A MATLAB-SIMULINK APPROACH TO SHUNT ACTIVE POWER FILTERS

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ABSTRACT

Due to the wide spread of power electronics equipment in modern electrical systems, the increase of the harmonics disturbance in the ac mains currents has became a major concern due to the adverse effects on all equipment. This paper presents the analysis and simulation using Matlab Simulink of a three-phase four wire neutral clamped active power filter (APF) compensating the harmonics and reactive power created by nonlinear balanced and unbalanced low power loads in steady state and in transients. The usefulness of the simulation approach to APF is demonstrated so APF designers have a better insight using Matlab Simulink in order to develop new APFs.

INTRODUCTION

Modern electrical systems, due to wide spread of power conversion units and power electronics equipments, causes an increasing harmonics disturbance in the ac mains currents. These harmonics currents causes adverse effects in power systems such as overheating, perturbation of sensitive control and communication equipment, capacitor blowing, motor vibration, excessive neutral currents, resonances with the grid and low power factor (Maswood and Haque 2002). As a result, effective harmonic reduction from the system has become important both to the utilities and to the users.

The total harmonic distortion is the ratio between the RMS value of the sum of all harmonic components and the RMS value of the fundamental component, for both current and voltage, as in equation (1):

$$THD[\%] = 100 \cdot \sqrt{\sum_{h=2}^{\infty} \left(\frac{I_h}{I_1}\right)^2} \qquad (1)$$

where h is the order of the harmonic.

Traditionally, the simplest method to eliminate current harmonics is the usage of passive LC filters, but they have many drawbacks such as large size, tuning problems, resonance and fixed compensation characteristics. The solution over passive filters for compensating the harmonic distortion and unbalance is the shunt active power filter (APF). In order to compensate the distorted currents the APF injects currents equal but opposite with the harmonic components, thus only the fundamental components flows in the point of common coupling (PCC) as in equation (2):

$$i_f = \sum_{h=2}^{\infty} i_{lh} \qquad (2)$$

where h is the order of the harmonic
i_l is the load current.

The APF, connected in parallel to the disturbing loads, unbalanced and non-linear, as seen in figure 1, causes the supply currents to be near sinusoidal and balanced.

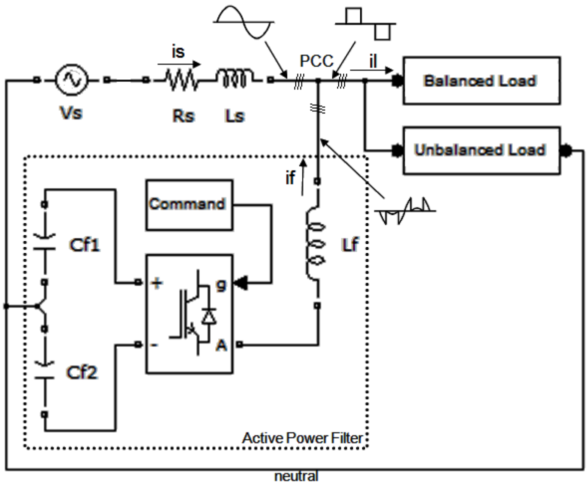

Figure 1 : Active filter principle

For the design of active power filters, simulation has been proved a very useful tool, using different programs, like Matlab (Zamora et al. 2003; Singh et al., 1999), RT-LAB (Balan et al.) or PSCAD (Iyer et al, 2005). The usage of computer in the design phase has a great impact in understanding the APF behavior, selection of components, tuning controllers and optimizing.

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The studied APF in this paper by using the Matlab Simulink environment is a three-phase four wire neutral clamped APF compensating harmonics, unbalance and reactive power created first by a nonlinear balanced load and then by a nonlinear unbalanced load based on the Instantaneous Reactive Power Theory (IRPT).

REACTIVE POWER CONTROL

This theory was proposed by (Akagi et al. 1983) for three-phase systems with or without neutral wire, and it is valid for both steady state and transients. It consists in the algebraic transformation of the current and voltage of the system from the abc system to αβ0 system using the Clarke transformation as in equation (3) and (4).

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (3)$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} \qquad (4)$$

where i_{La}, i_{Lb}, i_{Lc} are the load currents and v_{La}, v_{Lb} and v_{Lc} are the load voltages.

According to the p-q theory, the active, reactive and zero-sequence powers are defined as in equations (5a and 5b) and (6):

$$p = v_\alpha i_\alpha + v_\beta i_\beta \qquad (5a)$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha \qquad (5b)$$

$$p_0 = v_0 i_0 \qquad (6)$$

The currents, voltages and powers in the α-β system can be decomposed in mean and alternating values, corresponding to the fundamental and harmonic components, as in equation (7).

$$x = \bar{x} + \tilde{x} \qquad (7)$$

where x can be currents, voltages or powers.

The power components have the following physical meaning (Afonso J.L. et al., 2003):

p_0 zero sequence power. It only exists in three-phase systems with neutral wire. Since it is an undesired power component because it only exchanges energy with the load, it must be compensated. From equation (6) it can be seen that $p_0=v_0i_0$, but $i_0{}^*=p_0/v_0=i_0$, so there is no need for computing p_0.

$\bar{p}$ mean value of the instantaneous real power. It is the only desired power component to be supplied by the source because it corresponds to the energy transferred from the source to the load.

$\tilde{p}$ alternating value of instantaneous real power. Since it does not involve any energy transfer from the source to the load, it must be compensated.

$\bar{q}$ mean value of imaginary power. It corresponds to the power exchanged between the phases of the load and is responsable for the existence of undesired current. It must be compensated.

$\tilde{q}$ alternating value of imaginary power. It corresponds to the conventional reactive power. It can be compensated by the APF, depending on the requirements of the system.

Since in the p-q theory the voltages are assumed sinusoidal, the power components must be computed using sinusoidal voltages. In the α-β voltage system, the AC components of the voltage are eliminated in order to the IRPT to provide good performance. Conventionally, in IRPT control, are used High Pass (HP) and Low Pass (LP) Filters, but this method has a high error in the phase and magnitude of the harmonics and also is sensitive to high-frequency noise. Even worse, there is a need of five HP or LP filters – for α-β voltage components, and for p,q and p_0 power components.

This paper presents a control scheme based on the usage of only two self-tuning filters.

The powers required to be compensated by the APF are calculated as in equation (8):

$$\begin{bmatrix} \tilde{p} \\ q \end{bmatrix} = \begin{bmatrix} \overline{v_\alpha} & \overline{v_\beta} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{i_\alpha} \\ \tilde{i_\beta} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\overline{v_\beta} & \overline{v_\alpha} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (8)$$

After adding the active power required to regulate the DC bus voltage, p_{loss} to the alternative value of instantaneous real power, the reference currents $i_{\alpha\beta}{}^*$ are calculated by equation (9):

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{\Delta} T \begin{bmatrix} 0 \\ \bar{q} \end{bmatrix} + \frac{1}{\Delta} T \begin{bmatrix} \tilde{p} + p_{loss} \\ \tilde{q} \end{bmatrix} \qquad (9)$$

where:

$$\Delta = \overline{v_\alpha}^2 + \overline{v_\beta}^2$$

$$T = \begin{bmatrix} \overline{v_\alpha} & -\overline{v_\beta} \\ \overline{v_\beta} & \overline{v_\alpha} \end{bmatrix}$$

From equation (8) it can be seen that the APF computes $\tilde{p}$ using the harmonic components of the currents while $q = \bar{q} + \tilde{q}$ are computed using the load current, including AC and DC components, according to figure 2.

The load currents are transformed from three-phase abc to αβ0 components using Clarke transformation, as in equation (10):

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \sqrt{2}/2 \\ -1/2 & \sqrt{3}/2 & \sqrt{2}/2 \\ -1/2 & -\sqrt{3}/2 & \sqrt{2}/2 \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \\ i_0^* \end{bmatrix} \qquad (10)$$

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The compensation strategy based on the p-q theory of all undesired power components ($\tilde{p}$, p_0 and q) can be accomplished with the use of the shunt active power filter.

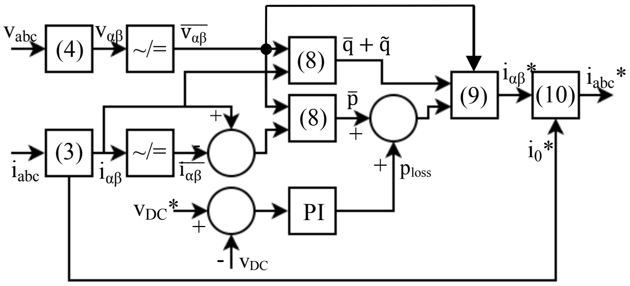

Figure 2: Proposed power control strategy

SIMULINK MODEL OF THE APF

The overall system model containing the power source, the APF and the nonlinear loads – balanced and unbalanced – is shown in figure 3.

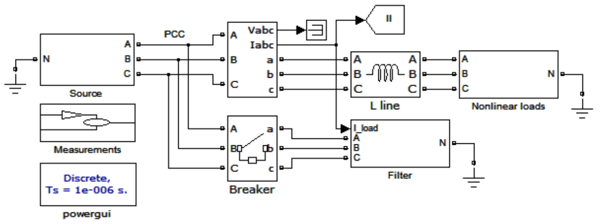

Figure 3 : System Simulink Model

The main components of the system are the following ones:

- the power source, which was designed as a three single-phase 220V/50Hz voltage sources connected together in a Y balanced configuration with neutral and a series RL circuit (R=0.01 Ω, L=10 µH).
- the loads, which are simulated as two nonlinear sets of loads. First one is balanced, containing one three-phase uncontrolled diode rectifier supplying a RL load. The second load is unbalanced, containing three uncontrolled diode rectifiers for each phase, supplying an RC load for phase A, a RL load for phase B and R load for phase C.

The loads are nonlinear. The first balanced load is connected from the start of the simulation, while the second unbalanced is connected from 0.6s using one three-phase breaker. The parameters of the nonlinear loads chosen for the simulation are listed in Table 1.

Table 1 : Load Parameters

Nonlinear Balanced Load	
R load	30 Ω
L load	30 mH
Nonlinear Unbalanced Load	
Ra	50 Ω
Ca	1000 µF
Rb	50 Ω
Lb	20 mH
Rc	50 Ω

- the VSI inverter, which contains a three-leg VSI inverter with neutral clamped DC capacitors, an inductance and the control scheme, as shown in figure 4.

Despite the fact that the loads currents are distorted and unbalanced from 0.6s, the source currents are balanced sinusoids and in phase with their respective voltages, due to the role of the APF. When the second load is connected, the load current will have a zero sequence component and the APF will be required to supply it.

The current fundamental extraction method used in this paper is the Self Tuning Filter proposed in (Abdusalam et al. 2009).

As there is a path from the neutral of the load and the midpoint of the DC capacitors, the zero sequence components will be compensated properly. By using a PI controller the sum of the voltages of the DC capacitors V_{DC} is maintained approximately constant to the reference value V_{DC}^* and then added to the alternative power as p_{loss}.

The parameters of the APF are presented in table 2.

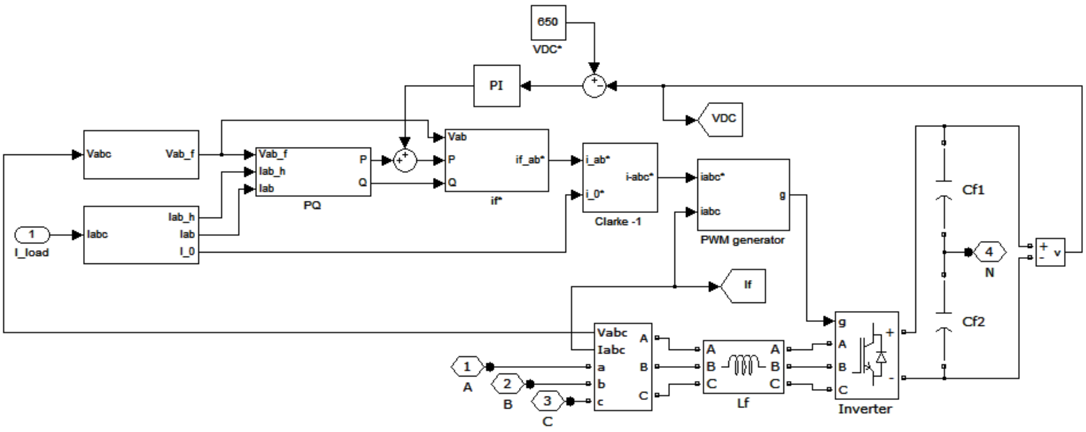

Figure 4 : Simulink Model of the Filter

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Table 2 : APF Parameters

Parameter	Value of the parameter
Inverter DC voltage	$V_{DC}* = 650$ V
Inverter side inductance	$L_f = 2$ mH
C_{DC} capacitors	$C_{f1} = C_{f2} = 1100$ µF

SIMULATION RESULTS

The overall model of the APF is presented in figure 1 and figure 4 and the results were obtained using Matlab-Simulink SymPowerSystems Toolbox software for a three-phase four-wire neutral clamped APF compensating harmonics, unbalance and reactive power produced by balanced and unbalance nonlinear loads.

Figure 5 shows the simulation results obtained in the harmonic distortion analysis of the load current, with nonlinear balanced loads. The total harmonic distortion (THD) is 26.86%. The highest harmonics are the 5th and the 7th, representing 20.83% and 12.12% of the fundamental.

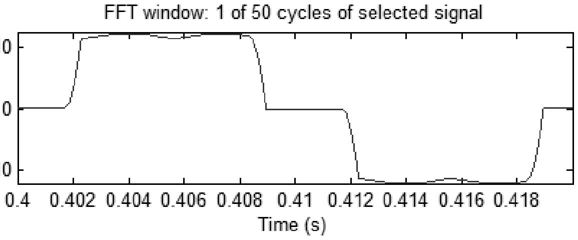


Figure 5 : Load Current Under Balanced Nonlinear Load

In figure 6 is presented the simulation results of the source current obtained using the APF to compensate harmonics created by nonlinear balanced load.

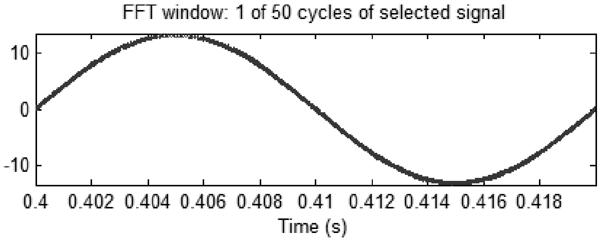


Figure 6 : Source Current Under Nonlinear Balanced Load

By using APF, the THD of the source current is reduced from 26.86% to 2.24%, thus meeting the limit of the harmonic standard of (IEEE STD. 519-1992). The highest harmonics are still the 5th and the 7th, but now they represent only 0.17% and 0.29% of the fundamental, which meets the harmonic standard of (IEEE STD. 519-1992).

Figure 7 shows the simulation results obtained in the harmonic distortion analysis of the load currents, for each phase, with nonlinear and unbalanced load.

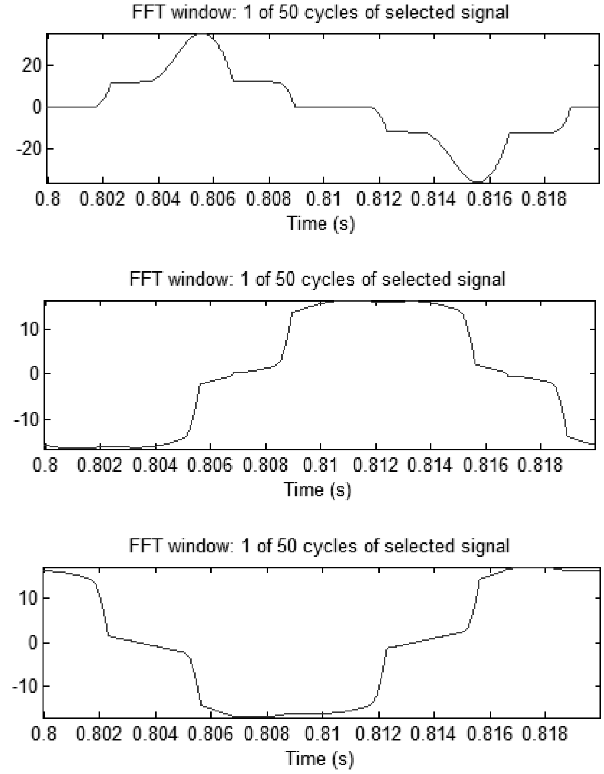
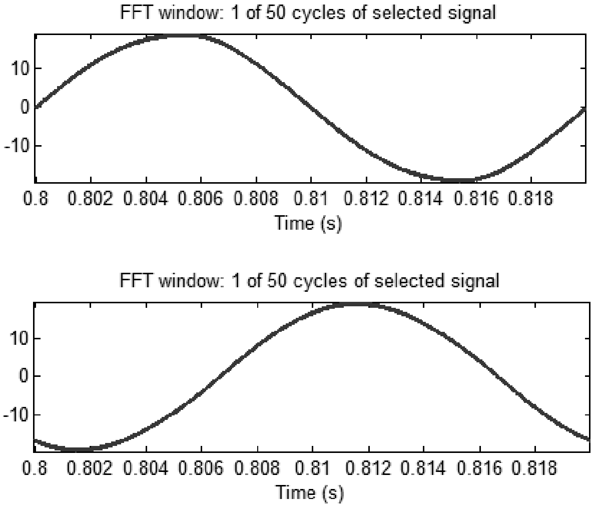


Figure 7 : Load Current in Phase A,B and C Under Nonlinear Unbalanced Load

The THD in phase A is 41.75% with high 3rd and 7th harmonics, which have over 20% of the fundamental value. In phase B the THD is 19.63% with a high 5th harmonic – 15.41% of the fundamental value. Phase C has a THD of 20.10%, with a high 5th harmonic.

The source currents after the compensation can be seen in figure 8.



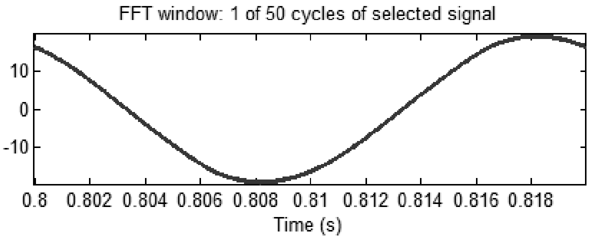


Figure 8 : Source Current in Phase A,B and C Under Nonlinear Unbalanced Load

In phase A the THD is now 2.66%, and the magnitude of the 3rd harmonic is now only 1.79% of the fundamental. In phase B the THD is 2.11% and in phase C the THD is 2.28%, thus meeting the harmonic standard of (IEEE STD. 519-1992).

In order to be effective, APF must also eliminate the neutral current from three-phase unbalanced loads. Figure 9 shows that even when connecting at 0.6s the unbalanced load the neutral current is close to 0A.

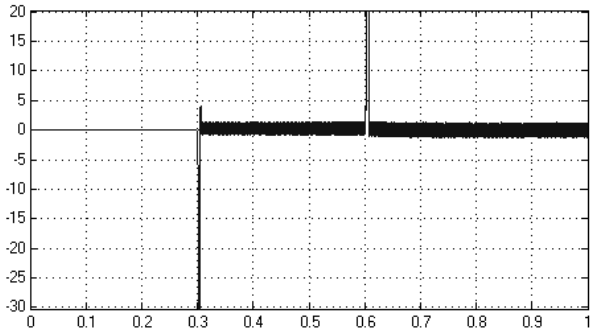


Figure 9 : Neutral Current Elimination

The following figure shows the simulation results of the APF under transient state. Since the start of the simulation the balanced load is connected. Since 0.3s, the APF is connected and since 0.6s the unbalanced load. Figure 10 shows the source current in phase A under transients.

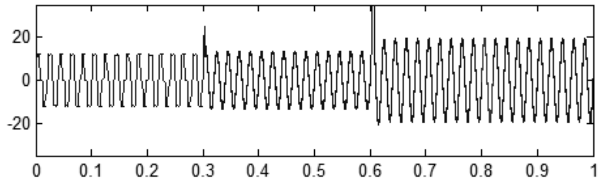


Figure 10 : Overall Source Current in Phase A

It can be seen that when connecting the filter it takes only 0.025s for the APF to compensate. When the second load is connected, it takes only 0.025s for the APF to follow the change of the load current.

The THD levels and harmonic magnitudes of the source currents with and without APF are shown in table 3 and table 4.

Table 3 : THD Levels of Source Currents

	THD level without APF [%]	THD level with APF [%]
Balanced load		
	26.86	2.24
Unbalanced load		
phase A	41.75	2.66
phase B	19.63	2.11
phase C	20.10	2.28

It can be seen from table 4 and figure 11 that under only unbalanced load without the APF, the fundamental has 3 different values. Using the APF the new fundamental on each phase has close to the same value of 19A, which prove that the APF also make the source currents symmetrical.

Table 4 : 1,3 and 5 Harmonic Magnitudes

	1^{st} [A]		3^{rd} [A]		5^{th} [A]	
	-	+	-	+	-	+
Balanced load						
	13.23	13.27	0	0.18	20.83	0.17
Unbalanced load						
A	21.56	18.98	32.75	1.81	10.92	0.7
B	17.53	18.88	0.45	0.87	15.41	0.54
C	17.66	19.26	0.46	1.27	15.88	0.63

where : "-" means without APF
"+" means with APF

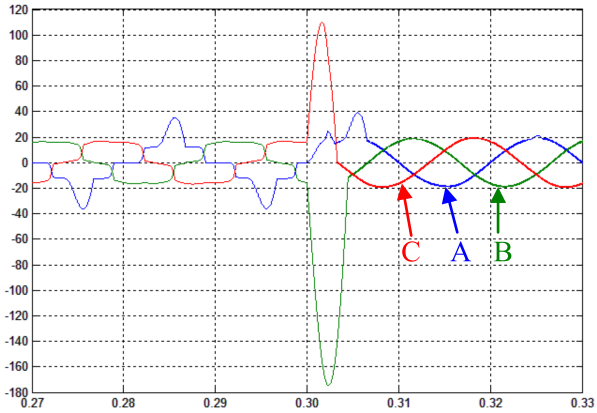


Figure 11 : Source Current Without and With APF Under Unbalanced Load

Figure 12 shows that when connecting the APF at 0.3s the reactive power decreases close to zero, even when the unbalanced load is connected at 0.6s, proven that the APF is a very effective tool to compensate reactive power.

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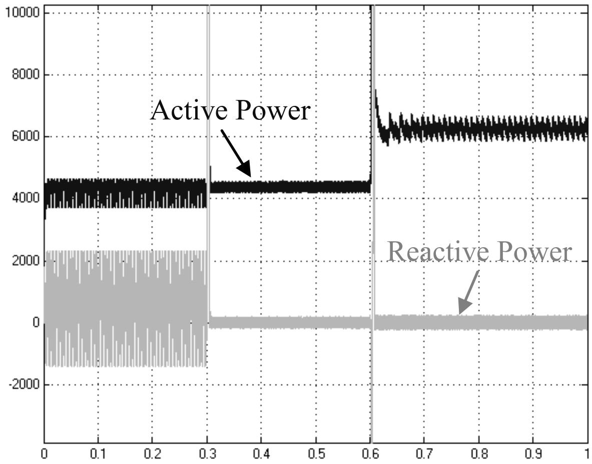

Figure 12 : Reactive Power Compensation

CONCLUSIONS

APF simulation using Matlab Simulink is proven to be very useful for studying the detailed behavior of the system for harmonic and unbalance compensation, under steady state and transients. The THD of the source current is reduced below the 5% limit imposed by (IEEE STD. 519-1992) standard both for balanced and unbalanced load using the APF. In addition, the reactive power decreases down to zero. More, the APF under unbalanced load helps making the source currents symmetrical and minimizes the neutral current.

Because in this paper only the current harmonics, unbalance and reactive power compensation is discussed, further research may be extended to the simulation of APF for voltage harmonics compensation using Universal Power Quality Conditioner.

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