Mitigation of harmonic distortion with passive filters

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***Abstract*—The growing use of nonlinear loads in commercial, residential and industrial sector has been distorting the currents and voltage waves of the power network. These distortions are known as harmonic distortions, and its presence can cause serious problems to equipment linked to polluted sources. One well known solution to mitigate this issue is the use of passive filter. This paper presents many aspects of passive filter, explaining about its types, the steps for a project, as well as simulation in a synthetic system and results.**

***Index Terms*-- Harmonic distortions; nonlinear loads; passive filter; simulation**

I. Introduction

The quality of power supply in recent decades has gained more attention [23]. At past, energy quality was seen as an implicit responsibility of system operators. But, nowadays, energy quality has clear objectives. The free competition at energy market made enterprises prepared to report quality information linked to its supply [20]. The survey of information through statistical data on these types of loads has become an important parameter for the development of new standards of control, limits and procedures established by the agencies responsible for auditing the generation and distribution companies in the world [8], [26], [27].

The development of industry and national trade brought the installation of nonlinear loads, like personal computer, battery charger, compact fluorescent lamp and others, representing distortions in the electric power system [7]. They are basically classified into ferromagnetic devices (transformers, motors, reactors, etc.), static power converters (frequency inverters) and devices that work with electric arc (welding machines, industrial arc furnaces, etc.) [14].

This kind of load is nonlinear, since they have a nonlinear relationship between the voltage and current [24], what represents wave distortions. Harmonic distortion is a sinusoidal component of the voltage or current at a multiple frequency of the fundamental frequency [24].

The Fig. 1 shows a signal at the fundamental frequency (60Hz) with 3rd order harmonic signal (180Hz).

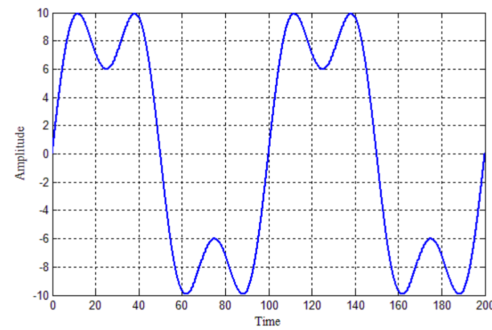

Figure 1. Signal of fundamental frequency with 3th harmonic order.

This issue can bring a lot of problems to operation of devices sourced by polluted network, like:

- Increased losses within the equipment like transformers, generators, motors, cables, that are often oversized because harmonics effects;
- Pulsating and reduced torque in rotating equipment;
- Premature aging due to increase stress in the equipment insulation;
- Increased audible noise from rotating and static equipment;
- Substantial amplification of currents and voltages due to resonances;
- Communication interference due to inductive coupling between power and communication circuits [6], [17].

Passive filter is a well-known technology to solve this issue. Other option to mitigate harmonic waves is the use of active filters. Many works compare passive and active filters, and the use of both at hybrid composition, what can minimize the passive filter size [3], [4], [12], [18].

Active filters have the same function as passive filters, but they are developed with electronic equipment and they are made to inject harmonic currents adequately lagged to those generated by the loads. When the currents are added together they will cancel each other. While passive filters are usually

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dependent and specified by the values of inductors, capacitors and switching elements that compose them, active filters are specified by the current they will filter [2].

Talking about the two filter settings, passive and active, each one has advantages and disadvantages. The main advantage of passive filter is its cost [16]. However, there may be resonances with electric system elements. For good performance, a large capacitive compensation in the fundamental frequency is required. The load variability, which the filter is connected, influences its performance. The active filter must have equal capacity or greater than the nonlinear load to be filtered, which makes it economically unfeasible in some cases. More expensive than the passive filter, the active filter has consistent performance, independent of load variability [3].

There are other types of approaches that use artificial intelligence to choose the optimum performance and configuration of a passive filter. Like it is done at [5], [13], genetic algorithm is used to set the capacitor and inductor size. [22] uses mathematical models to size an economical optimum filter.

How to select filter topologies requires specialized knowledge, so [14], [24], [25] gives the steps to select the filter topology considering its cost. Before physical project, it is common the use of computer simulation to prove the efficiency of a filter solution just by simulating the project and showing the waves before and after the harmonic filtering [10], [11], [15], [21].

II. PASSIVE FILTER

One classical option to mitigate power grid distortions is harmonic passive filters that can attract the harmonic distortions to a low impedance ground way in a parallel link or dissipate it at high impedance in a series connection [23]. Harmonic filters are usually projected to be capacitive at fundamental frequency, so they also can source reactive power required by converters and power factor correction.

Passive filters are typically composed by inductors, capacitors and resistors, tuned at a characteristic resonance frequency. They also may be constructed in many combinations, so they can be tuned to various frequencies simultaneously. The function of passive filters is to absorb the load harmonic currents, preventing them from circulating through the electrical system [25].

The classic solution to reduce harmonic currents in electrical systems is the use of filters connected in derivation feeder. The various series cells of inductors and capacitors are tuned to values closed of frequencies that are designed to eliminate, which are usually low order components. In general, for higher frequencies, it is used a simple capacitor functioning as high-pass filter.

A. Types

Passive filters can be recognized by its connection type on the main circuit, linked by shunt derivation (parallel) or in series connection as in Fig. 2.

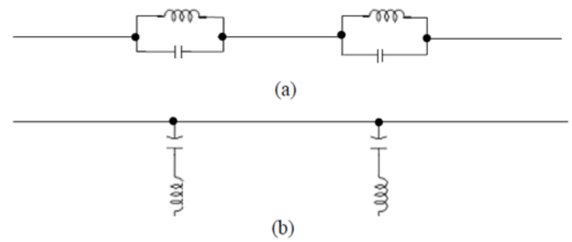

Figure 2. Filter connections: (a) Series; (b) Shunt derivation [1].

The shunt may be grounded in one of its terminations, and then it will be passed only for the tuned harmonic current and a part of the fundamental current. At the series filter, the total current passes through it [23]. So, thinking about the insulation, a filter in shunt derivation is cheaper than one in series with the same efficiency. Another shunt advantage, at the fundamental frequency, it sources the reactive power needed for the power factor regulation and, on the other hand, the series filter consumes this power.

The derivation filters can be divided in tuned and damped filter [24].

B. Tuned Filter

Tuned filter (band-pass) is chosen because the circuit can have one or more resonant frequencies. At the resonant frequency, this filters show low resistive impedance and, at other frequencies, it has higher impedances. They are capacitive at low frequencies and inductive at high frequencies. One important point, this filter has to be tuned a little down of the desired frequency (detuning), to assure efficiency even with fundamental frequency oscillations [25] (what moves harmonic frequencies on time), uncertainties of components size (capacitances, inductances) and impedances variations. It prevents the filter to act as a short circuit on resonance frequency, what can damage components [10]. An alteration about 2% of capacitance or inductance causes the same detuning of 1% at the system frequency [23].

In comparison of other alternatives, this filter is simple and cheap. It’s efficient on the tuned frequency but has low influence at high order harmonics.

C. Damped Filter

Damped filters are capacitive at fundamental frequency and it shows mainly resistive impedance at high frequencies. They can be classified as first order, second order, third order or type C [24]. As shown at Fig. 3.

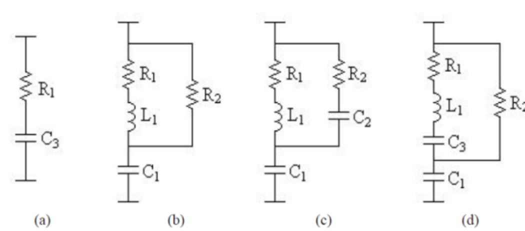

Figure 3. Damped Filters: (a) First order; (b) Second Order; (c) Third order; (d) Type C [24]

The first order filter is infeasible, because it needs a big capacitor and it causes much losses at fundamental frequency [24].

The second and the third order filter (high-pass) work well at tuned frequency and superior harmonics, where they are more used (7th order or higher), but they cause big losses at the resistor at the fundamental frequency.

The damped filters show advantage for being indifferent about frequency variations next to the tuned frequency

One disadvantage is that damped filter needs more reactive power to reach the same efficiency of a tuned filter with lower reactive capacity.

In practice, when there is a big amount of harmonic on the grid, the damped filters are usually used in combination with the tuned filters. The tuned filters work well for low harmonic frequency (5th, 7th, 11th) and the damped filters works better at high frequencies (13th and higher). [25]

D. Type C

The type C filter has a behavior pretty similar to a high-pass filter. It is an intermediate solution between the tuned filter and the damped filter, but the capacitor bank is decomposed in two banks. One part is installed in series with reactor of the filter in a way that in 60Hz, the both, bank and reactor, will be in parallel resonance with the damping resistor. It causes a short circuit on resistor at 60Hz. This fact reduces significantly the power of dissipation on resistor, reducing these component size and costs.

III. HARMONIC FILTER DESIGN

Passive filter projects must be done to filter undesirable harmonic distortions of the system with the best cost-benefit [16]. First, it must be considered that passive filters are composed basically for: reactor, capacitor bank and damped resistors at most cases. All passive filter projects have a reactive power specification, and it will filter the selected harmonic at the tuned frequency. The filter effectiveness depends on relation between the effective impedance of the filter and the system impedance in each harmonic frequency. Harmonic distortions are more significant in weak systems with high impedance [28]. So, firstly it must be done a study of the system. Through measurements and analyses it must be verified which harmonics are present in the system, the limits required on standards, power factor and requirements of installation. The amount of frequencies to be filtered and the number of filters to be installed in certain bar depends on some points: 1) Economic factor; 2) Low order frequencies, usually, show high amplitudes, tuned filters are more used then the damped filters; 3) High order frequencies, usually, show low amplitudes, the damped filters are commonly chosen in these cases.

Next, follows the steps for a filter project at configuration shown in Fig. 4.

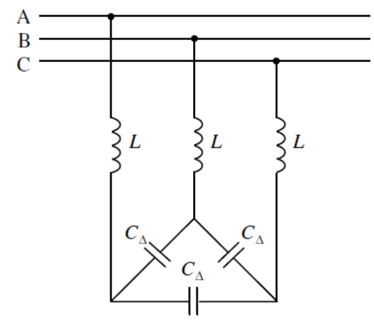

Figure 4. Passive filter at delta configuration. [19]

Delta configuration has three times less capacitance compared with star configuration. This is valid for material saving (less cost) at same reactive power [19].

A. Reactive power compensation

The first step is to determine the effective reactive power needed for compensation (Q_{eff}).

$$Q_{eff} = \gamma\, S\, fp_0 \left[tg(\arccos(fp_0)) - \frac{\sqrt{1-fp^2}}{fp} \right] \quad (1)$$

Where, γ and S are the transformer loading and its nominal apparent power, respectively. The power factor before the compensation is fp_0 and fp is the power factor needed.

B. Effective reactance

The filter effective reactance (X_{eff}) can be calculated by the relation between V_l, the nominal line voltage where the filter will be installed, and Q_{eff}.

$$X_{eff} = \frac{V_l^2}{Q_{eff}} \quad (2)$$

C. Tuning frequency

At tuning frequency, the filter must have high admittance to filter the selected harmonic component. Second [19], the tuning frequency must be calculated considering the variations between inductors and capacitors. These values are the components tolerances. Capacitors usually vary about 0% to 10%. Inductors usually vary about -3% to 7% [19].

So, the tuning frequency (f_r) can be achieved by (3):

$$f_r = \frac{f_h}{\sqrt{(1+t_c)(1+t_l)}} \quad (3)$$

Where, f_h is the harmonic frequency to be filtered. The tolerances of capacitor and inductor (in pu) are t_c and t_l, respectively.

Equation (3) sets a little detuning on the selected harmonic frequency. As it was on section III B, this detuning is essential to prevent resonance between the grid and the filter.

The parameter L (inductance) and C (capacitance) are related to f_r through (4).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

D. Indctance and Capacitance

The relation of the tuning frequency (f_r) and fundamental frequency (f_0) is h_r.

$$h_r = \frac{f_r}{f_0} \tag{5}$$

With X_{eff} calculated through (2), the capacitive reactance (X_c) is calculated by (6).

$$X_C = X_{eff}\frac{h_r^2}{(h_r^2-1)} \tag{6}$$

Then, the inductive reactance (X_L) can be calculated.

$$X_L = \frac{X_C}{h_r^2} \tag{7}$$

Capacitance (C) and inductance (L) are obtained by (8) and (9).

$$C = \frac{1}{2\pi f_0 X_C} \tag{8}$$

$$L = \frac{X_L}{2\pi f_0} \tag{9}$$

Capacitance per phase in delta configuration (C_Δ) is one third of C.

E. Inductor and Capacitor power

The capacitor voltage at delta configuration (Fig. 4) is obtained through the line voltage (V_l).

$$V_C = V_l\frac{h_r^2}{(h_r^2-1)} \tag{10}$$

The reactive power at fundamental frequency of the capacitors in delta configuration (C_Δ) is achieved by (11).

$$Q_C = 3(2\pi f_0)C_\Delta\left(\frac{h_r^2}{h_r^2-1}\right)^2 V_l^2 \tag{11}$$

The reactive power of inductors (Q_L) is the difference between Q_c and Q_{eff}.

F. Quality factor

The filter selectivity is measured by its quality factor (Q). For fig. 4 configuration, it can be calculated by (12).

$$Q = \frac{\sqrt{L/C}}{R} \tag{12}$$

In [24] other steps can be founded to consider commercial values of capacitors, achieving the total current and voltage on the filter.

IV. Simulation

A. Scene

It was used three bars with different loads that are generating harmonic distortions. One load is a motor and the others are rectifiers at low voltage (460V) that are causing distortions at bar of 13.8kV and at the bar of the motor. The single line diagram of this synthetic system is shown in Fig. 5, and its components are presented at Table I.

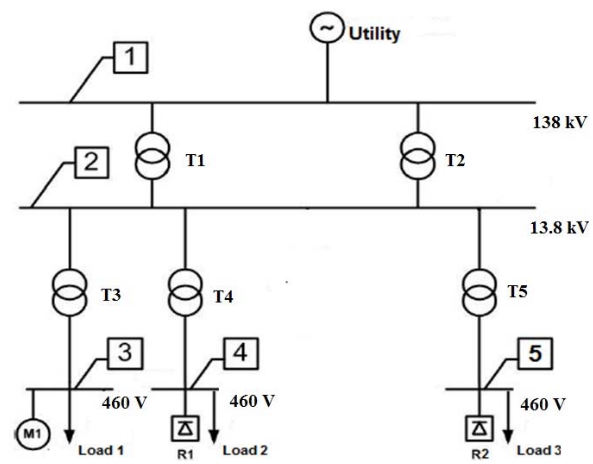

Figure 5. Simulation System

TABLE I. System Components

Transformer	kVA	Prim. Voltage (kV)	Sec. Voltage (kV)	R (%)	X (%)	RM (PU)	LM (PU)
T1, T2	30	138	13.8	1.0	8.0	500	500
T3	50	13.8	0.46	1.5	8.0	500	500
T4, T5	60	13.8	0.46	1.5	8.0	500	500
3 phase linear loads				3 phase Induction Motor			
Load	Active Power (kW)	Inductive Power (Var)		Ind. Motor	HP	RPM	
I	12.75	7.90		M1	20	1760	
II, III	1.27	0.79					
3 phase Rectifier	Power (kW)		DC Voltage (Vrms)			DC Current(A)	
R1, R2	50		648			77.16	

This system was modeled at Matlab Simulink and SimPowerSystems Toolbox Release 2014.

B. Calculations

Following the steps on section III, it was designed a 5th, 7th and 11th order passive filter to be installed at bars 4 and the same filters at bar 5. These bars are the main source of harmonics because of rectifiers (R1 and R2). As [28] suggests, when the sources of harmonic are known, and are not too widely dispersed, it is practical to install the filters close to the distortion source. The lower is the voltage level, the cheaper will be the solution. A detailed picture of the filters installation at bar 4 is presented on Fig. 6. The inputs for the calculations can be seen on Table II.

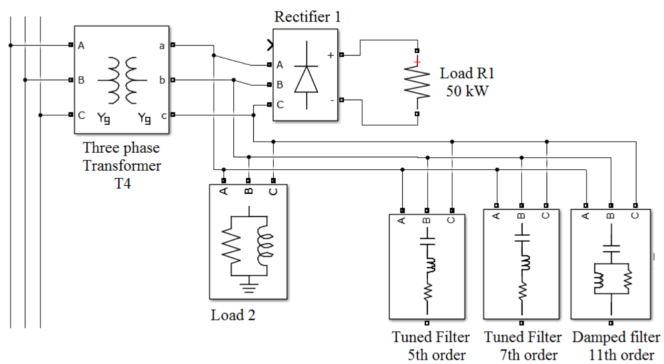

Figure 6. Filters installation on simulation (bar 4).

TABLE II. SYSTEM CONDITION

Bars	4	5
Nominal App. Power (VA)	$6x10^4$	$6x10^4$
Active Power 3ϕ (W)	32001	32001
Reactive Power 3ϕ (VAr)	8229	8229
Apparent Power (VA)	33042	33042
Loading	0.55	0.55
Voltage 3ϕ (V)	406	406
Current 1ϕ (A)	49	49
Power factor	0.96	0.96

The results of calculations, i.e. the parameters of the filter, are showed on Table III.

TABLE III. FILTER PARAMETERS

Filter	5^{th}	7^{th}	11^{th}
Q_{eff} (VA)	2807	2807	2807
X_c (Ω)	78.8	77.1	76.1
X_L (Ω)	3.4	1.7	0.68
C (μF)	33.7	34.4	34.9
L (*m*H)	9.1	4.5	1.8
t_c (%)	6.7	6.7	6.7
t_l (%)	1.5	1.5	1.5
f_r (Hz)	288.8	403.5	634.4
V_c (V)	480	470	464
Q_c (VAr)	2934	2871	2832
Q_L (VAr)	127	63	25
Q	50	50	50

C. *Filter Application*

Table IV shows the voltage harmonic levels and power factor of the bars before filter application. Red values are above of standard limits [26].

TABLE IV. VOLTAGE HARMONIC LEVELS BEFORE FILTER

Bars	1	2	3	4	5
THD	0.09	11.32	8.01	23.63	23.63
H5	0.07	9.24	6.69	19.15	19.15
H7	0.04	4.41	3.17	9.18	9.18
H11	0.02	2.78	1.95	5.82	5.82
H13	0.01	1.56	1.08	3.29	3.29
H17	0.01	1.80	1.20	3.82	3.82
H19	0.01	1.36	0.89	2.90	2.90
P. Factor	0.84	0.90	0.73	0.96	0.96

The results of filters application can be analyzed on table V, where all values are below standard recommendations [26].

TABLE V. VOLTAGE HARMONIC LEVELS AFTER FILTER

Bars	1	2	3	4	5
THD	0.09	2.93	1.80	5.12	5.12
H5	0.07	0.88	0.64	1.47	1.47
H7	0.04	0.29	0.21	0.49	0.49
H11	0.02	0.14	0.10	0.23	0.23
H13	0.01	0.95	0.65	1.60	1.60
H17	0.01	1.49	0.99	2.22	2.22
H19	0.01	1.03	0.67	1.78	1.78
P. Factor	0.92	0.99	0.73	0.99	0.99

The cumulative filter installation causes different steps of attenuation. This is shown on Fig. 7.

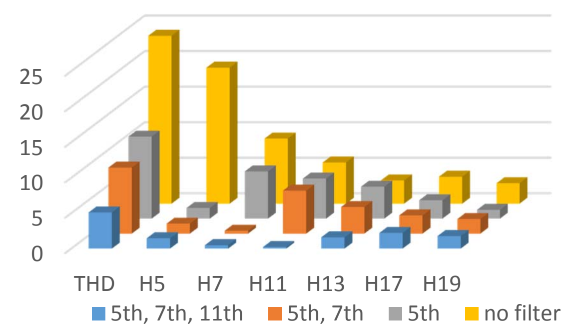

Figure 7. Harmonic Attenuations (bars 4 and 5)

By Fig. 8, it can be seen attenuations on impedance level nearby harmonic orders of the designed filters (5^{th}, 7^{th}, 11^{th}).

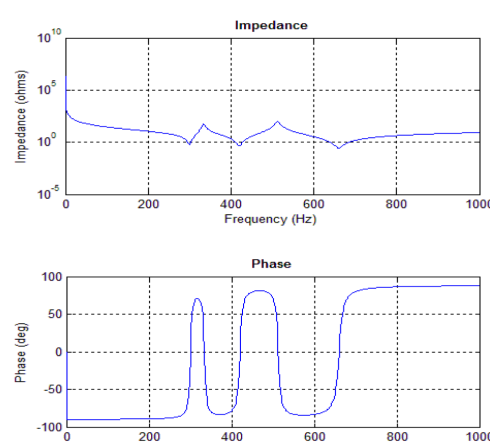

Figure 8. Frequency responses with filtering (bars 4 and 5)

V. Conclusion

Harmonic filters are simple solutions for systems with quality energy problems. By the simulation proposed, passive filters showed positive results on harmonic attenuations, with benefits on power factor too. The first step for a filter project is a quality study to detect the real causes and the severity of the problem. Then it will be determined the best solution with the correct power for the system, according to the lowest cost and the best result.

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References

Periodicals:

[1] Duarte, S.X., Kagan, N.A "Power-Quality Index to Assess the Impact of Voltage Harmonic Distortions and Unbalance to Three-Phase Induction Motors," *IEEE Transactions on Power Delivery*, vol. 25, pp. 1846-1854, 2010

[2] Singh Bhim, Al-Haddad, K.; Chandra, A." A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, pp. 960-961, 1999

[3] Fujita H., Akagi, H., "A practical approach to harmonic compensation in power systems-series connection of passive and active filters," *IEEE Transactions on Industry Applications*, vol. 27, pp. 1020-1025, 1991

[4] J.-H. Sung, S. Park, K. Nam, "New hybrid parallel active filter configuration minimising active filter size," IEEE *Proceedings - Electric Power Applications*, vol. 147, pp. 93 – 98, 2000

[5] Yaow-Ming Chen, "Passive filter design using genetic algorithms," Industrial *Electronics, IEEE Transactions*, pp 202 – 207, 2003

[6-] V.E. Wagner, "Effects of harmonics on equipment," *IEEE Trans. Power Del.*, vol. 8, no. 2, pp. 672-680, 1993.

[7] Wang, Y. J., O'Connell R.M., Brownfield G., "Modeling and prediction of distribution system voltage distortion caused by nonlinear residential loads" *IEEE Transactions on Power Delivery*, vol. 16, pp 744-751, 2001

[8] Key, Thomas S., Jih-Sheng Lai, "Comparison of standards and power supply design options for limiting harmonic distortion in power systems," *IEEE Transactions on Industry Applications*, vol. 29, pp. 688-695, 1993

[9] Gonzalez Damian A., McCall, John C. "Design of Filters to Reduce Harmonic Distortion in Industrial Power Systems," *IEEE Transactions on Industry Applications*, vol. IA-23, pp.505-511, 1987

Papers from Conference Proceedings (Published):

[10] F. N. Belchior, L.R. Lima, P. F. Ribeiro, J. F. C. Castro, "A Novel Approach Towards Passive Filter Placement", *in Proc. 2015 IEEE Power & Energy Society General Meeting*

[11] Huang, S.J, Wu, J. C., "Design and operation of cascaded active power filters for the reduction of harmonic distortions in a power system" In Generation, Transmission and Distribution," *IEE Proceedings* pp. 193-199, 1999

[12] L. Herman., I. Papič, "A parallel hybrid active power filter for resonance damping in industrial networks," *IEEE 15th International Conference on Harmonics and Quality of Power (ICHQP)*, 2012

[13] Chang, G.W., Hung-Lu Wang, Shou-Yung Chu, "Strategic placement and sizing of passive filters in a power system for controlling voltage distortion – *IEE Power Engineering Society General Meeting* - 2004

[14] Nassif A.B.; Wilsun Xu, Freitas W, "An Investigation on the Selection of Filter Topologies for Passive Filter Applications," *IEEE PES General Meeting*, 2009

[15] D.C. Bhonsle, R.B. Kelkar, "Harmonic pollution survey and simulation of passive filter using MATLAB" *Int. Conf. Recent Advancements in Elect., Electron. and Control Eng. (ICONRAEeCE)*, Sivakasi, pp. 230-236, 2011.

[16] M. T. Elmathana, A. F. Zobaa, S. H. E. Abdel Aleem, "Economical design of multiple-arm passive harmonic filters for an industrial firm - Case study," *IEEE 15th International Conference on Harmonics and Quality of Power (ICHQP)*, 2012.

[17] Radislav M., Milanko R., "Harmonics: Examples of negative impacts," *IEEE 16th International Conference on Harmonics and Quality of Power (ICHQP)*, 2014

[18] S. A. Temerbaev, V. P. Dovgun, "Improvement of Power Quality in Distributed Generation Systems Using Hybrid Power Filters*", IEEE 16th International Conference on Harmonics and Quality of Power (ICHQP)*, 2014

[19] Alves C.B.A., Santos E. B., Garcia R. F., Nielso, R., "Dimensionamento de filtro sintonizado para instalação na rede secundária", *Congresso Brasileiro de Automática (CBA)*, 2010

[20] A. Testa, R. Langella, "Harmonic Pollution in Italian Distribution Networks in Coincidence with Important Sport Events*," IEEE Power Engineering Society General Meeting*, 2007

[21] Vasconcellos A. B., Dr; Bismack C. C., Lambert J. A., Dr.; Tiemi E. A., Marques T. L., "Applications of Tuned Passive Harmonic Filters in a Busbar With Non-linear Loads," *IEEE 15th International Conference on Harmonics and Quality of Power (ICHQP)*, 2012

[22] Yonghai Xu, Yadi T., Wangsong H., "*Optimal Configuration of Filters for Harmonic Suppression in Microgrid*", *IEEE 16th International Conference on Harmonics and Quality of Power (ICHQP)*, 2014

Dissertations:

[23] M. M. D. Silva, "Análise de Filtros Passivos de Harmônicos de conversor CA/CC de seis pulsos, " Master degree dissertation, UFRJ, 2007

[24] R. P. Nascimento, "Propostas de procedimentos para projetar filtros harmônicos a partir de um programa de penetração harmônica, incluindo cálculos de desempenho e de suportabilidade, " Master degree dissertation UFU, 2007

[25] E. E. C. Moraes, "Estudo e projeto de filtros passivos para atenuação de harmônicos em instalações elétricas industriais, " Master degree dissertation, UFC,2011

Standards:

[26] Agência Nacional de Energia Elétrica (ANEEL) – "Procedimentos de distribuição de energia elétrica (PRODIST) no sistema elétrico nacional. Módulo 8 – Qualidade da Energia Elétrica, " 2014

[27] *IEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems,* IEE Std – 519 – 2014

Books:

[28] R. C. Dugan, D. T. Rizy, Harmonic Considerations for electrical distribution feeders, vol. I., Ed. McGraw – Edison Power Systems Cooper Industry, Inc., 1988, pp. 110 - 111.