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Enhanced analysis of oscillatory undamped overvoltages in transformer energization

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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 injection of harmonic currents by equipment with nonlinear characteristics. The improvement proposed comprehends inclusion of effects caused by nonlinear equipment into the frequency scan study, harmonic content survey, transformation of currents and/or voltages from phase to sequence domain, and application of the Windowed Fast Fourier Transform (FFT). This enhanced methodology was applied in the investigation and identification of unexpected resonant behavior causes observed in pre-operational electromagnetic transient studies for an autotransformer energization.

1. Introduction

J. Teixeira substation (SS) began its operation in 2014 in Northern Brazil 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 nonlinear 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 four complimentary steps to the typical methodology, namely:

1. Inserting transformer saturation 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;
2. Surveying 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;
3. Transforming the voltage found in the mentioned equipment terminals under energization from phase to sequence domain [7];
4. Decomposing into frequency domain the sequence voltages by applying the Fast Fourier Transform (FFT), over 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

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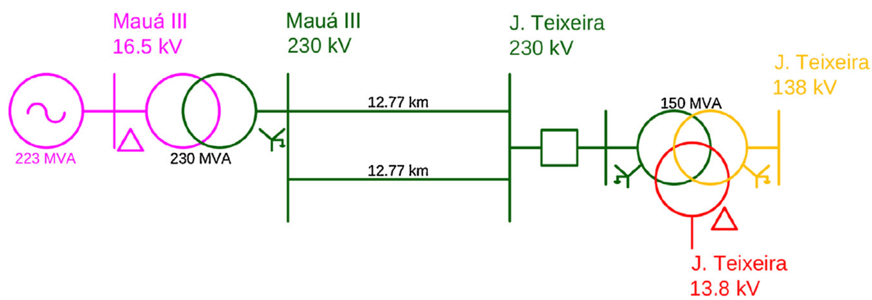

Fig. 1. Single line diagram of the electric network for J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) energization.

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.

2. Case under analysis

The energization of the first J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) was simulated from its high voltage side, radially through Mauá III thermoelectric power plant (TPP), via double circuit 230 kV transmission line (TL) J. Teixeira – Mauá III, as shown in Fig. 1. Its leakage reactance, X_{ps}, is 9.40 % on ATR rated base. The considered quality factor of the ATR windings is $X/R = 50$.

The TL which connects Mauá III and J. Teixeira 230 kV is 12.77 km long in double circuit. Its parameters are given in Table 1. Surge arresters of 192 kV – 4.5 kJ/kV were placed on both TL endings.

On Mauá III TPP (Fig. 1) was considered a single gas unit in operation, generating in 16.5 kV. This TPP was inserted into ATP using a model for three-phase synchronous electric machines, which takes into account electromagnetic transients effects, saturation of its magnetic components and the inertial behavior of its prime mover-generator set (Model 58) [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].

Statistical energization study was performed to define the most critical case to ATR energization in terms of overcurrent, overvoltage and surge arrester 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 worst 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).

Table 1
230 kV TL J. Teixeira – Mauá III parameters – 60 Hz.

Sequence	R (Ω/km)	X (Ω/km)	Y (µS/km)
Zero	0.19470	1.12260	3.0389
Positive/negative	0.03505	0.32834	4.8763

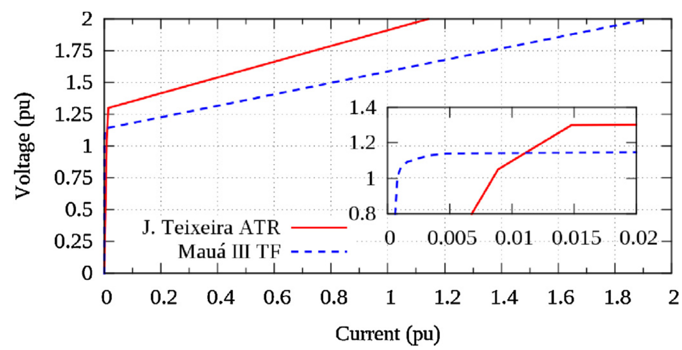

Fig. 2. Saturation curves of J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) and Mauá III SS 230/16.5 kV – 230 MVA transformer (TF).

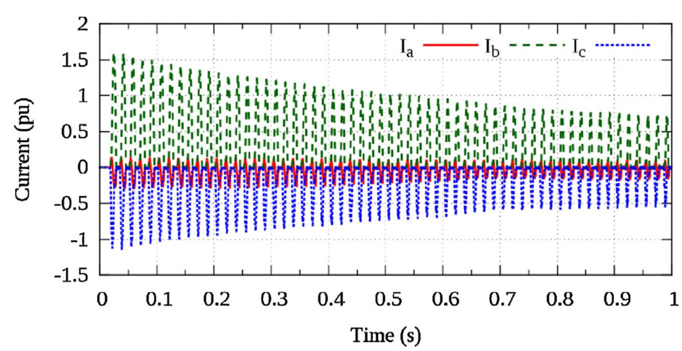

Fig. 3. Currents in the high voltage side windings obtained in J. Teixeira autotransformer (ATR).

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.

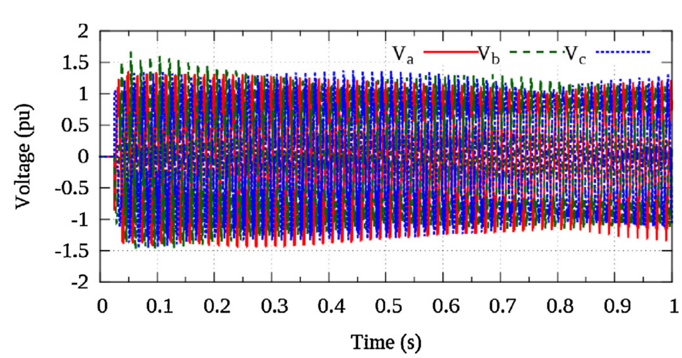

Fig. 4. Phase to ground voltage on the high voltage side of J. Teixeira autotransformer (ATR).

3. Proposed methodology steps applied to the case under analysis

3.1. Inserting transformers saturation effect in the frequency scan

The frequency scan routine processes successive phasor 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 phasor solution, also computed for the t_0^- of cases that will be processed in the time domain, the nonlinear elements are not entirely represented [8]. This means that, using this tool, it will not be possible to know precisely the frequency response of some electric network, if there are overvoltages nearby nonlinear equipment, such as surge arrester and/or transformers, whenever the voltage is higher than the linear region of their characteristic curve.

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

To determine the equivalent magnetizing branch reactance the $\Phi \times I$ 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 Eq. (1):

$$L_{eqv} = \frac{\Phi}{I} \tag{1}$$

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

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 computation, Mauá III TPP 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 $V \geq 1.1$ 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 2.

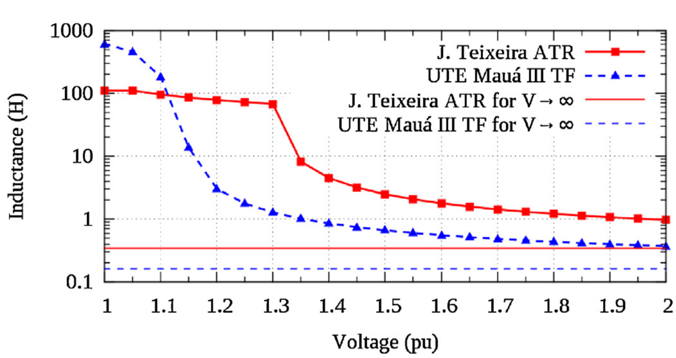

Fig. 5. Transformers units equivalent magnetizing branch inductance variation in function of voltage.

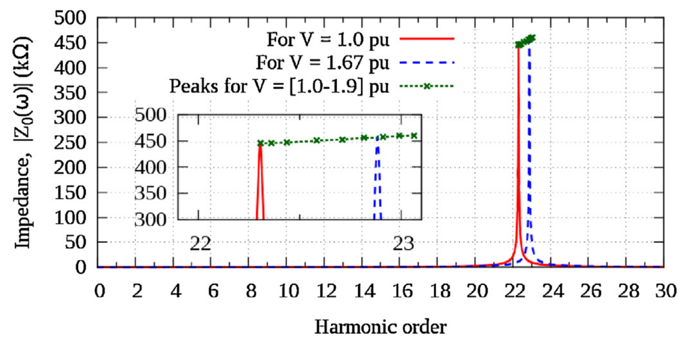

Fig. 6. Zero sequence – variation of electric network resonant peak when considered the dependence of transformer equivalent magnetizing branch inductance with voltage.

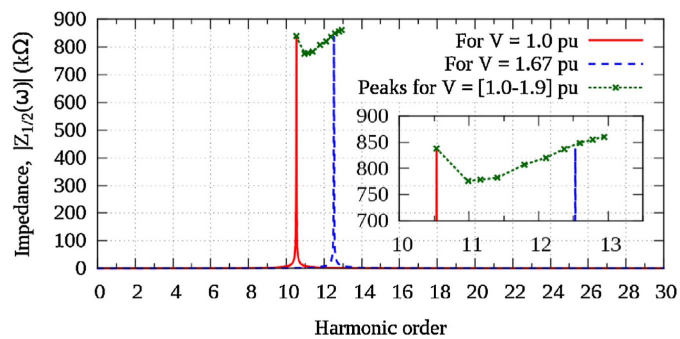

Fig. 7. Positive/negative sequence – variation of electric network resonant peak when considered the dependence of transformer equivalent magnetizing branch inductance with voltage.

Table 2
Maximum sequence impedance peak values seen from J. Teixeira 230 kV bus bar when considering the dependence of transformer equivalent magnetizing branch inductance with voltage.

V (pu)	max(|Z(ω)|) (kΩ)	f (Hz)	h	Sequence
1	445.7	1338.4	22.3	
1.67	455.0	1373.1	22.9	Zero
∞	478.3	1451.1	24.2	
1	837.9	632.1	10.5	
1.67	838.7	751.6	12.5	Positive/negative
∞	842.5	918	15.3	

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 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 3.

Table 3
Maximum sequence impedance peak values frequency deviation seen from J. Teixeira 230 kV bus bar – V = 1.0 pu as reference.

	Sequence			
	Zero		Positive/negative	
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

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 Eq. (2):

$$f_{osc} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Therefore, with the net L decreasing, due to both ATR and TF 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 tend to the slope of the last segment of $\Phi \times$ 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 3). 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 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.

3.2. Surveying harmonic current 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 resonance points, a survey of 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 side that the ATR was energized, a Type 1 source was connected [8]. And, for each TF 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):

$$\phi(t) = |\phi_0| + |\phi_1|\cos(\omega_1 + \angle\phi_1) \tag{3}$$

   Therefore the higher frequencies were eliminated;
4. Finally, the voltage source Type 1 points were calculated by means of the differentiation of Eq. (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 which these equipments 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.

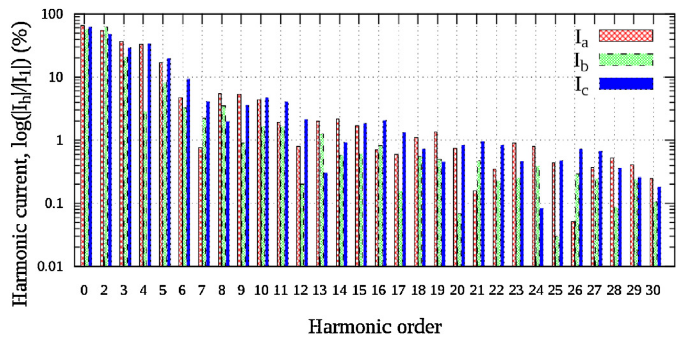

Fig. 8. Harmonic response of J. Teixeira SS autotransformer (ATR) when subjected to overvoltages due to the energization in study.

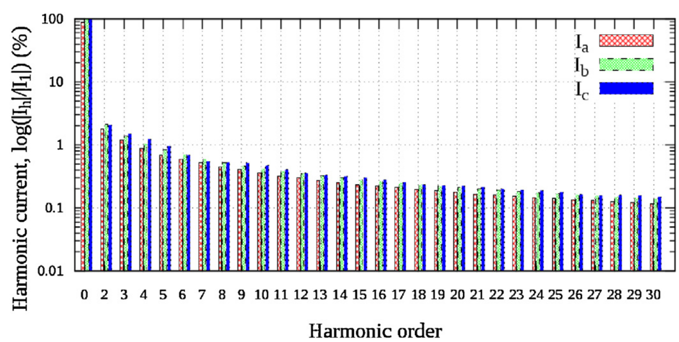

Fig. 9. Harmonic response of Mauá III SS transformer (TF) when subjected to overvoltages due to the energization in study.

The harmonic content found in these currents (Figs. 8 and 9), when the transformers were subjected to the voltages synthesized by the procedure described above, is rich and extends through several harmonic orders, both even and odd, in accordance with what is expected [2,6,10].

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

3.3. Applying 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].

3.4. Decomposing into frequency domain 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.

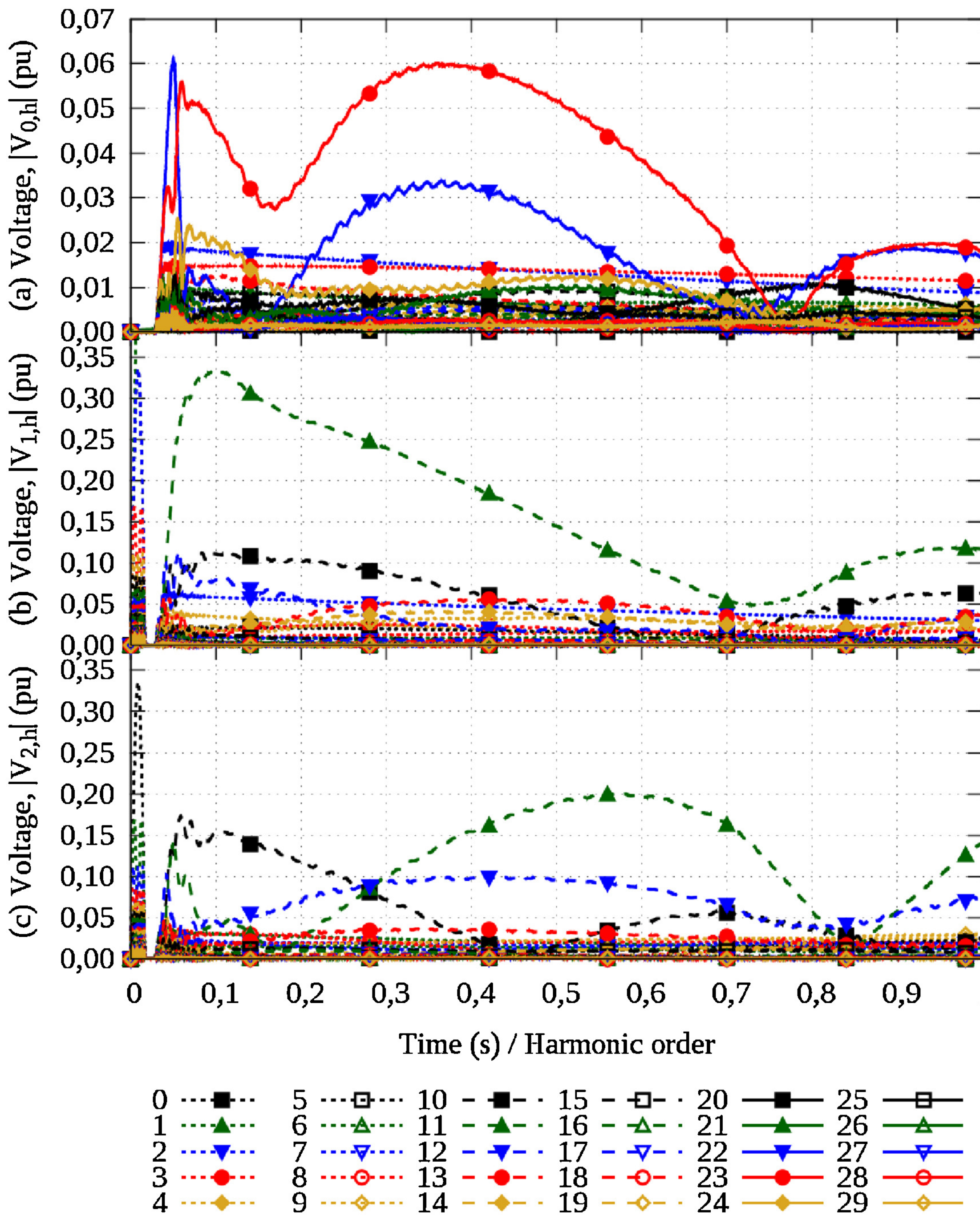

Fig. 10. Zero (a), positive – disregarding the fundamental component (b) and negative (c) sequence voltages decomposed in frequency over time.

In the zero sequence voltage curves, it is possible to verify that two harmonic orders, 22nd and 23rd, are dominant (Fig. 10(a)). Regarding the resonant peaks obtained to $|Z_0(\omega)|$ (Fig. 6) and the current profile injected by the ATR and TF (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 10th and 11th orders, but it is possible to see the 12th 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.

In the absence of L_{eqv} 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 difficult to explain the sustained harmonic orders 22 and 23 overvoltages, which could emerge 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.

4. Further analysis

It is known that the core self inductance is inversely proportional to the frequency, in a nonlinear manner [13,14]. Thus, if the core frequency dependence had been considered in the first step of the proposed methodology (Section 3.1), the entire resonance range would be shifted to higher frequencies because of the extra reduction of L_{eqv}.

Additionally, as a consequence of the aforementioned nonlinearity, depending on where the resonance range is placed on the $L \times f$ curve [13,14], which is a core design characteristic, its extremes could be uneven shifted, resulting in a smaller or larger frequency band.

5. 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 resonance points of the electric network are shifted to higher frequencies when the transformers are subjected to overvoltages;
- An electric network which contains nonlinear elements, whose characteristics are voltage dependent, will not present resonance points (if existent), but regions, due to the resonant peaks shifting;
- The wider theoretical resonant peaks range, motivated by the variation of the equivalent magnetizing branch inductance, is upper bounded by the slope of the last segment of $\Phi \times I$ curve;
- 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;
- It would not be possible to thoroughly understand the occurrence of few sequence voltages, decomposed in frequency along time, of higher harmonic orders if the magnetizing branch inductance variation were not considered in the frequency scan;
- It was possible to verify which resonant points were excited by transforming the voltages from phase to sequence domain, decomposing them in frequency, over time, and comparing its results with the electric network sequence impedances acquired with frequency scan;
- The harmonic content study of the transformer, which was already in service, was important to identify that this equipment also contributed to the excitation of resonance points found in the electric network.

In summary it is suggested the application of the proposed methodology in future electromagnetic transient studies involving nonlinear elements when undamped oscillations are observed.

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