time domain, the amplitude relative to the operating frequency of the simulated transient voltage results was withdrawn. Voltage transient measurements were performed with the 138 kV substation connected to the low voltage terminal of the transformer.

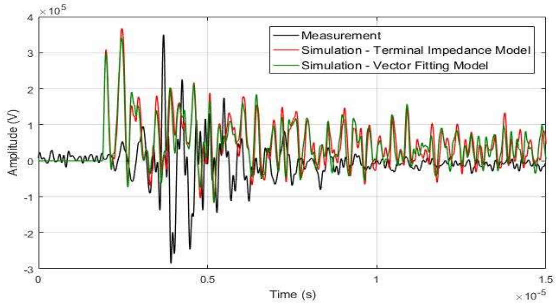

Fig. 16. Transient voltage from the switching operation – Measurement x Simulation.

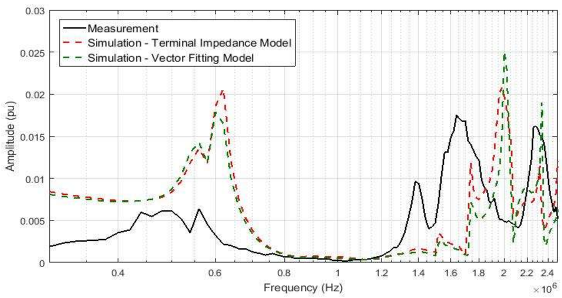

Fig. 17. FFT of the transient voltage from the switching operation – Measurement x Simulation.

However, in the simulations, the 138 kV substation was not represented. The models were obtained considering opened the low voltage terminal, and the synthesis represents the impedance seen from the high voltage terminal to the ground. The amplitude components, in general, are larger in the simulation compared to the measurement and the frequencies are displaced. Through the comparisons in the time domain it is possible to notice that the oscillations have larger amplitudes in the results of the simulations. However, in relation to the maximum signal peak, the simulation and measurement results have very close amplitudes.

It is believed that the representation of the aerial section (output of the GIS substation of 500 kV to the transformers) through the JMarti model will damp the amplitude of the frequency components of the simulations. In order to do so there are necessary parameters related to the cables and distances of the aerial section, information requested from the energy company responsible for the substation.

Vector Fitting is a robust and well-established method for black-box modeling. The Terminal Impedance model presents a simplified synthesis that, depending on the application and the modeling point of view, works well. The series resonances, in addition to f2, that were not considered in the Terminal Impedance model are between 10 kHz and 100 kHz. The simulated transient voltage features components starting at 560 kHz (in the range of 20 kHz), a range to which both models respond closely. Because of this, the results of the simulations are close between the two models, but relatively far from these field measurements.

V. Final Considerations

The Vector Fitting model suffers most with the influence of interference, since the Terminal Impedance model is based on the resonant points and the Vector Fitting generates a function that responds in frequency approximately to the measured curve. However, through the Terminal Impedance model it is not possible to model the transformer from more than one access point and there are limitations in relation to the number of resonant points, especially if the frequencies are very close. Using Vector Fitting with the impedance seen from the terminals and the transfer of voltage between the terminals at the frequency range it is possible to build the admittance matrix. However, such measurements are not simple to perform for modeling purposes in field environments.

It is pointed out the need for studies on measurement methods and signal processing techniques related to frequency response for the purpose of modeling, aiming to achieve models that represent the electrical equipment with greater precision and in a greater frequency range, increasing the reliability of the simulation results. In addition, the influence of the impedance of the copper tapes on the frequency response measurement is greater with the increase in frequency and does not have good repeatability, since the arrangement and its geometry can influence the measurement. Therefore, in relation to characterization in the frequency domain, the use of coaxial cable, associated with techniques to eliminate the effect of the cable, is also pointed out [1-10]. The measurement of electromagnetic transients in the field still presents challenges. It is suggested studies that seek and evaluate alternatives for the measurement method, regarding the evaluation of the interferences and the response of the measurement system in the frequency range.

VI. References

[1] P. C. V. Esmeraldo, F. M. Salgado Carvalho. "Surge Propagation Analysis: an Application to the Grajaú 500 kV SF6 Gas-Insulated Substation". International Conference on Large High Voltage Electric Systems. Cigre. Paris, 1988.

[2] A. da C. O. Rocha et al. "Electrical Transient Interaction Between Transformers and the Power System - Part 1: Expertise". Cigre. Joint Working Group A2/C4.39. April 2014. Technical brochure 577A.

[3] B. Gustavsen. "Wide Band Modeling of Power Transformers", IEEE Transactions of Power Delivery, v. 19, n. 01, pp.414-422, January 2004.

[4] B. Gustavsen, A. Portillo. R. Ronchi, A. Mjelve. "High-Frequency Resonant Overvoltages in Transformer Regulating Winding Caused by Ground Fault Initiation on Feeding Cable", IEEE Transactions on Power Delivery, pp.1-9, 2017.

[5] B. Jurisic, I. Uglesic, A. Xemard, F. Paladian, P. Guuini. "Difficulties in high frequency transformer modelling" in Proc. Int. Conf. Power Systems Transients, Cavtat, Croatia, 2015.

[6] B. Jurisic, A. Xemard, O. Moreau, I. Uglesic, F. Paladian, S. Lallechere. "Comparison of transformer models on a practical case of lightning overvoltages" in International Colloquium on Lightning and Power Systems – Cigré, Paris, 2016.

[7] B. Jurisic, P. Poujade, A. Xemard, I. Uglesic, F. Paladian. "Application of wide band transformer models" in Proc. Int. Conf. Power Systems Transients in Seoul, Republic of Korea, 2017.

[8] B. Jurisic, I. Uglesic, A. Xemard, , F. Paladian. "High frequency transformer model derived from limited information about the transformer geometry". International Journal of Electrical Power & Energy Systems. Volume 94, January 2018, Pages 300-310.

[9] B. Gustavsen. "Eliminating Measurement Cable Effects From Transformer Admittance Measurements", IEEE Transactions on Power Delivery, v. 31, n. 4, pp. 1609-1617, August, 2016.

[10] B. Gustavsen, A. Semlyen. "Rational Approximation of Frequency Domain Responses by Vector Fitting", IEEE Transactions on Power Delivery, v. 14, n. 3, pp.1052-1059, July 1999.

[11] B. Gustavsen. "Matrix Fitting Toolbox – User's Guide and Reference". Sintef Energy Research. 2009.

[12] B. Gustavsen. "Computer Code for Rational Approximation of Frequency Dependent Admittance Matrices", IEEE Transactions on Power Delivery, v. 17, n. 4, pp.1093-1098, October 2002.