International Conference on Renewable Energies and Power Quality (ICREPQ'13)
Bilbao (Spain), 20th to 22th March, 2013
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.11, March 2013

Analysis of the Energy Quality in a Building Acclimated Through a System of Evaporative Cooling Operated by Frequency Converters.

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Abstract. The present article has as the aim to analyze the level of harmonic distortion of voltage in the bus in an electric system in the presence of evaporative refrigerators used for the cooling of environments operated by converters of frequency in which measurement campaigns were carried out in field. Considering that the frequency converters with the filters absence make the system presents nonlinear characteristics whose analyses are of great matter in what concerns about the quality of the electric energy and the fulfillment of the law and the existing rule, established by the national and international regulating agencies. In this context, through computational simulations, there was observed the efficiency of the passive filters tuned with objective to reduce the levels of harmonic distortions of voltage in the bus in study and to adapt these levels to the standards of reference contained in the existing resolutions. [1]

Key words

Passive Tuned Filters; non-linear Load; Power Factor; Harmonic Distortion.

1. Introduction

The development of the electronic power and the technological advancement of semiconductor devices, microprocessed and microcontrolled, checked in the last years, introduced new electro-electronic equipments in the consumer unities. We have for example, compact fluorescent light, electronic reactors, appliances of heating with static control of temperature, microcomputers, television sets with modern feeding by solid state, among others. In common, all these new loads have non-linear characteristics, i.e. they provoke the distortion of waveforms of current and voltage of the system and "inject"currents in the secondary circuits of distribution of the dealerships of energy with whole multiple frequencies of the fundamental frequency, called harmonic frequencies.

The distortion effects of the waveforms of current and / or tension can be as varied as possible like, for example, compromising the energy meters precision of the type Watt-hour inductive, microprocessed reles malfunction, as well as, reles that depend on peak values or voltage/current wave passage for zero for operation, bringing in supply interruption of electrical energy. Among other effects, they can quote also the interferences in telecommunication systems and computerized control systems, the useful life loss of transformers and electric motors, etc.

Besides, currently, some Brazilian dealerships are installing low voltage capacitors in secondary distribution circuits. This action, undoubtedly, brings several benefits to the circuit like, for example, the load reduction of the distribution transformers, the voltage level increase, the power factor improvement (PF), among others. However, all these benefits are related only to the fundamental frequency of the electrical system. So, this technique can be shown much unsatisfactory when in the parallel resonance occurrence between the capacitor installed in the low voltage and the equivalent inductance of the electric system, in this case, the distribution transformer, in one frequency of the harmonic components.

In this context, there has been a large mobilization by the national regulators and international power sector aiming to limit the harmonic distortion level of the voltage with which the electric systems can operate and impose that the new equipments do not "contaminate" the nets with harmonic voltage amplitude that exceeds certain values (IEE 519, IEC 61000 and EM 59160).

In Brazil, the System National Operator (ONS), the National Agency of Electric Energy (ANEEL), and the dealerships of electric energy are treating this question with the proper rigidity. Through "Distribution Proceedings" (PRODIST), published in December of 2008, in its module 8 (eight), ANEEL treats the quality of energy as regards the service and product in national extent [1]-[2]-[3]-[4].

For these problems mitigation related to the harmonic components presence, one of the most usual practices in Brazil is the application of passive harmonic filters, as soon as these are easy to install and use, because of being already consolidated enough, elevated reliability guarantees them. There are presented measurements carried out in field in the bus that feeds the evaporative refrigeration system operated through a microprossed system of a commercial building. In this sense, the present work proposes a solution to improve the electric energy quality levels and to make the harmonic distortion of voltage level adaptation to the reference regularized values by ANEEL through the Resolution 345 of 2008, using the computational tool ATPDraw in which the present electric loads were modelled in the bus, as well as his electric components such as voltage, current, powers, etc. and their respective multiple frequencies. For the present harmonic distortions mitigation in the bus solicited currents there were used passive tuned filters projected through the software Matlab.

2. Harmonics Conceptualization and Classification

Voltage or current signs with the presence of harmonics present periodic behavior. These signs have, besides the fundamental stated frequency, entire multiple frequencies of this, making the waveform presents itself warped in relation to a purely sin signal.

The harmonics can be classified as its order or frequency and sequence of phases, according to the Table I example.

TABLE I. HARMONICS ORDER OR FREQUENCY AND SEQUENCE

Order	Frequency (Hz)	Sequence
1	60	+
3	180	0
5	300	-
7	420	+

Because of not having characteristic presence in the electric systems, the even order harmonics are not contemplated in this work. The Table I shows that the harmonics can be of positive sequence (+), negative (-) or zero (0), which can be justified through the Equations (1), (2) and (3). Analysing such equations, it is noticed that the sequence of phase of the harmonics depends straightly on its order (h).

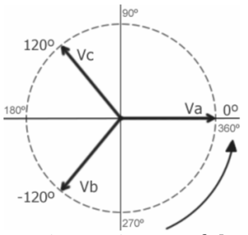
$$v_{ha}(t)=V_{ham}\sin h(\omega t) \quad (1)$$
$$v_{hb}(t)=V_{hbm}\sin h(\omega t-120^\circ) \quad (2)$$
$$v_{hc}(t)=V_{hcm}\sin h(\omega t+120^\circ) \quad (3)$$

Where:

$v_{ha}(t)$, $v_{hb}(t)$, $v_{hc}(t)$ - instant values of the fundamental and harmonic voltages in the phases *A*, *B* e *C*.

V_{ham}, V_{hbm}, V_{hcm} - maximum values of the fundamental and harmonic voltages in the phases *A*, *B* e *C*.

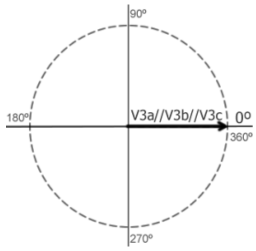
The Equations (4) to (9) describe the mathematical model for the voltages in the fundamental frequency, and the Figure 1 illustrates in the trigonometric circle the sequence of phases for the same.



$$v_{1a}(t)=V_{1am}\sin 1(\omega t) \quad (4)$$
$$v_{1a}(t)=V_{1am}\sin (\omega t) \quad (5)$$
$$v_{1b}(t)=V_{1bm}\sin 1(\omega t-120^\circ) \quad (6)$$
$$v_{1b}(t)=V_{1bm}\sin (\omega t-120^\circ) \quad (7)$$
$$v_{1c}(t)=V_{1cm}\sin 1(\omega t+120^\circ) \quad (8)$$
$$v_{1c}(t)=V_{1cm}\sin (\omega t+120^\circ) \quad (9)$$

Fig. 1. Diagram of the fundamental voltages and its sense of spin.

For the third harmonic case, Equations (10) to (17) illustrate the mathematical development for the voltages whereas the Figure 2 shows its performance in the trigonometric circle.



$$v_{3a}(t)=V_{3am}\sin 3(\omega t) \quad (10)$$
$$v_{3a}(t)=V_{3am}\sin (3\omega t) \quad (11)$$
$$v_{3b}(t)=V_{3bm}\sin 3(\omega t-120^\circ) \quad (12)$$
$$v_{3b}(t)=V_{3bm}\sin (3\omega t-360^\circ) \quad (13)$$
$$v_{3b}(t)=V_{3bm}\sin (3\omega t) \quad (14)$$
$$v_{3c}(t)=V_{3cm}\sin 3(\omega t+120^\circ) \quad (15)$$
$$v_{3c}(t)=V_{3cm}\sin (3\omega t+360^\circ) \quad (16)$$
$$v_{3c}(t)=V_{3cm}\sin (3\omega t) \quad (17)$$

Fig. 2. Diagram of the harmonic voltages of sequence zero.

The mathematical demonstrations of the other harmonics, namely, 5ª, 7ª, 9ª, 11ª, 13ª, 15ª, 17ª, 19ª, 21ª, 23ª and 25ª are analogous to the previous ones, as soon as these alternate in the sequences zero, negative and positive. [4]

3. Values of reference for the harmonic distortion levels in the electric system

The Table II summarizes the applicable terminology to the harmonic distortions, regularized by ANEEL through the Resolution 345 of 2008, which in its module 8 treats the harmonics levels allowed in the national electric distribution system [5].

TABLE II. TERMINOLOGY

Identification of Greatness	Symbol
Individual voltage harmonic distortion of order h	DIT_h%
Total harmonic distortion voltage	DTT %
Individual current harmonic distortion of order h	DII_h%
Total harmonic distortion of current	DTI %
Harmonic voltage of order h	V_h
Harmonic order	h
Maximum order harmonic	Hmáx
Minimum order harmonic	Hmin
Fundamental voltage measured	V_1

The same resolution states that the expressions for the computation of DIT_h% and DTT% are represented by Equations (18) and (19). The harmonic spectrum to be considered for purposes of calculating the total distortion shall have a frequency band that considers the fundamental frequency and up to at least the 25th harmonic (Hmin = 25), and the reference values for the harmonic distortions total are those shown in Table III.

$$DIT_h\% = \frac{V_h}{V_1} x100 \qquad (18)$$

$$DTT\% = \frac{\sqrt{\sum_{h=2}^{hmáx} V_h}}{V_1} x100 \qquad (19)$$

TABLE III. TOTAL HARMONIC DISTORTION REFERENCE VALUES (IN PERCENTAGE OF FUNDAMENTAL VOLTAGE)

Rated voltage bus	Total Voltage Harmonic Distortion (DTT) [%]
Vn ≤ 1kV	10
1kV < Vn ≤ 13,8kV	8
13,8kV < Vn ≤ 69kV	6
69kV < Vn < 230kV	3

4. Background on evaporative coolers

The evaporative air coolers have a fan that draws external air through a special evaporative panel, on which water is continuously circulated by a small pump. The water that evaporates is reset by a float which keeps a constant level in the reservoir. The evaporative panel RE is the most modern and efficient means evaporative existing consisting of high quality layers of kraft paper, corrugated, porous, impregnated with a resin which gives great rigidity and strength. Once glued, the layers form blocks or hives very large surface area which offer low resistance to airflow. The result is an equipment of high efficiency, compact, simple, durable, low-maintenance that produces excellent quality clean air, not saturated and cooled up to 12 ° C below the external air temperature.

The continuous exchange of ambient air for cooling air is fundamental to maintain thermal comfort conditions in the environment. Thus, the air produced by evaporative cooler must have adequate output environment. The air must travel across the region to be cooled and find natural exits (doors, windows or other openings in an area compatible with the airflow produced), located in the appropriate places. When the natural outputs are insufficient or inexistent, exhausters must be installed. The correct location of natural openings or exhausters is essential to create the airflow pattern in the desired environment. The evaporative coolers are extremely useful in industrial environments by providing thermal comfort at a very low cost. In most industries the installation of conventional air conditioning systems is totally impractical and a simple ventilation is ineffective in environments with high thermal load. The use of evaporative coolers in this environment contributes to the wellbeing of workers, increasing their productivity and efficiency and reducing health and safety problems. Evaporative air coolers are environmentally friendly because they only work with water and have a very low power consumption. In addition, using no CFC or HCFC, harmful to the environment.

5. Measurements in field

The building analyzed shown in Figure 3 is a hall social events modeled in EnergyPlus software that has three evaporative coolers driven by microprocessed system.

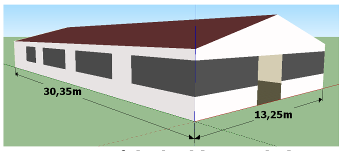


Fig. 3. 3D View of the building with dimensions

The frequency converter system studied feeds three engines of 0.5 CV responsible for the speed of the refrigerators propellers, whose nameplate data are illustrated in Table IV.

Along with the system, but in direct start, there were three pumps of 0.16 CV that were used for pumping water into the system.

TABLE IV. Data Equipment

Enginess	Pumps	Fans
Power	1/6 CV	0,5 CV
Rotation	3500 RPM	3500 RPM
Poles	2 Poles	2 Poles
Voltage	220/380/440 V Three phase	220/380/440 V Three phase
Frequency	50/60 Hz	50/60 Hz
Protection	IPW-55	IPW-55
Frequency Converter		
Feed	Three phase 200-240	
In (Out)	7,3 A	
Mark	Weg	
Model	CFW100073T2024POCPZ	

The equipment used for the electrical events recording in the social hall is the energy analyzer MARH-21, RMS manufacturer, which is a magnitudes measurer recorder in real-time for single-phase electrical systems, two phase and three phase in low, medium and high voltage. It has three input channels for voltage signals, three input channels for current signals and three input channels for user-defined auxiliary quantities. Based on the input voltage and current signals, the MARH 21 calculates and displays in the alphanumeric display the phase voltages values, line voltages, currents, power factors per phase and total, active power, reactive and apparent power per phase and total, total active energy (consumed or provided), total capacitive / inductive reactive energy, THD of voltage and currents per phases, voltage and current THD (% by frequency band), total reactive power required to change the power factor, auxiliary quantities, voltage frequency, the voltage maximum and minimum frequency, phase sequence, demands in peak and off peak per phase and total displacement factor, etc..

A. Voltages and currents measurements

Initially voltages and currents profiles were monitored in three-phase bus that feeds the hall social events, whose three-phase waveforms are shown in Figures 4 and 5.

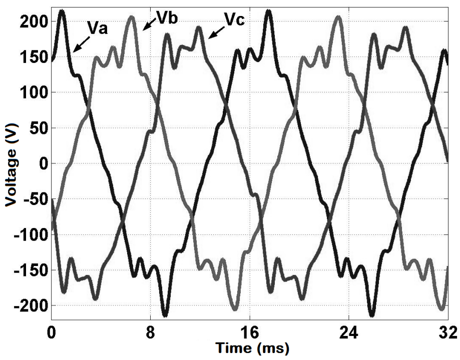


Fig. 4. Voltages waveform in phases A, B and C on the bus that feeds the hall social events.

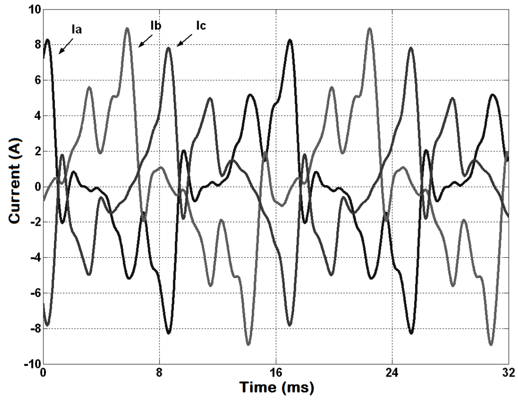


Fig. 5. Currents Waveform in phases A, B and C on the bus that feeds the hall social events.

Figure 5 allows the observation, beyond the distortion of the waveform of currents, a marked distortion of the waveform of the voltages shown in Figure 4.

Whereas both currents and voltages harmonic distortion for the three phases are similar, was chosen to show the relative magnitudes to phase A. Thus, Figures 6 and 7 show the harmonic spectra corresponding to the voltage and current in phase A on the hall social events bus. The rotational speed of the induction motor which drives the cooling system is maintained in accordance with the frequency delivered by the converter. In this study was used the frequency of 30 Hz. A spectrum analysis of the A-phase current, illustrated in Figure 7, shows that the electronic actuation of the evaporative system implies the appearence of positive, negative and zero harmonic sequence in the current, and that the positive and negative sequences change currents effective values in phases and zero sequence add up in the neutral and can reach high values, which can, depending on the situation, entail overheating cable performance and protection, etc.. This situation, and the voltage drops in the lines impedances due to the harmonic content verified in the currents, cause the bus voltages become quite distorted, as shown in the voltage spectrogram shown in Figure 6.

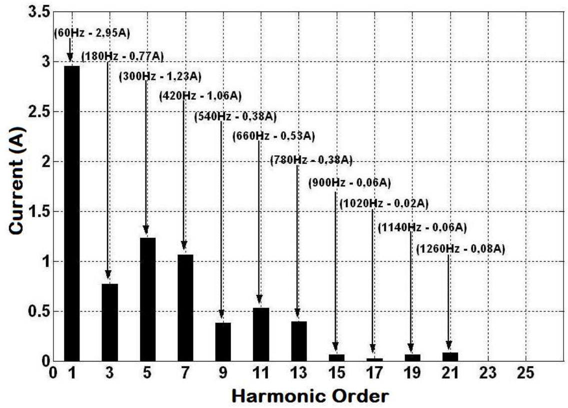


Fig. 6. Phase A current spectrum in Z bus before installing filter for 5th harmonic.

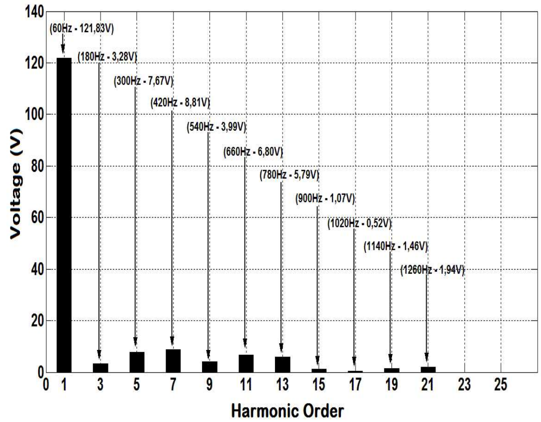


Fig. 7. Phase A voltage spectrum in Z bus before installing the 5th harmonic filter.

The individual and total voltage and current harmonic distortion are recorded in Tables V and VI, respectively. Analyzing Tables V and VI reveals that the harmonic distortion present in the evaporative system current powered by frequency converter led a total voltage distortion of bus in the bus of 12% which is above the baseline established by Resolution 345 of 2008 by ANEEL, which in its module 8 deals with the harmonic voltage levels allowed in the national electrical distribution system, as shown in Table III.

TABLE V. HARMONIC DISTORTIONS

Harmonic Order	DII_h	DTI%	DIT_h	DTT%
1ª	2,97		121,9	
3ª	0,78		3,28	
5ª	1,24		7,74	
7ª	1,05		8,78	
9ª	0,37		3,99	
11ª	0,54	66,347%	6,88	13,016%
13ª	0,38		5,74	
15ª	0,05		0,97	
17ª	0,02		0,54	
19ª	0,06		1,49	
21ª	0,08		1,96	
23ª	0,00		0,01	

6. Computational simulations

Aiming to analyze the behavior of passive harmonic filters and their ability to correct the harmonic distortion levels was performed a computational simulation, as shown in Figure 8, from the cooling system in this study using the software ATPDraw.

The system in question consists of three sources of harmonic injection that represents the converter three-phase input connected to the network. Thus, the distortion caused by the inverter in the electrical system can be depicted by these distortions represented in the model simulated as nonlinear load. In parallel with the converter are three pumps that were connected at direct start, represented by the linear load.

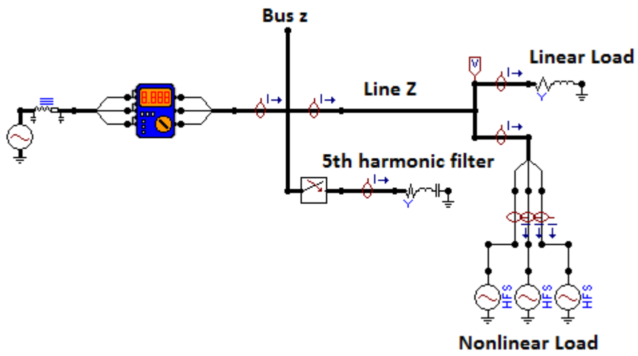


Fig. 8. Evaporative cooling system simulation in ATPDraw.

Due to its non-linear characteristic this load causes the bus which it is connected to be "contaminated" by harmonic currents and voltages whose characteristics are shown in Table IV.

TABLE VI. SIMULATED SYSTEM FEATURES IN ATPDraw

Feature	Value
Total Apparent Power in Z bus [kVA]	1,292
Voltage [V]	122,87
Total Harmonic Distortion of Voltage in Z bus (DTT) [%]	13,016%
Total Harmonic Distortion of Current in Z line (DTI) [%]	66,347%

B. Sizing of a Tuned Filter.

In order to mitigate the total distortion of voltage in Z bus, the refrigeration system driven by frequency converter modeled on ATPDraw Software shown in Figure 8 was used for simulation of sizing of a tuned filter to the 5th order harmonic, this being the highest amplitude present in the current as seen from Figure 6.

The tuned filters are series resonant circuits that in the tuned or resonance frequency have low resistive impedance. These filters constructive simplicity determines low deployment costs and/or maintenance, compared to other filtering techniques.

Assuming the negligible resistive part, the angular frequency of the series resonance circuit can be determined through Equation (20).

$$W_0 = \frac{1}{\sqrt{LC}} = 2\pi f_0 = \frac{2\pi}{T_0} \quad (20)$$

In the present study, the impedance behavior and its angle of a tuned filter to the frequency on the 5th harmonic order is illustrated in Figure 9.

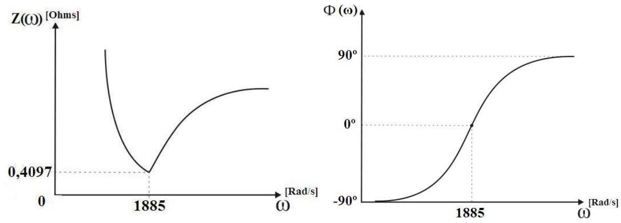


Fig. 9. Module and impedance angle of a series RLC circuit versus frequency.

For the calculations basis of the filter is necessary to define the quality factor (Q) which determines the selectivity of the filter and whose variation range is from 30 to 60, so that the closer to 60 Q is more selective is the filter and the closer to 30, the greater the extent of the filter to adjacent harmonic frequencies to the frequency tuning, as shown in Figure 10, [4].

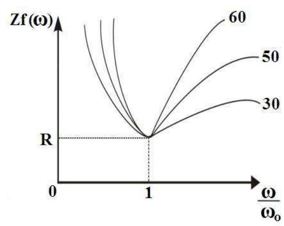


Fig. 10. Impedance versus frequency for different values of the factor Q.

The electrical parameters used for the filter design using the software Matlab tuned to the 5th harmonic order, are presented in Table VII. Were obtained by simulation of the modeled system in ATPDraw in Figure 8. We chose a Q equal to 30 by providing a good selectivity for the harmonic frequency in question.

TABLE VII. ELECTRICAL QUANTITIES USED IN Z BUS TO THE FILTER DESIGN

Harmonic Order (h)	5ª
Harmonic Current [A]	1,242
Voltage Bus [V]	220
Network Frequency [Hz]	60
Quality Factor (30<Q'<60)	30
Basis Frequency [Rad/s]	377
Maximum Allowable Voltage [pu]	0,01

Table VIII shows the values obtained for the RLC parameters used in the computational implementation of ATPDraw tuned harmonic filter of 5th order. These were installed in the system according to the schematic diagram of Figure 8.

TABLE VIII. TUNED FILTER PARAMETERS TO THE 5th ORDER HARMONIC

Resistance (Ω)	0,5104
Inductance (mH)	8,1232
Capacitance (μF)	34,6457

After the filter insertion, it was observed a decrease in the system harmonic content and, as expected, a decrease in the value of voltage and current individual harmonic distortion for the 5th order harmonic, as illustrated by spectrograms of Figures 11 and 12. This provided the reduction of the total voltage harmonic distortion on Z bus that fell from 13.016% to 7.7394%, as well as provided the mitigation of total harmonic distortion in the current on Z line that before the harmonic filter installation was 66.347% and reduced to 31.372%, these results being expressed in Table IX.

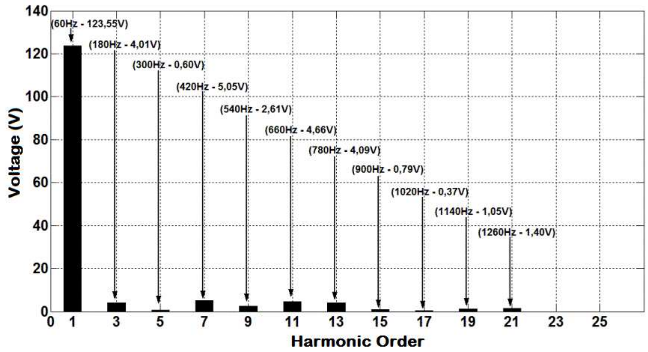


Fig. 15. Z bus voltage spectrum after the5th order harmonic filter installation.

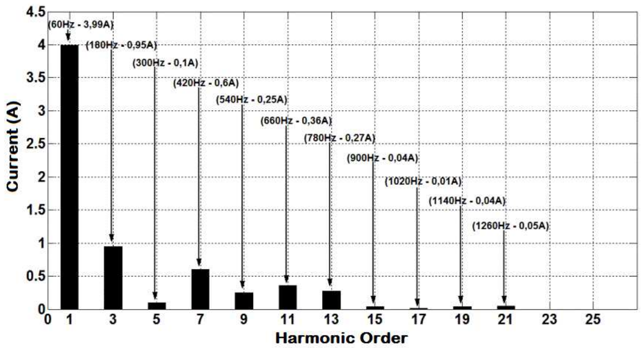


Fig. 16. Z bus current spectrum after the5th order harmonic filter installation.

TABLE IX. CURRENT AND VOLTAGE TOTAL HARMONIC DISTORTION COMPARISON (DTI% E DTT%)

	DTI%	DTT%
Before	66,347 %	13,016%
After	31,372 %	7,7394%

Besides the reduction of the harmonic content, there was an increase in voltage in the fundamental frequency of 122.87 V to 123.97 V in Z bus. It is verified the passive harmonic filters tuned effectiveness in the harmonic currents and voltages reduction present in the electrical systems, providing a suitability of the voltage total harmonic distortion to the reference values established by Prodist in electrical busbars that show nonlinear characteristics, as shown in this study.

Conclusion

This study focus was to analyze the electrical energy quality in a real evaporative cooling system actuated by frequency converters through computational simulations using the software ATPDraw, showing the mitigation of voltage total harmonic distortion of a nonlinear system through the use of tuned harmonic filters and provided their suitability to the reference values established by legislation. It has been found through this study the importance of prior analysis of the harmonic distortion value in the system in order to accurately tune the filter at that frequency whose order is the most significant and therefore minimize what is desired to. In this study, the filter used was highly efficient for the frequency at which it was tuned and reduced voltage total harmonic distortion in the bus studied. Therefore, as seen in this article, the harmonic currents cause changes in the electrical magnitudes effective values and the consequent overload on conductor and equipment, also affecting the proper protective devices operation that can act due to peak or rms values increments of these magnitudes. Thus, the awareness of disturbances present in electrical systems deserve special care, corrective actions should be taken to mitigate the problem through the use of harmonic filters, ensuring in this way, safe projects and avoiding risk situations for users and equipment, beyond the adequacy of voltages in electric buses to new standards of power quality established by legislation.

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