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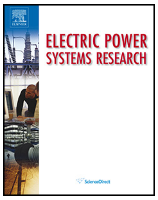

Enhanced analysis of oscillatory undamped overvoltages in transformer energization

L.M.N. de Mattos[a,b,*], A.M.P. Mendes[b,c], M.C. Tavares[b], J.F. de Lima Filho[a]

[a] *Potência Engenharia, SCLRN 708, Block A, Entrance 39, Room 102, Brasília, DF 70740-551, Brazil*
[b] *University of Campinas, School of Electrical and Computing Engineering, Av. Albert Einstein, 400, Campinas, SP 13083-852, Brazil*
[c] *Eletrobras Eletronorte, SCN 06 A, Block C, Room 1107, Brasília, DF 70716-901, Brazil*

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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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[*] Corresponding author.
E-mail address: l@mattos.eng.br (L.M.N. de Mattos).

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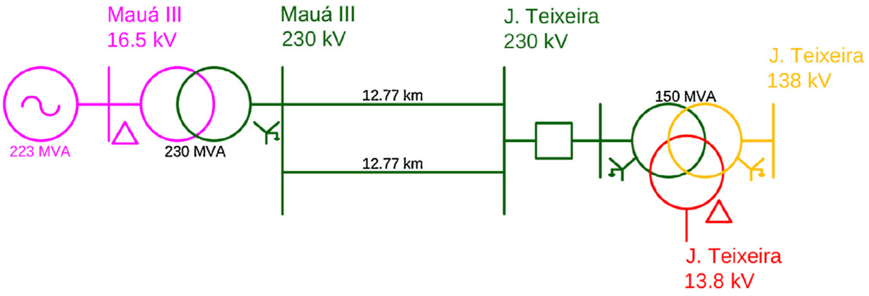

Fig. 1. Single line diagram of the electric network for J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) energization.

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

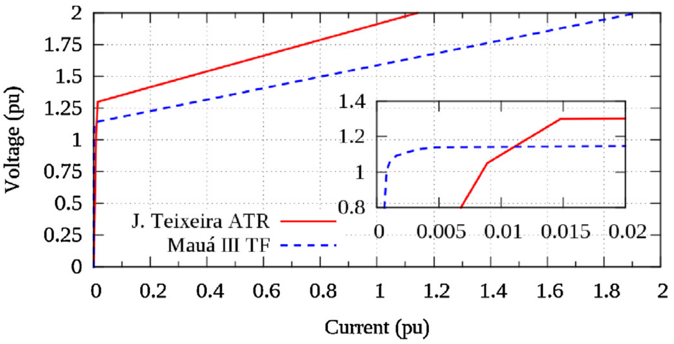

Fig. 2. Saturation curves of J. Teixeira SS 230/138/13.8 kV – 150 MVA autotransformer (ATR) and Mauá III SS 230/16.5 kV – 230 MVA transformer (TF).

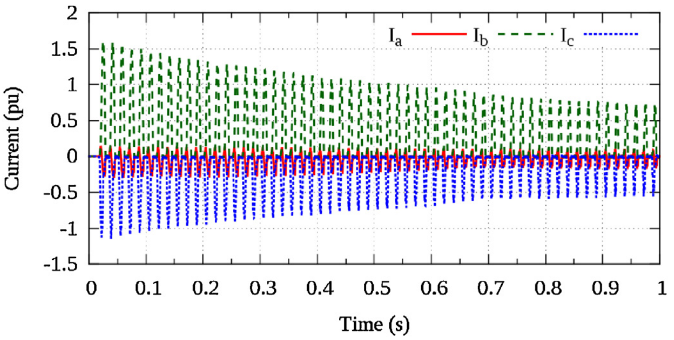

Fig. 3. Currents in the high voltage side windings obtained in J. Teixeira autotransformer (ATR).

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.

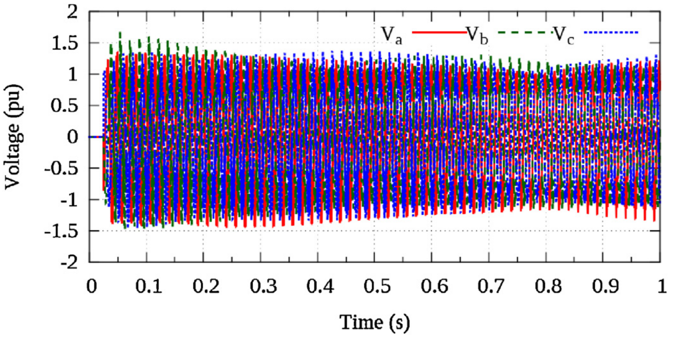

Fig. 4. Phase to ground voltage on the high voltage side of J. Teixeira autotransformer (ATR).