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Harmonic Distortion Evaluation of CEA's FAB Feeder

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Abstract. This paper presents a harmonic analysis performed an urban feeder named FAB located in Macapá City whose objective is to evaluate how a set of nonlinear loads impact in the voltage harmonic distortion rate of this network. The harmonic currents of the nonlinear loads were obtained by one-month measurement campaign carried out in this feeder during July, 2017, and it was verified that the nonlinear loads did not caused a significant impact in FAB's harmonic levels.

Key words

Current summation, harmonic distortion, harmonic load flow.

1. Introduction

The presence of nonlinear loads in electrical distribution grids is responsible for the arise of distortion observed in voltage and current waveforms.
This disturbance may cause several damaging effects to electric and electronic devices as overload in phase and neutral cables, malfunction of electronic relays, overheating in transformers and others. In addition, the presence of harmonic in distribution grids may excite resonances, and, therefore, provoke an amplification of the harmonic voltages, which yields to overvoltages and an increase of the harmonic distortion rate.
Then, according to this fact, this paper presents a harmonic analysis performed in FAB feeder of the "Companhia de Eletricidade do Amapá" located in Macapá city, whose objective was to evaluate impact caused by a set of nonlinear loads in the voltage and current harmonic distortion rate during a light loading operational condition.

2. Current Summation Harmonic Load Flow

The current summation method is an algorithm used to solve the power flow issue in radial and weakly-meshed grids by direct application of Kirchhoff's laws.
Differently from the typical harmonic load flow algorithms, the current summation method is an oriented-branch algorithm, that means that it divides a distribution grid into layers. Fig 1 depicts a generic distribution grid divided in layers.

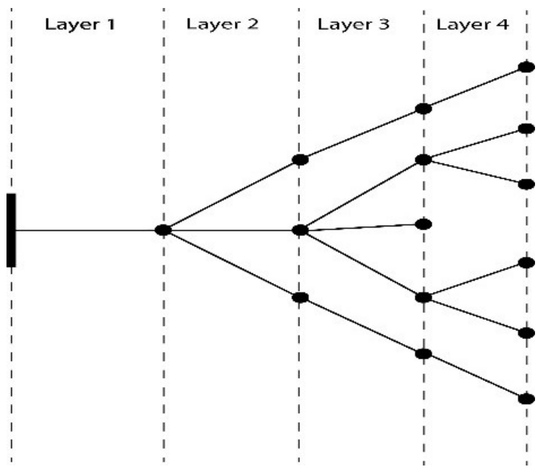

Fig 1. Electrical distribution grid divided in layers

The current summation algorithm is based in two main steps: backward sweep and forward sweep. The first one consists in determining the branch current of the grid, which are the currents of the line and transformer, while the forward sweep determines the node voltages of the grid.

The branch current obtained during the backward sweep is calculated by (1). This procedure starts in the last layer and ends in the first one.

$$\begin{bmatrix}\bar{I}_{ij}^{a}(h)\\ \bar{I}_{ij}^{b}(h)\\ \bar{I}_{ij}^{c}(h)\end{bmatrix}=\sum_{r=1}^{nb}\begin{bmatrix}\bar{I}_{jr}^{a}(h)\\ \bar{I}_{jr}^{b}(h)\\ \bar{I}_{jr}^{c}(h)\end{bmatrix}-\begin{bmatrix}\bar{I}_{shj}^{a}(h)\\ \bar{I}_{shj}^{b}(h)\\ \bar{I}_{shj}^{c}(h)\end{bmatrix}-\begin{bmatrix}\bar{I}_{Lj}^{a}(h)\\ \bar{I}_{Lj}^{b}(h)\\ \bar{I}_{Lj}^{c}(h)\end{bmatrix}-\begin{bmatrix}\bar{I}_{NLj}^{a}(h)\\ \bar{I}_{NLj}^{b}(h)\\ \bar{I}_{NLj}^{c}(h)\end{bmatrix} \quad (1)$$

Where:

$\begin{bmatrix}\bar{I}_{ij}^{a}(h)\\ \bar{I}_{ij}^{b}(h)\\ \bar{I}_{ij}^{c}(h)\end{bmatrix}$ are the branch´s currents between nodes *i* and *j* of phases A, B and C for each harmonic order;

$\begin{bmatrix}\bar{I}_{jr}^{a}(h)\\ \bar{I}_{jr}^{b}(h)\\ \bar{I}_{jr}^{c}(h)\end{bmatrix}$ are the branch´s currents between nodes *j* and *r* of phases A, B and C for each harmonic order;

$\begin{bmatrix}\bar{I}_{shj}^{a}(h)\\ \bar{I}_{shj}^{b}(h)\\ \bar{I}_{shj}^{c}(h)\end{bmatrix}$ are the capacitor bank´s currents of phases A, B and C for each harmonic order;

$\begin{bmatrix}\bar{I}_{Lj}^{a}(h)\\ \bar{I}_{Lj}^{b}(h)\\ \bar{I}_{Lj}^{c}(h)\end{bmatrix}$ are the linear load´s currents at node *j* for phases A, B and C for each harmonic order;

$\begin{bmatrix}\bar{I}_{NLj}^{a}(h)\\ \bar{I}_{NLj}^{b}(h)\\ \bar{I}_{NLj}^{c}(h)\end{bmatrix}$ are the nonlinear load´s currents at node *j* of phases A, B and C for each harmonic order.

The node voltage obtained by the forward sweep procedure is calculated by (2), starting in the first layer and ending in the last one.

$$\begin{bmatrix}\bar{V}_{j}^{a}(h)\\ \bar{V}_{j}^{b}(h)\\ \bar{V}_{j}^{c}(h)\end{bmatrix}=\begin{bmatrix}\bar{V}_{i}^{a}(h)\\ \bar{V}_{i}^{b}(h)\\ \bar{V}_{i}^{c}(h)\end{bmatrix}-\begin{bmatrix}\bar{z}_{ij}^{p}(h) & \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{m}(h)\\ \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{p}(h) & \bar{z}_{ij}^{m}(h)\\ \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{p}(h)\end{bmatrix}\begin{bmatrix}\bar{I}_{ij}^{a}(h)\\ \bar{I}_{ij}^{b}(h)\\ \bar{I}_{ij}^{c}(h)\end{bmatrix}$$

Where:

$\begin{bmatrix}\bar{V}_{j}^{a}(h)\\ \bar{V}_{j}^{b}(h)\\ \bar{V}_{j}^{c}(h)\end{bmatrix}$ are the voltages of node *j* in phases A, B and C for each harmonic order;

$\begin{bmatrix}\bar{V}_{i}^{a}(h)\\ \bar{V}_{i}^{b}(h)\\ \bar{V}_{i}^{c}(h)\end{bmatrix}$ are the voltages of node *i* in phases A, B and C for each harmonic order;
$\begin{bmatrix}\bar{z}_{ij}^{p}(h) & \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{m}(h)\\ \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{p}(h) & \bar{z}_{ij}^{m}(h)\\ \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{m}(h) & \bar{z}_{ij}^{p}(h)\end{bmatrix}$ are the three-phase branch impedance for each harmonic order.

3. Harmonic Analysis in FAB Feeder

A. FAB Feeder Description

FAB feeder is 13.8kV distribution feeder that is connected to substation Santa Rita and is 17km long. In addition, this distribution feeder has 771 distribution towers, 170 transformers and 3 capacitor banks.
At this feeder there are several commercial electric consumers, such as schools, forums, drugstores, supermarkets, etc. Some of these consumers are considered nonlinear loads, because they have equipment that generate and inject harmonic into the grid.
The harmonic spectrum of each nonlinear load considered during the harmonic study was measured using the power quality analyzer HIOKI PW3198, which is a class-A measurement device according to the IEC 61000-4-30 standard. Besides, this device is also classified as class I according to IEC 61000-4-7 standard. The HIOKI PW3198 has a 256-sample-per-cycle sampling rate for harmonic measurements, and 1-MHZ frequency sampling for transient measurements. Moreover, this measurement device is capable of acquiring harmonic phasor voltage and current, transients, flicker, voltage sags, voltage swells, and voltage interruptions.
In FAB feeder, there are three capacitor banks in which two of them have a rated power of 300kVAr, and the other one´s is 600kVAr. Furthermore, those capacitor banks are connected to the grid in grounded-wye. Fig 2 shows the one-line diagram of the FAB feeder, where the red spots indicate the nonlinear locations in this network.

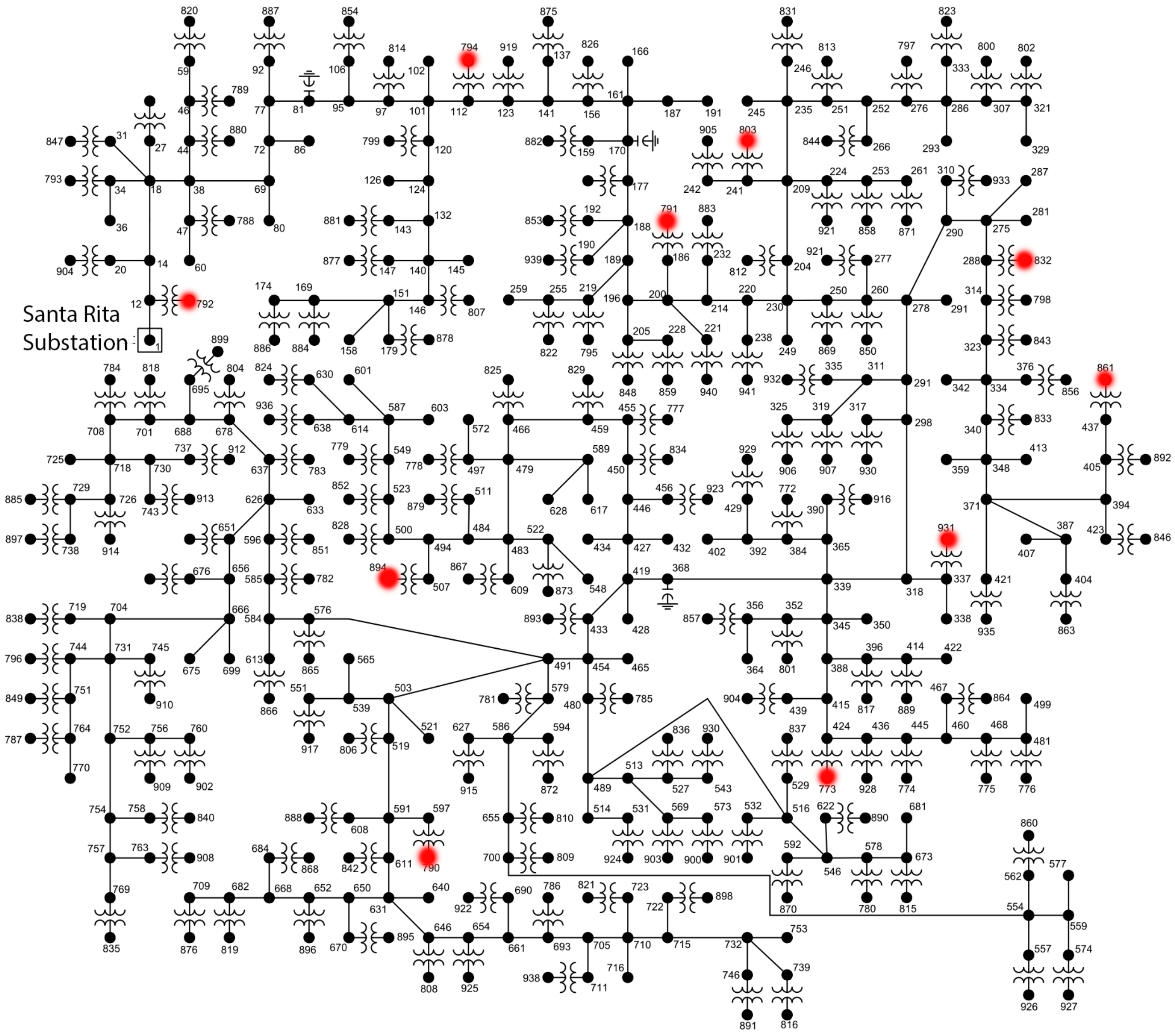

Fig 2. One-line diagram of FAB feeder

B. *Light Loading Operational Condition*

A harmonic analysis was carried out in FAB feeder considering the presence of 10 nonlinear loads: TJAP, Forum, Sebrae, Fortaleza, HEMOAP, colégio Tiradentes, drogaria popular, sorveteria, UC 904 and UC909 during light loading condition. Moreover, this study neglected the background distortion from the upstream grid since the measurements acquired at substation presented rather small levels of distortion.

During the light load condition some node voltages along the distribution presented levels below 0.93p.u. which, according to the eighth module of the Distribution Procedure of Electric Energy (PRODIST) developed by the National agency of Electric Energy (ANEEL), is not an adequate voltage level. The situation mentioned can be observed in Fig 3, where some voltages reach around 0.8p.u.

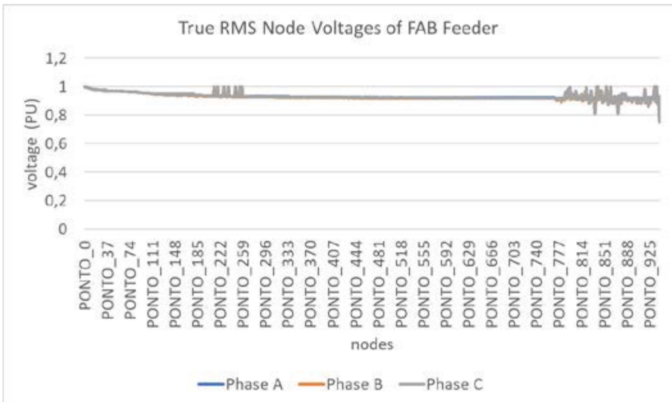

Fig 3. Node voltage along FAB feeder of phases A, B and C.

The total harmonic distortion rate of voltage (THDv) along the feeder´s nodes presented levels between 1.5% and 3%, as it can be seen in Fig 4. According to the

eighth module of PRODIST, revision 7, the total harmonic distortion level of voltage must be below 8% for 13.8kV distribution grids, therefore the harmonic levels of voltage in FAB are adequate.
Moreover, it can be observed that the total harmonic distortion reached very small values. This fact can be justified that, in theses locations, the harmonic are very small.

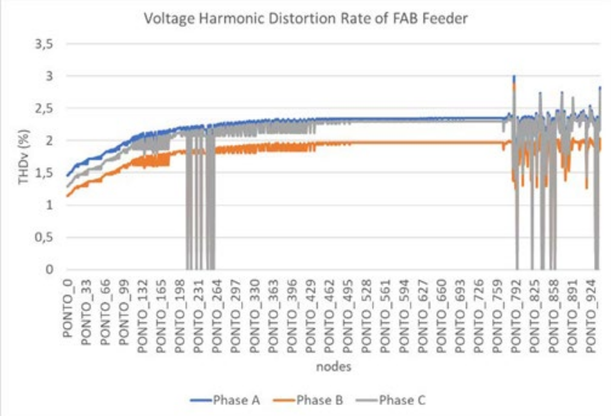

Fig 4. Total harmonic distortion rate of voltage along the FAB feeder´s nodes.

Analyzing the individual harmonic distortion rate in phases A, B and C as depicted in Fig 5, Fig 6 and Fig 7, respectively, is possible to conclude that the individual harmonic distortion rates are adequate in all three phases, since the maximum value was 2.5%. Moreover, it was observed that the fifth and seventh harmonic voltages were more predominant in relation to other harmonic orders.

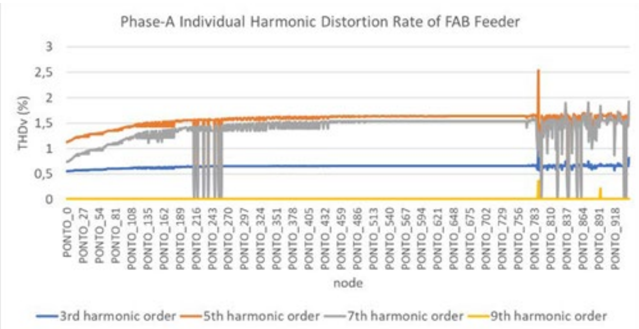

Fig 5. Phase-A´s individual voltage harmonic distortion rate along the FAB feeder´s nodes.

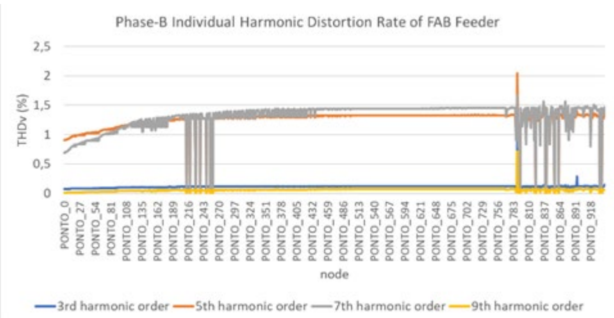

Fig 6. Phase-B´s individual voltage harmonic distortion rate along the FAB feeder´s nodes.

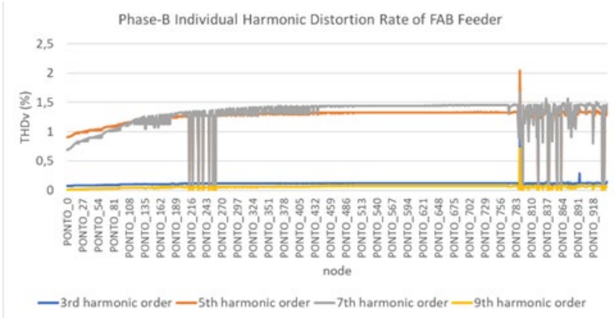

Fig 7. Phase-C´s individual voltage harmonic distortion rate along the FAB feeder´s nodes.

Another parameter analyzed during the harmonic analysis was the total demand current harmonic distortion in FAB feeder´s lines. It´s largest value observed was, in phases A, B and C respectively, around 44%, 44% and 56%, as it is shown in Fig 8. However, the total current harmonic distortion in most lines remained between 2% and 6%.

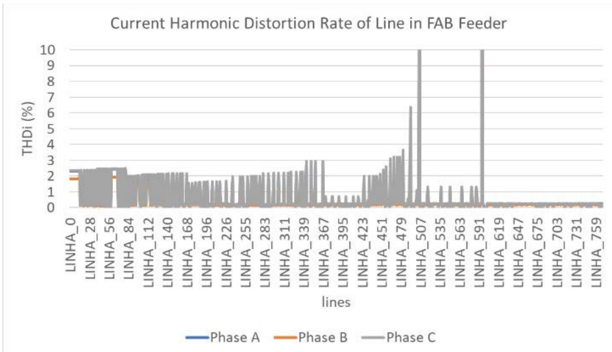

Fig 8. Total current harmonic distortion rate along FAB feeder´s lines.
Assessing the individual harmonic distortion in phase A of the distribution´s lines, shown in Fig 9, it is possible to verify that the seventh harmonic distortion rate reached more than 10% at node 592 while the fifth harmonic distortion reached 16% at node 506. This fact shows that these two harmonic orders have significantly contributed to the high harmonic distortion level found in those nodes.

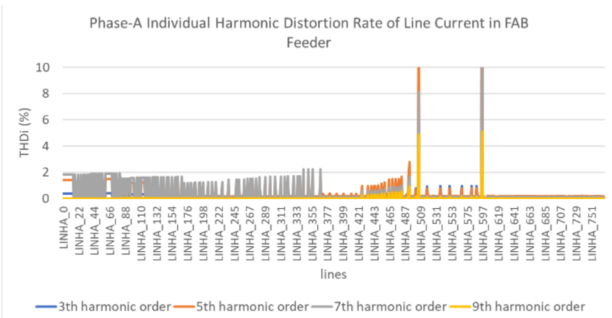

Fig 9. Phase A´s individual current harmonic distortion rate along FAB feeder´s lines.

In phase B, the third harmonic distortion demand current has excelled at node 506, since its value reached more than 10%. While the ninth harmonic distortion current contributed significantly to the distortion at node 592 as it is depicted in Fig 10.

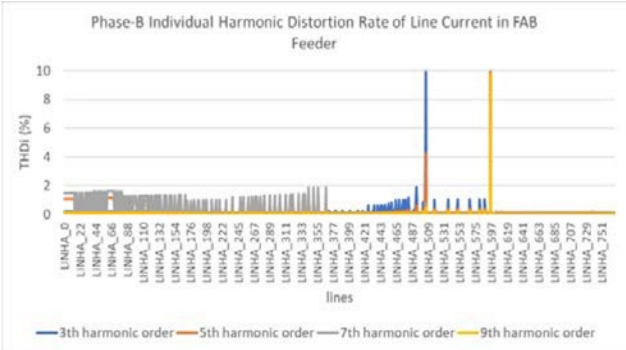

Fig 10. Phase B´s individual current harmonic distortion rate along FAB feeder´s lines.

In phase C, the fifth harmonic demand current has excelled in both nodes 506 and 592, because its values reached more than 10%, as depicted in Fig 11. However, it is important to emphasize that the seventh and the ninth harmonic currents have also contributed to increase the distortion levels at both nodes mentioned.

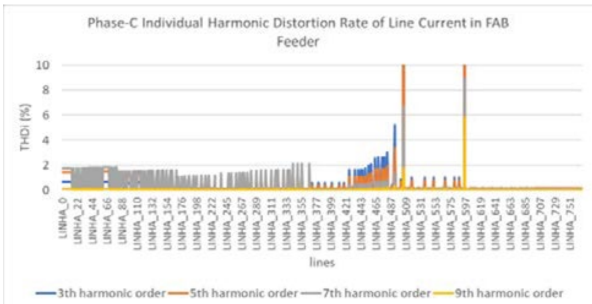

Fig 11. Phase C´s individual current harmonic distortion rate along FAB feeder´s lines

Analyzing the total harmonic distortion levels of current in FAB feeder's transformers, shown in Fig 12, it was observed that the harmonic distortion levels were below 0.5%, therefore, they are adequate according to the reference value defined in IEEE 519.

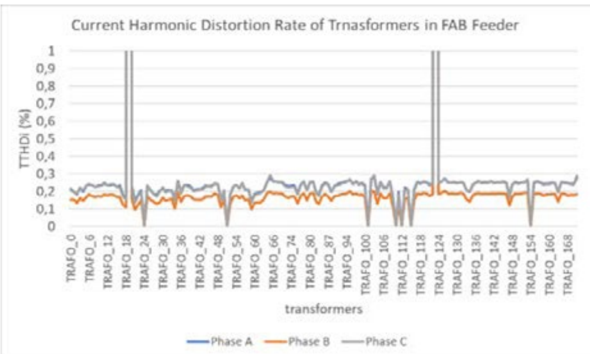

Fig 12. Total current harmonic distortion rate along FAB feeder´s transformers.

In Fig 13, Fig 14 and Fig 15, it is possible to observe that the third harmonic and fifth harmonic currents influenced significantly to the distortion levels of currents in the feeder's transformers.

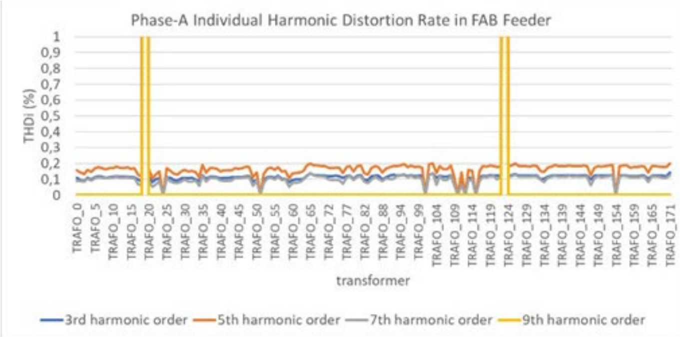

Fig 13. Phase A´s current harmonic distortion rate along FAB feeder´s transformers.

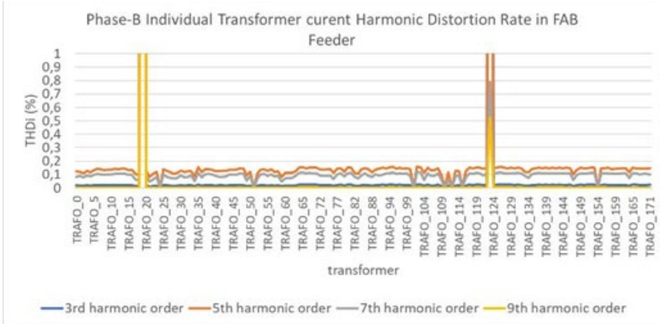

Fig 14. Phase B´s current harmonic distortion rate along FAB feeder´s transformers.

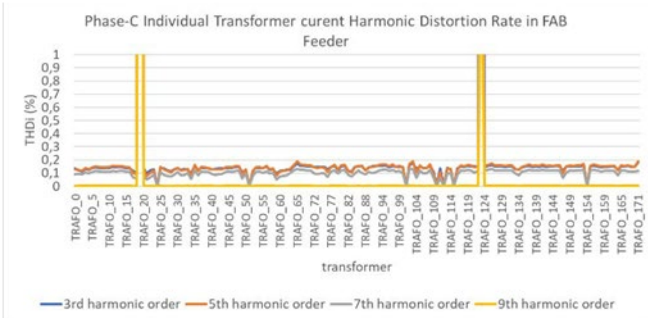

Fig 15. Phase C´s current harmonic distortion rate along FAB feeder´s transformers.

During the harmonic analysis, it was also assessed the impact of the presence of harmonic currents and voltages on capacitor Banks.

The capacitor bank power calculated in each capacitor bank considering the third, fifth, seventh and ninth harmonic components ranged from 6% to 13%, which is below the reference value of 135% recommended by IEEE 1036-1992. This fact can be visualized in Fig 16.

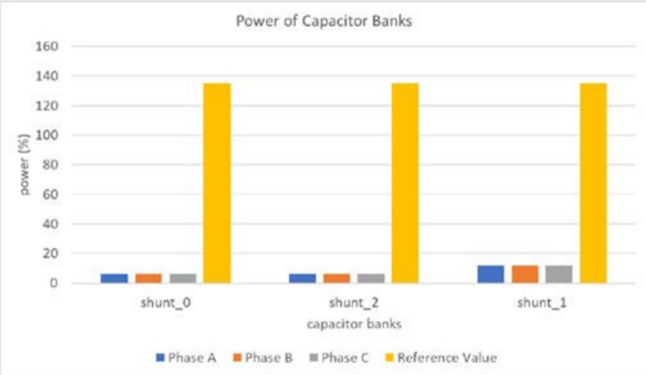

Fig 16. Power in FAB feeder´s capacitor banks.

Analyzing the true rms voltage in each capacitor bank, it is possible to observe that their values were approximately 96%, 94% and 93% of the nominal voltage for shunt1, shunt2 and shunt3, respectively, as shown in Fig 17. Thus, they are in compliance with the IEEE 1036-1992 recommendation of 110% of the nominal voltage.

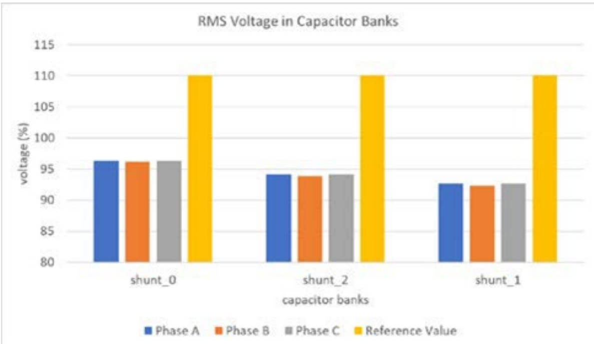

Fig 17. RMS voltage in capacitor banks shunt1, shunt2 and shunt3.

Despite the fact that the RMS voltage in each capacitor bank has presented values considered safe, the peak voltage reached levels considered dangerous to the capacitor bank operation. They presented values above 120% of the nominal peak voltage, which is the reference value recommended by IEEE 1036-1992. This situation is illustrated in Fig 18. Moreover, It is also important to emphasize that the most critical capacitor bank is shunt1 because it reached values above 250% of the nominal peak voltage.

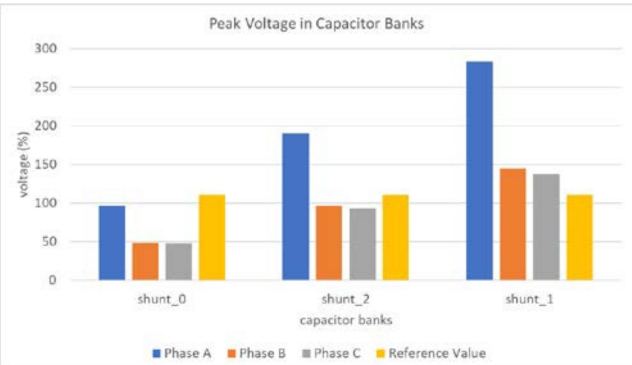

Fig 18. Peak voltage in capacitor banks shunt1, shunt2 and shunt3.

Although the peak voltage presented a value above the reference value established by IEEE 1036:1992, it may not be sufficient to cause a significant damage to the system as the other quantities remained within the limits. The last parameter evaluated was the RMS current in each capacitor bank. The values ranged from 6% to 13% of the nominal rms current. Thus, all three capacitor banks presented values in compliance to the reference value recommended by IEEE 1036-1992 which is 180%, as shown in Fig 19.

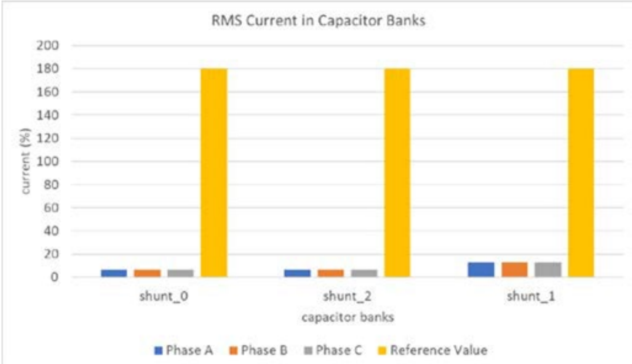

Fig 19. RMS current in capacitor banks shunt1, shunt2 and shunt3.

4. Conclusion

A harmonic analysis was carried out in FAB feeder, assuming a light loading operational condition and considering the presence of 10 nonlinear loads in the network. It was evaluated that the harmonic voltage of each node along the feeder presented safe levels to the grid's devices. It was also evaluated the harmonic current levels that presented high levels in two specific distribution lines. Moreover, the three capacitor banks were assessed, and it was observed dangerous levels of peak voltage in each capacitor bank.

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