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## Article

# Impact of Background Voltage Distortion and Unbalances on Phase-Crossed-Frequency Harmonics

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**Abstract:** This paper investigates the impact of harmonic distortion and system unbalances on harmonic generation via simulations and measurements. The interactions between different phases, frequencies, and resonances are examined, highlighting their effects on phase and cross-frequency behavior. Amplifications and attenuations occur and are studied in a micro-grid system. The analysis focuses on the influence of background voltage distortions at the 5<sup>th</sup>, 23<sup>rd</sup>, 49<sup>th</sup>, and 103<sup>rd</sup> harmonic orders, as well as unbalances, under various simulation scenarios. Finally, comparisons are made to illustrate the relationship between background voltage distortions and the existing non-linear loads within the system.

**Keywords:** harmonics; resonance; capacitor bank; industrial environment; crossed - frequency; background distortion

## I. Introduction

Harmonic distortions and unbalances are common in electric grids, often generated by devices such as frequency converters, electric furnaces, and through load imbalances [1][2]. Capacitor banks are frequently used to correct the power factor; however, this can create resonances in the electrical system, leading to attenuation or amplification of harmonic levels [3].

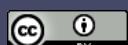
With the increasing presence of new types of loads and generation sources [3], ensuring power quality has become essential, requiring further studies on harmonic modeling. These studies can contribute to advancements in calculations, metering, and estimations related to power quality [4,5]. The rise of renewable energy generation, which often involves power electronic converters, also increases the need for harmonic system analysis due to the harmonic distortions these converters produce [6–8].

Similar experiments were conducted in [9–12], where the concept of the cross-frequency admittance matrix was introduced and validated by applying voltage harmonic distortions to the power supply, varying the phase from 0° to 180°, and analyzing harmonic measurements on a single-phase asynchronous motor.

In [13–15], the cross-frequency admittance matrix was further validated through experimental results, where voltage harmonic distortions were superimposed on the fundamental voltage, with phase variations between 0° and 360°. The impacts were analyzed in a small circuit consisting of a voltage generator, a non-linear load (such as a fluorescent lamp or a single-phase asynchronous motor), and data acquisition equipment.

In [16], a PSPICE simulation of a six-pulse converter, combined with an application of 5th-order voltage background distortion at phases of 0°, 30°, and 60°, demonstrated that distortions in currents and voltages exhibit a certain degree of independence.

In [17–19], some approach to load harmonic modeling were introduced using the cross-frequency admittance matrix instead of the traditional harmonic Norton model. However, none of



these studies addressed the impact of resonances, line impedance, and unbalances on cross-frequency behavior. This is the primary focus of this paper.

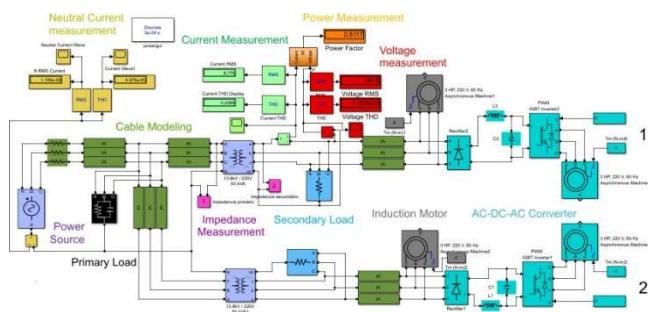
This paper presents results related to the impact of resonances and background distortions on busbar harmonic distortions, amplifications, and cross-frequency effects in a model representing an industrial environment.

## II. Modeling and Simulations

### A. Model

Creating a model utilizing MatLab Simulink which contains common elements of an electrical industrial environment, as transformers, motors, capacitor banks and frequency drivers and resistive loads was the first step.

The model used is shown in Figure 1 and described below:



**Figure 1.** Circuit model of electrical industrial environment.

- Power Source: Contains a Three-Phase Programmable Voltage Source, which allows generate voltage waveforms with harmonic components and two Three-Phase Transformers 13.8kV/0.22kV, 60Hz which allows to configure parameters as rated power and frequency, windings rated voltages, resistances and inductances;
- Secondary Load: Contain an RC shunt load per phase, connected in "Y". The values of resistor and capacitors are not determined in Ohms or Farads. Instead of that, the block used allow to choose rated voltage and Frequency, Active Power, and Capacitive Reactive Power, which was adjusted to reach power factor around 0.97. Without using capacitors, the power factor was around 0.71. The resistances consumption is 1kW per phase. This part is duplicated;
- Primary Load: Contain an RC shunt load per phase, connected in "Y". The VAr compensation is twice the compensation on Secondary and the resistive load has the same power consumption of RC load on Secondary;
- AC-DC-AC Converter: This group represents a PWM Inverter which contains a Diode-based rectifier, DC Filter, IGBT DC-AC Inverter and a PWM Generator. There is a Three-Phase Induction Motor connected to the output of the inverter. This block is duplicated;
- Induction Motor: The model represents the three- phase induction motor parametrized with squirrel cage rotor type, 3HP, 220V and 60Hz. This block is duplicated;
- Current Measurement: The phase "A" current -  $I_a$  was measured and it was possible to get the followings information: Waveform, harmonics from 2<sup>nd</sup> to 109<sup>th</sup> orders (magnitude, phase and percentage from fundamental wave), THD (Total Harmonic Distortion [1]) and RMS value, in Ampere (A);
- Power Measurement: This group provides data as Active Power, Reactive Power and Power Factor; A block was created on Simulink to calculate Power Factor - PF from Active Power - AP and Reactive Power - RP measured on phase A, accordingly to equation (1).

$$PF = \cos \left( \tan^{-1} \left( \frac{RP}{AP} \right) \right) \quad (1)$$

- Voltage Measurement: The phase A Voltage -  $V_a$  is measured and it was possible to get the followings information: Waveform, harmonics from 2<sup>nd</sup> to 109<sup>th</sup> orders (magnitude, phase and percentage from fundamental wave), THD (Total Harmonic Distortion [1]) and RMS value, in Volt (V);
- Impedance Measurement: This block work together PowerGui block to provide analysis of magnitude and phase;
- Cable Modeling: By using pi-equivalent model, cable impacts were considered between loads and power source and between loads and transformer windings (Primary and Secondary).

#### B. Harmonics Application and Variation

Four background harmonic distortions were applied to the system: 5<sup>th</sup>, 23<sup>rd</sup>, 49<sup>th</sup> and 103<sup>rd</sup> orders. Follow the reasons:

- 5<sup>th</sup>: This is the most significate distortion measured on the grid [2];
- 23<sup>rd</sup>: It corresponds to the resonance frequency on Secondary when capacitor bank was connected to the system;
- 49<sup>th</sup>: This frequency is the last odd harmonic considered to calculate THD accordingly to IEEE 519 [4] and is also the last frequency considered on equipment emission limits accordingly to IEC 61000- 3-2 [5];
- 103<sup>rd</sup>: This frequency was chosen because it is within Supraharmonics range (2kHz – 150kHz) [6] and is close to the first resonance on Primary, as will be shown ahead.

The grid measurement done in [2] shows 2.271% for 5<sup>th</sup> harmonic distortion but there was applied 1% for all frequencies in order to facilitate comparisons. 5<sup>th</sup> and 23<sup>rd</sup> harmonics are essentially negative sequences for balanced systems, so they were simulated just as negative sequences and 49<sup>th</sup> and 103<sup>rd</sup> harmonics were simulated as positive sequences due to the same reason.

The conditions simulated for harmonics application are:

- Balanced power supply with capacitor bank connected on Secondary;
- Balanced power supply with capacitor bank not connected on Secondary;
- Unbalanced power supply with capacitor bank connected on Secondary;
- Unbalanced power supply with capacitor bank not connected on Secondary.

The Reference signal to be used on Results section for comparisons was the distortion when the system was supplied by a sinusoidal waveform and all capacitors and inverters were connected.

#### C. Simulation Methods

Through PowerGui tool in MatLab Simulink, it is possible to get system impedance, FFT analysis and others information. This facility was used to determine impedance magnitude, resonance frequency and all harmonic data.

All results were taken just on  $V_a$ . This allowed comparing the effect of an unbalanced voltage against the balanced condition. The impedance results were obtained between Phase A and Neutral line in Primary and Secondary.

### III. Results

#### A. Impedance Analysis

Note in Figure 2 that some resonances appear due to RC loads and cable modeling on Primary. The first peak of impedance on Primary happens near 6280Hz, which is close to 103<sup>rd</sup> order.

Furthermore, Figure 3 shows some resonance happening on Secondary around 1380Hz, which is the 23<sup>rd</sup> order. For comparisons, Figure 4 shows the impedance on Secondary when there are no capacitors connected and Figure 5 compare Figures 3 and 4 results.

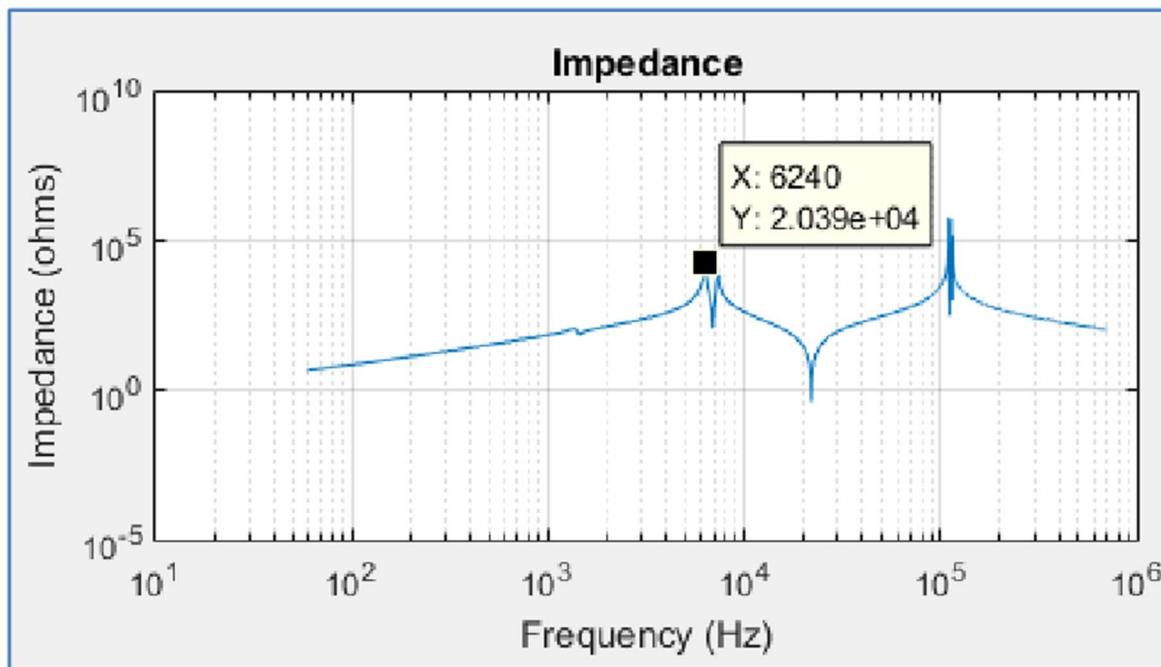


Figure 2. Impedance on Primary.

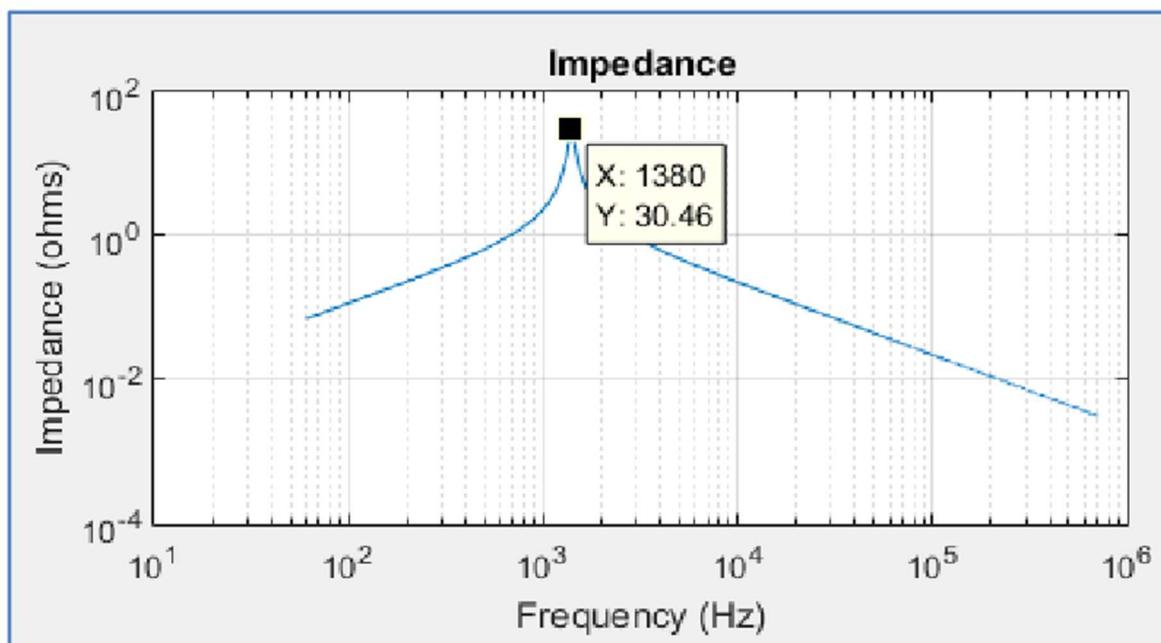
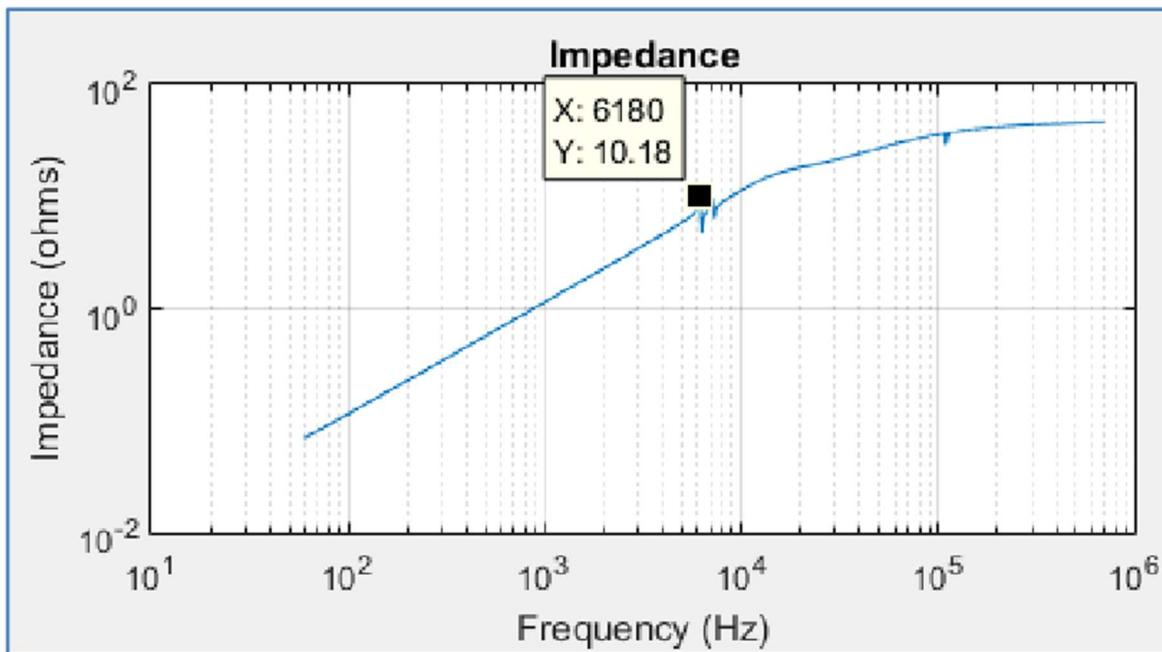
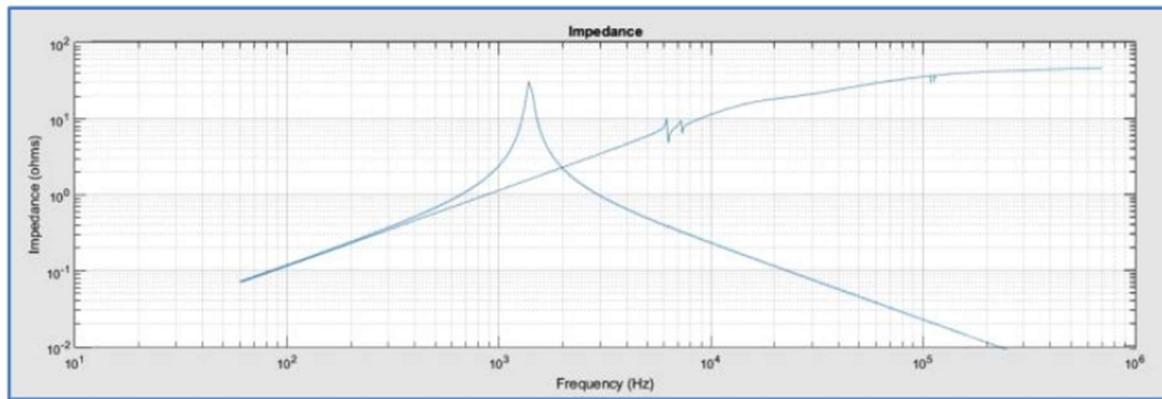


Figure 3. Impedance on Secondary with capacitors.



**Figure 4.** Impedance on Secondary without capacitors.

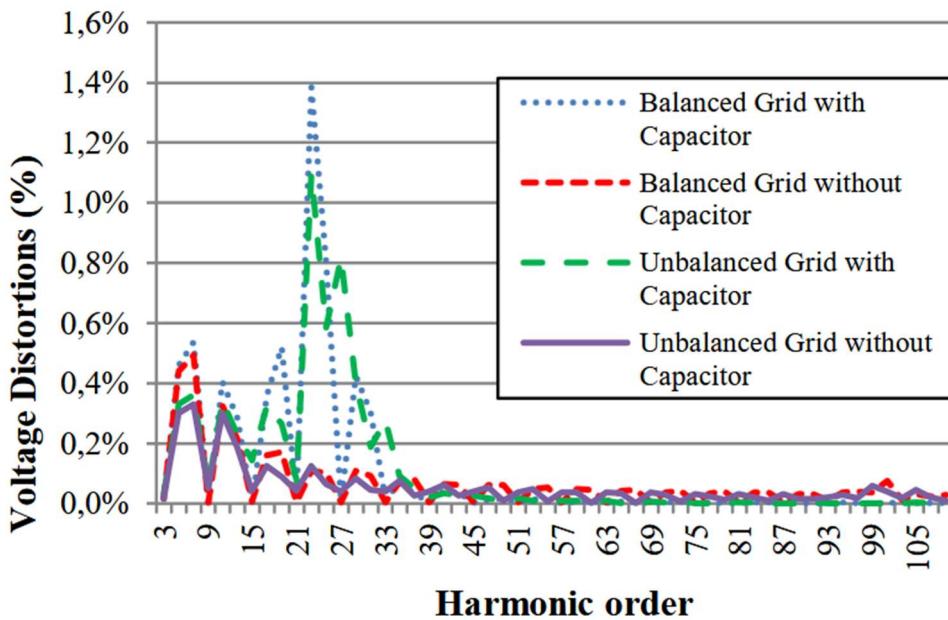


**Figure 5.** Effect of capacitor bank on impedance of Secondary.

#### *B. Harmonic Analysis Without Applying Distortions*

At beginning, the Grid was providing a sinusoidal voltage, which means 0% of distortions.

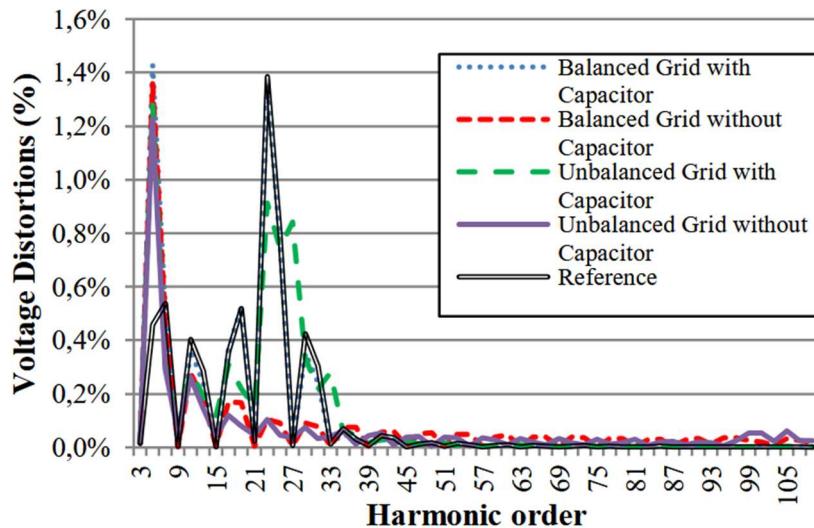
The AC-DC-AC converter acts as harmonic source at the same time that it is a non-linear load. This equipment is very common on the industry and it changes completely the characteristics of the voltage signal, as can be seen on Figure 6.



**Figure 6.** Voltage Harmonic results in a pure sinusoidal voltage wave after connecting the Inverter.

#### C. Application of Voltage Distortions of 5<sup>th</sup> Order

In this case, it was applied 1% of distortion on 5<sup>th</sup> order over a sinusoidal voltage supply. The results are shown on Figure 7.



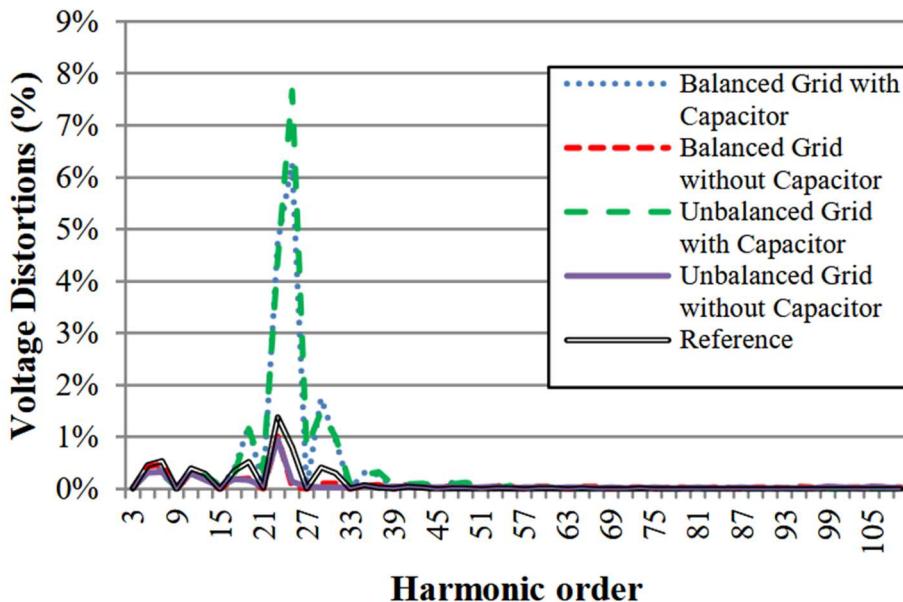
**Figure 7.** Voltage harmonic results after applying 1% on 5<sup>th</sup> order.

- Crossed-frequency until the 33<sup>rd</sup> harmonic, but the distortions were lower than the reference;
- Zero-sequence harmonics appeared when the system was unbalanced;
- The resonances presented on the system did not cause any relevant amplification or attenuation around to the 5<sup>th</sup> order.

#### D. Application of Voltage Distortions of 23<sup>rd</sup> Order

Following the same procedure of topic C, 1% of distortion on 23<sup>rd</sup> order was applied over a sinusoidal voltage supply.

The results are shown on Figure 8.

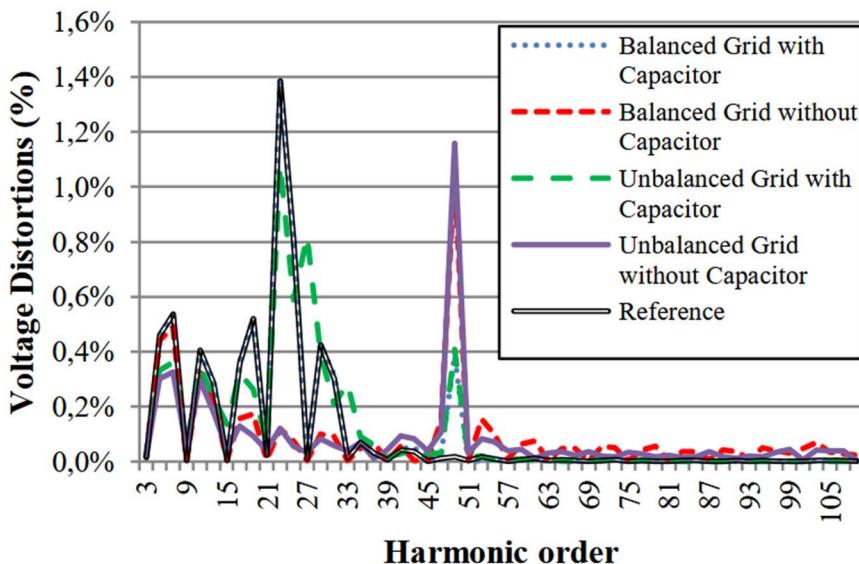


**Figure 8.** Voltage harmonic results after applying 1% on 23<sup>rd</sup> order.

- Crossed-frequency distortion between 17<sup>th</sup> and 37<sup>th</sup> order;
- 25<sup>th</sup> order showed its distortion higher than the 23<sup>rd</sup> order;
- The resonance on Secondary caused a strong amplification near its frequency;
- 23<sup>rd</sup> and 25<sup>th</sup> order had their distortions higher than 6% while 1% was applied;
- Unbalancing did not show to have any relevant impact on distortions.

#### E. Application of Voltage Distortions of 49<sup>th</sup> Order

Accordingly, to the purpose mentioned, 1% of distortion on 49<sup>th</sup> order was applied over a pure sinusoidal voltage supply. The results are shown on Figure 9.



**Figure 9.** Voltage harmonic results after applying 1% on 49<sup>th</sup> order.

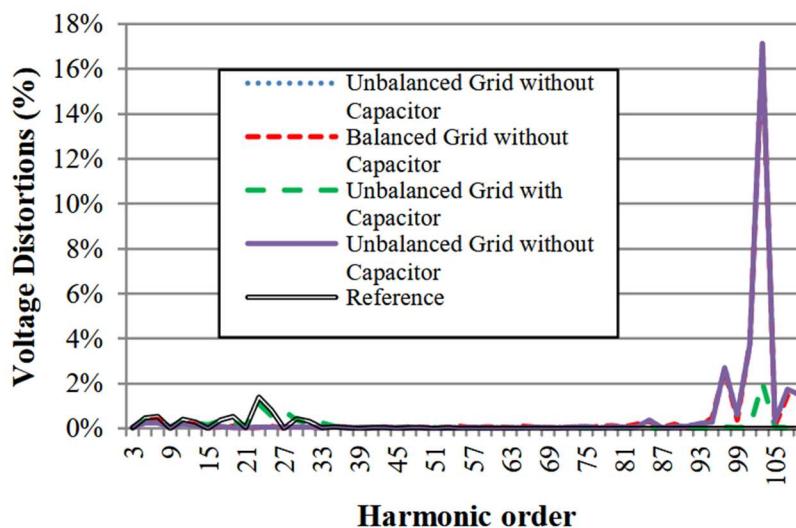
- No relevant crossed-frequency was notable within the balanced system;
- Crossed-frequency happened around 23<sup>rd</sup> order when the system was unbalanced;
- Comparing results with and without capacitors to Figure 5, a relationship between harmonics distortion and impedance can be noted: after the resonance – 23<sup>rd</sup> order – as lower the impedance

is, more it attenuates the distortion and crossed- frequency;

- Unbalancing caused significative distortion only on harmonics 27 and 33, which are zero-sequence.

#### F. Application of Voltage Distortions of 103<sup>rd</sup> Order

Finally, 1% of distortion on 103<sup>rd</sup> order was applied over a sinusoidal voltage supply. The results are shown on Figure 10.



**Figure 10.** Voltage Harmonic distortion after applying 1% on 103<sup>rd</sup> order.

- Crossed-frequency happens near the resonance frequency;
- There is crossed-frequency around 103<sup>rd</sup> order, but it only happens where there are no capacitors on Secondary;
- The crossed-frequency happens due to the resonance on Primary;
- Voltage harmonics attenuate strongly after the resonance frequency when capacitors are connected on Secondary;
- There is amplification around 103rd order when applying 1% on 103<sup>rd</sup> order, which caused voltage distortions of 16%;
- The amplification is caused by the resonance on Primary;
- The unbalancing caused some distortion only on harmonics 27 and 33, which are zero-sequence.

## IV. Conclusions

The findings of this paper can help in understanding and anticipating potential issues when connecting PV inverters or wind turbines to an existing grid that already experiences background harmonic distortion and unbalances [4,5].

Based on the results, some key observations can be made:

- Amplifications and attenuations of harmonic distortions due to resonances are evident;
- Background voltage distortion and voltage unbalance have a measurable impact on the magnitude of both self-frequency and cross-frequency harmonics.

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