Enhanced Analysis of Oscillatory Undamped Overvoltages in Transformer Energization

L. M. N. de Mattos, A. M. P. Mendes, J. F. de Lima Filho, M. C. Tavares

***Abstract*--This paper proposes an enhancement on the methodology commonly used for overvoltage analysis motivated by the excitation of electric network resonance points due to the injection of harmonic currents by equipment with non-linear characteristics. The improvement proposed comprehends the inclusion of effects caused by non-linear equipment into the frequency scan study, the harmonic content survey, the transformation of currents and/or voltages from the phase to the sequence domain and the application of the Windowed Fast Fourier Transform (FFT). This enhanced methodology was applied in the investigation and identification of the unexpected resonant behavior causes observed in the pre-operational electromagnetic transient studies for the energization of a 230/138/13.8 kV – 150 MVA autotransformer.**

***Keywords*: Electromagnetic transients, analysis methodology, undamped overvoltages, frequency scan, sequence components, magnetizing branch representation, Fast Fourier Transform, harmonic content.**

I. Introduction

THE J. Teixeira substation (SS) began its operation in 2014 on Brazilian North Region and is located in the Amazon Rainforest. In the course of the pre-operational electromagnetic transient studies for autotransformers energization, unexpected voltage behaviors on nearby bus bars were detected. Those voltages were shown to be oscillatory and undamped, regardless the simulation duration, which led to suspicion of having excited a resonance or quasi-resonance in the electric network. As in [1], one of the most common causes of transient overvoltages motivated by resonances is the energization of transformers connected to lightly loaded radial circuits.

This type of scenario, where there is a suspicion of some non-linear element exciting resonant points in the electric network, is usually investigated through its impedance frequency scan study, which is then compared to commonly expected [2] harmonic orders for the phenomenon under evaluation. This comparison can also be carried out with harmonic orders obtained through the one cycle Fourier decomposition [3], or even applying a sliding window with the same time length [4], of the currents and/or voltages in the phase domain of the case in study. Although this methodology is consolidated [5] [6], it can be further enhanced, providing a deeper understanding of the observed resonance characteristics.

This work proposes a new procedure to research and identify the causes of the mentioned oscillations observed, consisting of the insertion of four steps to the typical methodology, namely:

a. Insertion of transformer saturation's effect in the frequency scan, by means of the magnetizing branch equivalent inductance reproduction when subject to a certain overvoltage, even in a simplified manner;

b. Survey of the harmonic currents content injected by the transformers present in the simulation when subject to overvoltage, similar to those obtained in the reference case, to enlighten which network resonance points could be excited by those equipment;

c. Transform the voltage found in the mentioned equipment terminals under energization from phase to sequence domain [7];

d. Decompose into frequency domain the sequence voltages by applying the Fast Fourier Transform (FFT), along time, making use of the sliding window technique.

The procedure proposed allowed the identification of which one or ones points of resonance have been excited, their sequence and which equipment provoked the phenomenon. Furthermore, it enabled a deeper understanding of the behavior and the origin of the resonant process, allowing a mitigation strategy, the evaluation of its effectiveness and/or making decision with better technical basis.

The simulations were carried out with the Alternative Transients Program (ATP) [8]. Specific tools were developed to compute sequence voltages, its frequency decomposition and to calculate the approximate equivalent inductance of the transformer magnetizing branch when subjected to voltages above the knee point of its saturation curve.

II. Case Under Analysis

The J. Teixeira SS, in the year 2014, contains two 230 kV circuits to Lechuga, two 230 kV circuits to Mauá III, two 230/138/13.8 kV - 150 MVA autotransformers (ATR) and the 138 kV interconnection trunk, in double circuit, J. Teixeira – Mutirão – Cachoeira Grande.

The first ATR energization, with the second unit off service, was simulated from the high voltage side, radially through Mauá III thermoelectric power plant (TPP), via

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

double circuit 230 kV transmission line (TL) J. Teixeira – Mauá III, as shown in Fig. 1. Its leakage reactance, Xps, is 9.40 % on the ATR's rated base. The considered quality factor of the ATR windings is X/R = 50.

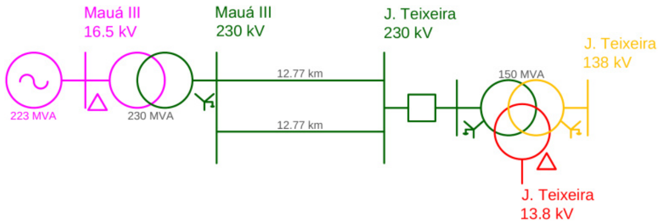

Fig. 1. Single line diagram of the electric network for the J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) energization.

The TL which connects the Mauá III and J. Teixeira 230 kV is 12.77 km long in double circuit. Its parameters are given in Table I. Surge arresters of 192 kV – 4.5 kJ/kV were placed on both TL endings.

TABLE I
230 KV TL J. TEIXEIRA – MAUÁ III PARAMETERS - 60 HZ

	R (Ω/km)	**X (Ω/km)**	**Y (μS/km)**
Zero sequence	0.19470	1.1226	3.0389
Positive/Negative sequence	0.03505	0.32834	4.8763

On Mauá III TPP (Fig. 1) was considered a single gas turbine machine in operation generating in 16.5 kV, inserted into ATP using the 58 model for three-phase synchronous electric machines [8]. The power plant 16.5/230 kV – 230 MVA step-up transformer (TF) has Z_{ps} = 13.0 % in its rated base and X/R = 48.75.

Both TF and ATR saturation curves are shown in Fig. 2. They were represented with the saturable transformer component model [8].

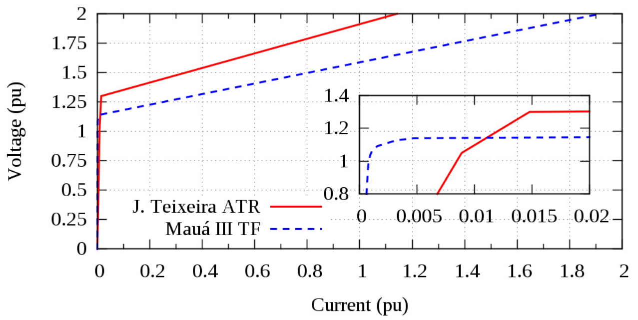

Fig. 2. Saturation curves of J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) and Mauá III SS 230/16.5 kV – 230 MVA transformer (TF).

Statistical energization study was performed to define the most critical case to ATR energization in terms of overcurrent, overvoltage and surge arrester's dissipated energy. The settings used consisted of 200 shots, standard deviation of 1.5 ms and time step of 1.0 μs. This small time step was necessary because the 230 kV TL J. Teixeira - Mauá III is very short and was represented with Bergeron's model [8]. The worse cases, to those cited variables, were reproduced in deterministic simulations. The pre-energization voltage was 1.054 pu on J. Teixeira 230 kV bus bar.

The magnitude of maximum inrush current found is to some extent small to what is usually obtained in transformers energization (Fig. 3).

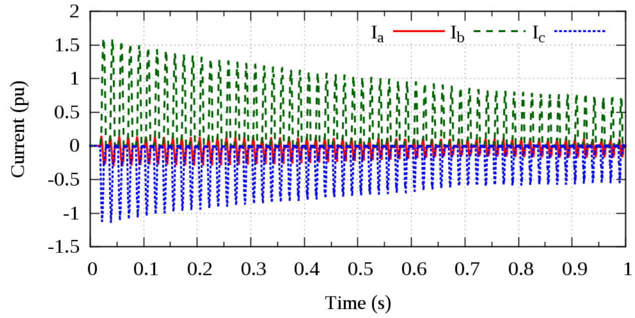

Fig. 3. Currents in the high voltage side windings obtained in the J. Teixeira autotransformer (ATR).

The case that presented the higher overvoltage amplitude and also the undamped oscillatory behavior, illustrated in Fig. 4, will be analyzed using the proposed methodology in the following section.

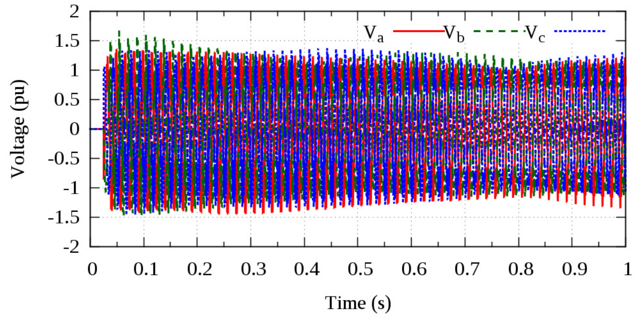

Fig. 4. Phase to ground voltage on the high voltage side of J. Teixeira autotransformer (ATR).

III. Proposed Methodology Steps Applied To The Case Under Analysis

A. Insertion of Transformers Saturation's Effect in the Frequency Scan

The frequency scan routine processes successive phasorial solutions increasing the frequency of the voltage and/or current sources present in the case under study, in a given range chosen by the user [8]. When the ATP solves the phasorial solution, also computed for the t_0^- of cases that will be processed in the time domain, the non-linear elements are not entirely represented [8]. This means that it will not be possible to know precisely the frequency response of some electric network, if there are overvoltages nearby non-linear equipment, such as surge arrester and/or transformers, while the voltage is higher than the linear region of their characteristic curve.

As in the resonance observed in the presented study the transformers were subjected to overvoltages of 1.67 pu, a simplified way to include the magnetizing branch inductance variation of those equipment in the frequency scan routine was sought.

To determine the equivalent magnetizing branch reactance the φ x I curve generated by the auxiliary routine SATURA [8] was used. The magnetic flux and current points that were not available in the SATURA output were linearly interpolated [9]. The equivalent magnetizing branch inductance, L_{eqv}, could then be calculated by (1):

$$L_{eqv} = \frac{\varphi}{I} \qquad (1)$$

The inductance L_{eqv} shows great variation of its magnitude in function of voltage (Fig. 5), especially in the boundaries of the saturation curve's knee point [4].

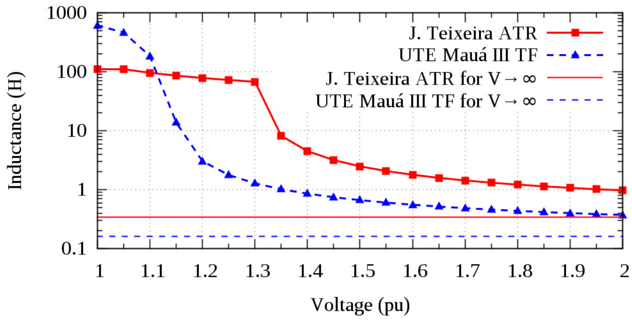

Fig. 5. Transformer units' equivalent magnetizing branch inductance variation in function of voltage.

After acquiring the equivalent magnetizing branch inductances of TF and ATR, the frequency scan study was carried out both considering the original and the modified electric network, where the magnetizing branch was replaced by L_{eqv} calculated to the maximum overvoltage found in the energization under analysis. For frequency scan simulation, Mauá III TPP, represented in the time domain with 58 model, was modeled by its subtransient reactance ($X''d_{ns}$ = 0.1766 pu for V < 1.1 pu and $X''d_s$ = 0.1522 pu for V ≥ 1.1 pu) and then grounded [1] [4].

The zero, positive and negative sequence impedance absolute values, seen from 230 kV J. Teixeira SS bus bar, are shown in Figs 6 and 7, respectively. The electric network resonant peaks' geometric locus is also presented to a variation of magnetizing branch associated to a voltage range values from 1.0 to 1.9 pu. Additionally, the resonant peak values for 1.0 pu, 1.67 pu and infinite voltages are better described in Table II.

It is possible to observe that there are resonant points of great magnitude and sharply tuned to specific frequencies, in zero sequence impedance as well as in positive/negative ones.

Moreover, it can be noted that the modification of magnetization branch made an important difference in the resonant point's location, shifting them to higher harmonic orders. The zero sequence impedance skipped roughly half harmonic order and the positive/negative, almost two, as detailed in Table III.

The reason why resonant peaks shifted to higher harmonic orders comes from the fact that for a generic RLC oscillator circuit, the resonance frequency is defined by (2):

$$f_{osc} = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

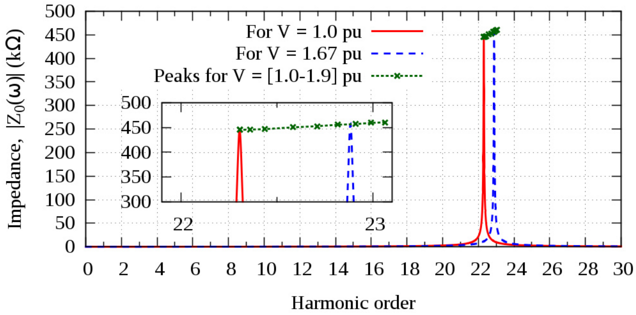

Fig. 6. Zero sequence – Variation of electric network resonant peak when considered the dependence of transformer's equivalent magnetizing branch inductance with voltage.

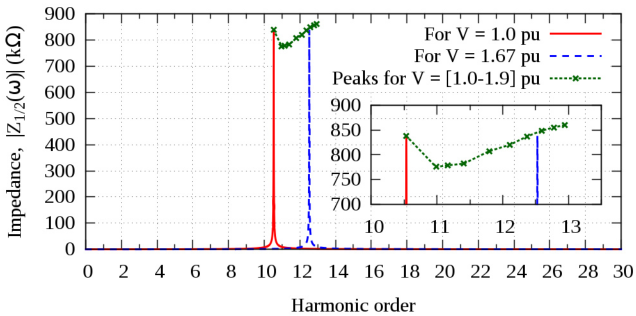

Fig. 7. Positive/negative sequence – Variation of electric network resonant peak when considered the dependence of transformer's equivalent magnetizing branch inductance with voltage.

TABLE II
MAXIMUM SEQUENCE IMPEDANCE PEAK VALUES SEEN FROM J. TEIXEIRA 230 KV BUS BAR WHEN CONSIDERING THE DEPENDENCE OF TRANSFORMER'S EQUIVALENT MAGNETIZING BRANCH INDUCTANCE WITH VOLTAGE.

V (pu)	max(|Z(ω)|) (kΩ)	f (Hz)	h	
1.00	445.7	1338.4	22.3	**Zero Sequence**
1.67	455.0	1373.1	22.9	
∞	478.3	1451.1	24.2	
1.00	837.9	632.1	10.5	**Positive/ Negative Sequence**
1.67	838.7	751.6	12.5	
∞	842.5	918.0	15.3	

TABLE III
MAXIMUM SEQUENCE IMPEDANCE PEAK VALUES FREQUENCY DEVIATION SEEN FROM J. TEIXEIRA 230 KV BUS BAR - V = 1.0 PU AS REFERENCE.

	Zero Sequence		**Positive/Negative Sequence**	
V (pu)	**Δf (Hz)**	**Δh**	**Δf (Hz)**	**Δh**
1.67	34.7	0.6	119.5	2.0
∞	112.7	1.9	285.9	4.8

Therefore, with the net L decreasing, due to both ATR's and TF's L_{eqv} reduction caused by the voltage increasing, f_{osc} goes to higher values. Henceforth 1.5 pu of voltage, there is a decrease in L_{eqv} variation for the same given ΔV (Fig. 5), thus reducing f_{osc} growth rate. That is coherent with the approximation of points which belong to resonant peaks' geometric locus of $|Z_0(\omega)|$ and $|Z_{1/2}(\omega)|$ (Figs. 6 and 7). Hence, for a voltage approaching to infinity, L_{eqv} will tends to the slope of the last segment of φ x I curve, and to its minimum value, which would result in the maximum value of f_{osc}. This would limit the electric network widest theoretical resonance range caused by the variation of the inductance in question. E. g., for the case in investigation, considering an infinite voltage exciting the transformers units' terminals, the zero and positive/negative impedance resonance peaks would shift 1.9 and 4.8 harmonic orders, respectively (Table III). Those deviations are still meaningfully greater than the ones obtained with 1.67 pu voltage.

Accordingly, it is important to point out the need to calculate the L_{eqv} to match with the overvoltage peak effectively found in the reference case, since a higher voltage value would result in a wider expected resonant frequency band than that in fact would be excited in the electric network (Figs. 6 and 7). On the other hand, the calculation of L_{eqv} considering a smaller voltage magnitude can lead to neglect a true piece of resonant frequency range.

The frequency scan common usage methodology, where only the linear region of saturation curve is taken into account, incurs in the foregoing incomplete analysis.

B. Survey of the Harmonic Content of the Transformer and Autotransformer Involved in the Simulation

In order to confirm that the ATR and verify if the TF could excite the electric network's resonance points, a survey of the possible harmonic currents which these elements may inject when subjected to overvoltages was implemented.

This procedure was realized in specific simulations, containing one of the referred elements each time. On the ATR's high voltage side to be energized, a Type 1 source was connected [8]. And, for each TF's side, a source of same type was placed. The points to generate the Type 1 sources have been calculated as follows:

1. The voltages obtained, on both transformers present in the simulation, have been numerically integrated for one cycle starting from the energization instant, in order to acquire the flux in the equipment under study [1] [2] [4];
2. Subsequently, the FFT was applied to the fluxes obtained in the previous item;
3. The fluxes were approximately synthetized by their DC and fundamental components, using the equation (3):

$$\varphi(t) = |\varphi_0| + |\varphi_1| \, cos(\omega_1 t + \angle\varphi_1) \qquad (3)$$

Therefore the higher frequencies were eliminated;

4. Finally, the voltage source Type 1 points were calculated by means of the differentiation of equation (3) along time.

In the procedure presented the fluxes measured in the ATR and TF terminals, during the energization simulation, were reproduced through the manipulation of voltages waveforms in a simplified manner. The idea was to generate similar fluxes to those for whom these equipment were subjected in the reference case, but without the direct injection of a harmonic content besides the unidirectional and fundamental ones. This technique was adopted in order to ensure that the source of harmonic currents is exclusively the transformation unit under analysis.

The harmonic content found in these currents (Figs. 8 and 9), when the transformers were subjected to the voltages synthetized by the procedure described above, is rich and extends through several harmonic orders in accordance with what is expected [6] [10].

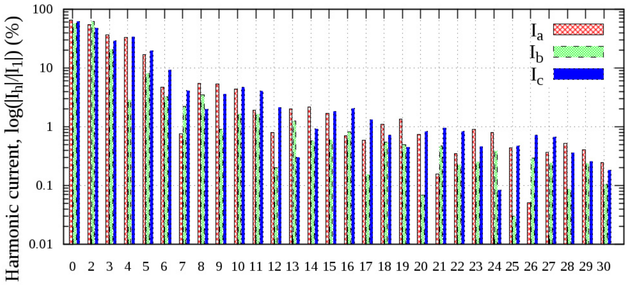

Fig. 8. Harmonic response of the J. Teixeira SS autotransformer (ATR) when subjected to the overvoltages due to the energization in study.

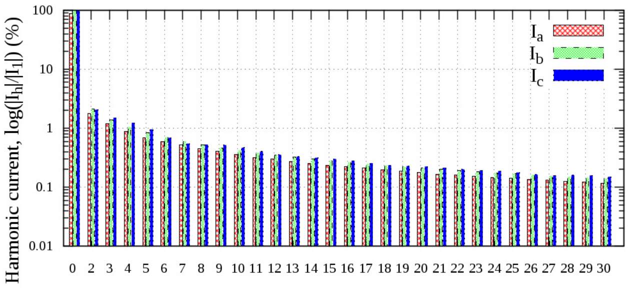

Fig. 9. Harmonic response of the Mauá III SS transformer (TF) when subjected to the overvoltages due to the energization in study.

This frequency range contains the electric network resonance points, with the possibility, thus, that these equipment are exciting the referred resonances. Nevertheless, only these information are not enough to precisely identify which resonance points are being effectively excited.

C. Application of the Fortescue Transformation on the Voltages Obtained in the Energization

A more effective comparison between the overvoltages observed on the reference case and the resonance points, determined in sequence domain, can be realized when the phase variables are converted to sequence components by applying the Fortescue Transformation [7].

D. Frequency Decomposition of the Sequence Voltages

The sequence voltages obtained by the application of Fortescue Transformation on the line to ground voltages of 230 kV J. Teixeira SS (Fig. 4) were decomposed in frequency domain by using FFT [11], employing the one cycle sliding window technique [4] for every time step. The program developed to perform this task made use of a free mathematical package [12]. The results are displayed in Fig. 10.

In the zero sequence voltage curves, it is possible to verify that two harmonic orders, 22^{nd} and 23^{rd}, are dominant (Fig. 10 (a)). Regarding the resonant peaks obtained to $|Z_0(\omega)|$ (Fig. 6) and the current profile injected by ATR and TF

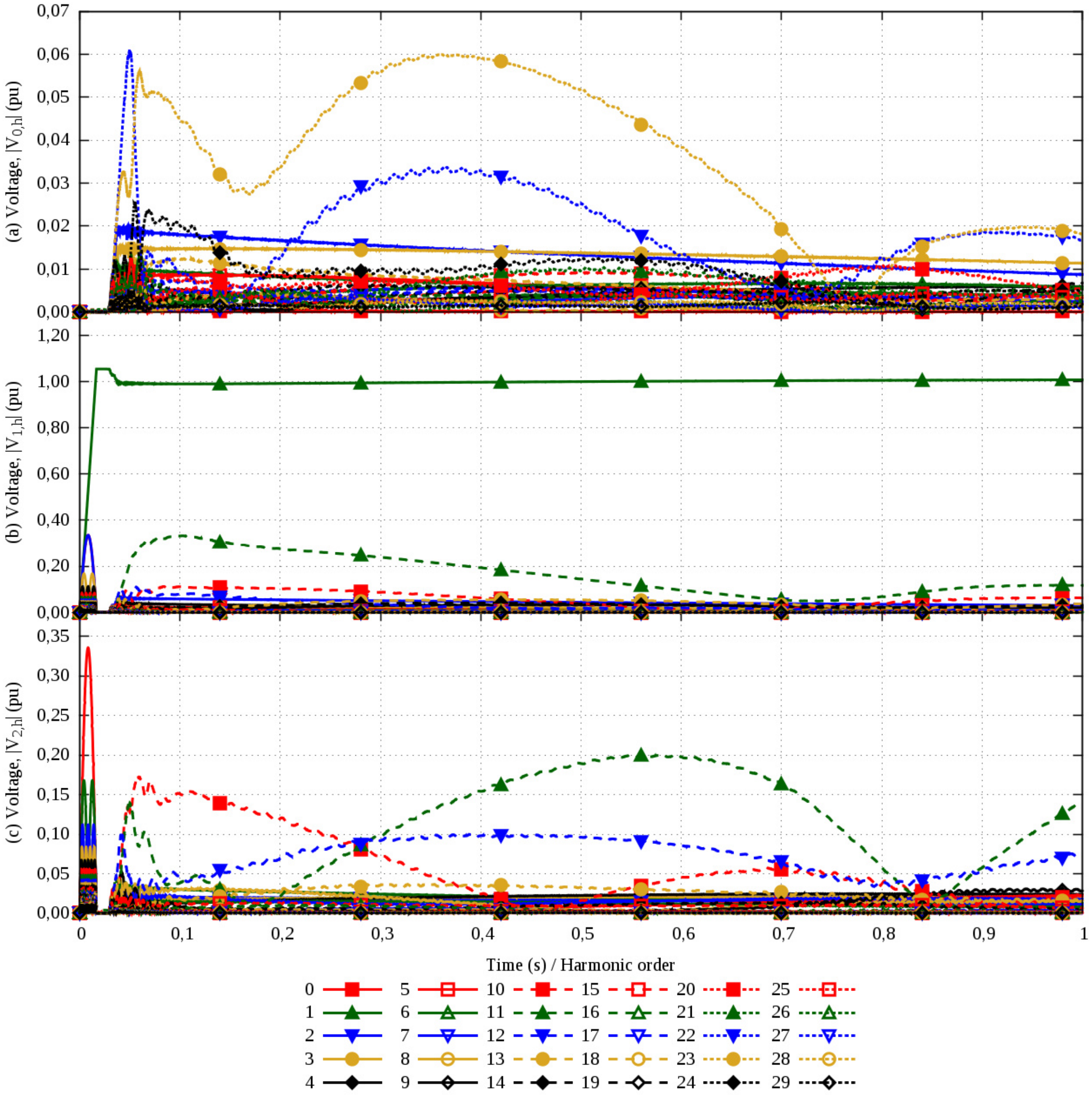

Fig. 10 Zero (a), positive (b) and negative (c) sequence voltages decomposed in frequency along time.

(Figs. 8 and 9), it is understood that the electric network has zero sequence resonance for harmonics 22 and 23.

The positive sequence voltage contains non-fundamental oscillatory components with meaningful magnitudes (Fig. 10 (b)). The most significant harmonics are of 10^{th} and 11^{th} orders, but it is possible to see the 12^{th} with minor amplitude. These orders are located in the resonant peaks region obtained with frequency scan to $|Z_{1/2}(\omega)|$ (Fig. 7). In addition, the studied ATR and TF harmonic content (Figs. 8 and 9) suggests that those equipment may inject currents in the mentioned frequencies, what results that the network has positive sequence resonance for harmonics 10, 11 and 12.

The negative sequence voltage (Fig. 10 (c)) showed a similar behavior to the positive sequence. The more prominent harmonic orders are 10, 11 and 12, presenting oscillatory and undamped curves. There are resonance points for these harmonic orders (Fig. 7), which have been possibly injected by the ATR and TF in analysis (Figs. 8 and 9). For this reason, it is understood that the network also has negative sequence resonance in the same orders of positive sequence.

IV. Conclusions

In the present paper a new procedure to study oscillatory undamped overvoltages observed in an autotransformer energization was presented. The main conclusions are:

- The equivalent inductance of a transformer's magnetizing branch varies significantly with voltage, especially for voltages in the boundaries of saturations curve's knee point;
- The insertion of the magnetizing branch's equivalent inductance, calculated in function of voltage, in the study realized through the frequency scan routine, allowed to visualize that the resonance points of the electric network shifted to higher frequencies when the transformers were subjected to overvoltages;
- The analysis confirms that an electric network which contains non-linear elements, whose characteristics are voltage dependent, will not present resonance points (if existents), but regions, due to the resonant peaks shift caused by voltage variations associated to its V x I characteristic;
- For a voltage approaching to infinity in the transformer terminals, which will generate a flux approaching to infinity, the magnetizing branch's equivalent inductance will tend to the slope of the last segment of φ x I curve, limiting the higher resonance frequency and, thus, the wider theoretical resonant peaks range motivated by the variations of the inductance in question;
- It is important to calculate the equivalent inductance of the magnetizing branch to match the overvoltage effectively found in the reference case. Otherwise, there will be the risk of expecting different resonant peaks range than the one which will be truly excited in the electric network;
- The typical methodology use the frequency scan considering only the linear region of transformers units' saturation curve, which drives to the visualization of only the lower resonant range frequency value, neglecting the higher ones;
- In the absence of inductance variation representation in the frequency scan, the analysis of harmonic sequence voltages decomposed in frequency along time would be hindered, once it would not be possible to explain in a conclusive manner the appearing of some higher order harmonics with important magnitudes;
- The survey of zero sequence impedance with frequency scan was extremely important, or else it would be very difficult to explain the sustained harmonic orders 22 and 23 overvoltages, which could appear in an analysis carried out only in phase domain;
- The voltage transformation from phase to sequence domain was essential to permit an effective analysis of which impedance was in resonance, through matching the results from sequence voltage decomposed in frequency with the electric network sequence impedances obtained with frequency scan;
- The harmonic content study of the transformer which was already in service was important to identify if this equipment would also contribute to the excitation of resonance points found in the electric network, since it was already known that the autotransformer during its energization would inject every order of harmonic currents;
- It is known that the core self inductance is inversely proportional to the frequency [13] [14]. Thus, if this effect was considered in the frequency scan as well, it is expected that the entire resonance range would be shifted to higher frequencies, because it would reduce the equivalent magnetizing branch inductance even more;
- Depending on where the resonance range is placed on the L x f curve [13] [14], which is a core design characteristic, its extremes could be uneven shifted, resulting in a smaller or larger frequency band.

In summary it is suggested the application of the proposed methodology in future electromagnetic transients studies involving non-linear elements when undamped oscillations are observed.

V. References

[1] I. Sadeghkhani, A. Ketabi and R. Feuillet, "New approach to harmonic overvoltages reduction during transformer energization via controlled switching," presented at 15th International Conference on Intelligent System Applications to Power Systems, 2009.

[2] J. Arrillaga and N. R. Watson, *Power system harmonics*, John Wiley & Sons, 2004.

[3] X. Jiang and A. Gole, "A frequency scanning method for the identification of harmonic instabilities in HVDC systems," *IEEE Trans. Power Delivery*, vol. 10, no. 4, pp. 1875-1881, 1995.

[4] R. Turner and K. Smith, "Resonance Excited by Transformer Inrush Current in Inter-connected Offshore Power Systems," presented at IEEE Industry Applications Society Annual Meeting, 2008.

[5] G. Sybille, M. Gavrilovic, J. Belanger and V. Do, "Transformer saturation effects on EHV system overvoltages," , *IEEE Trans. Power Apparatus and Systems,* no. 3, pp. 671-680, 1985.

[6] J. Witte, F. DeCesaro and S. Mendis, "Damaging long-term overvoltages on industrial capacitor banks due to transformer energization inrush currents," *IEEE Trans. Industry Applications,* vol. 30, no. 4, pp. 1107-1115, 1994.

[7] C. Fortescue, "Method of Symmetrical Co-Ordinates Applied to the Solution of Polyphase Networks," *Trans. of the American Institute of Electrical Engineers,* no. 2, pp. 1027-1140, 1918.

[8] H. Dommel, "Electromagnetic Transients Program-Rule Book," Oregon, USA, 1984.

[9] S. Community, "Scipy 0.14.0 Reference Guide," 2014.

[10] H. Bronzeado, P. Brogan and R. Yacamini, "Harmonic analysis of transient currents during sympathetic interaction," *IEEE Trans. Power Systems,* vol. 11, no. 4, pp. 2051-2056, 1996.

[11] J. W. Cooley and J. W. Tukey, "An algorithm for the machine calculation of complex Fourier series," *Mathematics of computation,* vol. 19, no. 90, pp. 297-301, 1965.

[12] N. Community, "NumPy 1.9.1 Reference," 2014.

[13] J. Avila-Rosales and F. L. Alvarado, "Nonlinear frequency dependent transformer model for electromagnetic transient studies in power systems," *IEEE Trans. Power Apparatus and Systems*, n. 11, pp. 4281-4288, 1982.

[14] D. Wilcox, W. Hurley and M. Conlon, "Calculation of self and mutual impedances between sections of transformer windings," *IEE Proceedings Generation, Transmission and Distribution*,1989.