A MATLAB-SIMULINK APPROACH TO SHUNT ACTIVE POWER FILTERS

George Adam, Alina G. Stan (Baciu) and Gheorghe Livinț
Department of Electrical Engineering
Technical University of Iaşi
700050, Iaşi, Romania
E-mail: yojorj@yahoo.com

KEYWORDS
Active Power Filters, Computer Simulation, Current Harmonics, Reactive Power, Unbalance

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 become 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):

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

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):

\[ i_f = \sum_{h=2}^{m} i_{ih} \]  

where \( h \) is the order of the harmonic
\( i_i \) 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.

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.
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).

\[
\begin{bmatrix}
    i_a^* \\
    i_b^* \\
    i_c^*
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & -1/2 & -1/2 \\
    0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
    \sqrt{3}/2 & \sqrt{3}/2 & \sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix} \tag{3}
\]

\[
\begin{bmatrix}
    v_a^* \\
    v_b^* \\
    v_c^*
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & -1/2 & -1/2 \\
    0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
    \sqrt{3}/2 & \sqrt{3}/2 & \sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
    v_a \\
    v_b \\
    v_c
\end{bmatrix} \tag{4}
\]

where \(i_a^*, i_b^*, i_c^*\) are the load currents and \(v_a^*, v_b^*, v_c^*\) 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):

\[
\begin{align*}
    p &= v_a^* i_a + v_b^* i_b \\
    q &= v_a^* i_b - v_b^* i_a \\
    p_0 &= v_0 i_0
\end{align*} \tag{5a, 5b, 6}
\]

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).

\[
x = \tilde{x} + \tilde{x} \tag{7}
\]

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 \(p_0 = v_0 i_0\), but \(i_0^* = p_0/v_0 = i_0\), so there is no need for computing \(p_0\).

- \(\bar{p}\) 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 responsible for the existence of undesired current. It must be compensated.

- \(\bar{q}\) 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):

\[
\begin{bmatrix}
    \bar{p} \\
    q
\end{bmatrix} = \begin{bmatrix}
    v_a^* & v_b^* \\
    0 & 0
\end{bmatrix} \begin{bmatrix}
    i_a^* \\
    i_b^*
\end{bmatrix} + \begin{bmatrix}
    0 & 0 \\
    -v_a^* & v_b^*
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix} \tag{8}
\]

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 \(i_{ref}^*\) are calculated by equation (9):

\[
\begin{bmatrix}
    i_{ref}^* \\\n    i_{ref}^*
\end{bmatrix} = \frac{1}{\Delta} T \begin{bmatrix}
    0 \\
    \bar{q} + \bar{p} + p_{loss}
\end{bmatrix} \tag{9}
\]

where:

\[
\Delta = v_a^2 + v_b^2
\]

\[
T = \frac{v_a^*}{v_a^*} \frac{-v_b^*}{v_b^*}
\]

From equation (8) it can be seen that the APF computes \(\bar{p}\) using the harmonic components of the currents while \(q = \bar{q} + \bar{q}\) 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):

\[
\begin{bmatrix}
    i_a^* \\
    i_b^* \\
    i_c^*
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & 0 & \sqrt{3}/2 \\
    -1/2 & \sqrt{3}/2 & \sqrt{3}/2 \\
    -1/2 & -\sqrt{3}/2 & \sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix} \tag{10}
\]
The compensation strategy based on the p-q theory of all undesired power components (\( p \), \( p_0 \) and \( q \)) can be accomplished with the use of the shunt active power filter.

**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.

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 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.

<table>
<thead>
<tr>
<th>Table 1 : Load Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>R load</td>
</tr>
<tr>
<td>30 Ω</td>
</tr>
<tr>
<td>L load</td>
</tr>
<tr>
<td>30 mH</td>
</tr>
<tr>
<td>Nonlinear Unbalanced Load</td>
</tr>
<tr>
<td>Ra</td>
</tr>
<tr>
<td>50 Ω</td>
</tr>
<tr>
<td>Ca</td>
</tr>
<tr>
<td>1000 μF</td>
</tr>
<tr>
<td>Rb</td>
</tr>
<tr>
<td>50 Ω</td>
</tr>
<tr>
<td>Lb</td>
</tr>
<tr>
<td>20 mH</td>
</tr>
<tr>
<td>Rc</td>
</tr>
<tr>
<td>50 Ω</td>
</tr>
</tbody>
</table>

- 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.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value of the parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter DC voltage</td>
<td>$V_{dc} = 650 \text{ V}$</td>
</tr>
<tr>
<td>Inverter side inductance</td>
<td>$L_f = 2 \text{ mH}$</td>
</tr>
<tr>
<td>$C_{dc}$ capacitors</td>
<td>$C_1 = C_2 = 1100 \mu\text{F}$</td>
</tr>
</tbody>
</table>

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

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.

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.

![Figure 8: Source Current in Phase A,B and C Under Nonlinear Unbalanced Load](image)

![Figure 9: Neutral Current Elimination](image)

![Figure 10: Overall Source Current in Phase A](image)

![Figure 11: Source Current Without and With APF Under Unbalanced Load](image)

**Table 3 : THD Levels of Source Currents**

<table>
<thead>
<tr>
<th></th>
<th>THD level without APF [%]</th>
<th>THD level with APF [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balanced load</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>26.86</td>
<td>2.24</td>
</tr>
<tr>
<td>Unbalanced load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>phase A</td>
<td>41.75</td>
<td>2.66</td>
</tr>
<tr>
<td>phase B</td>
<td>19.63</td>
<td>2.11</td>
</tr>
<tr>
<td>phase C</td>
<td>20.10</td>
<td>2.28</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th></th>
<th>1st [A]</th>
<th>3rd [A]</th>
<th>5th [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Balanced load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.23</td>
<td>13.27</td>
<td>0</td>
<td>0.18</td>
</tr>
<tr>
<td>Unbalanced load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>21.56</td>
<td>18.98</td>
<td>32.75</td>
</tr>
<tr>
<td>B</td>
<td>17.53</td>
<td>18.88</td>
<td>0.45</td>
</tr>
<tr>
<td>C</td>
<td>17.66</td>
<td>19.26</td>
<td>0.46</td>
</tr>
</tbody>
</table>

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

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.
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.

REFERENCES


Balan, H.; Botezan, A; Vadan, I; Duta, M. and Iacob, A. „Real time simulation of active filter with Emegasim 4508 platform. A case study.”


AUTHOR BIOGRAPHIES

GEORGE ADAM was born in Romania in 1984. He received the B.S. and M.S. degrees in electrical engineering from Technical University of Iaşi, Romania in 2009 and 2010 respectively. He is currently a Ph.D. student under the supervising of Professor Gheorghe Livint. His research interests include power electronics, active power filters and hybrid vehicles. His e-mail address is: yojorj@yahoo.com.

ALINA GEORGIANA STAN (BACIU) was born in Romania in 1980. She received the B.S. and M.S. degrees in electrical engineering from Technical University of Iaşi, Romania in 2005 and 2010 respectively. She is currently a Ph.D. student under the supervising of Professor Gheorghe Livint. Her research interests include hybrid vehicles, power electronics and Fuzzy logic. Her e-mail address is: alinutza_222000@yahoo.com.

GHEORGHE LIVINT was born at 20 December 1949 in Vaslui, Romania. He is a Professor in Technical University of Iaşi, Romania, Faculty of Electrical Engineering since 1996, head of department since 2000 and Ph.D. mentor since 2004. His research interests include systems theory, automatic control, power electronics, electric motor control and hybrid vehicles. His e-mail address is: glivint@tuiasi.ro.

ACKNOWLEDGEMENTS

This paper was realised with the support of POSDRU CUANTUMDOC “DOCTORAL STUDIES FOR EUROPEAN PERFORMANCES IN RESEARCH AND INOVATION” ID 79407 project funded by the European Social Found and Romanian Government.