Harmonic and reactive power compensation with shunt active power filter under non-ideal mains voltage

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Abstract

This paper presents a new control algorithm for an active power filter (APF) to compensate harmonic and reactive power of a 3-phase thyristor bridge rectifier under non-ideal mains voltage scenarios. Sensing load current, dc bus voltage and source voltages compute reference currents of the APF. APF driving signals are produced with these signals via a hysteresis band current controller. Matlab/simulink power system toolbox is used to simulate the proposed system. The proposed method’s performance is compared with conventional instantaneous power ($p-q$) theory. The simulation results are presented and discussed showing the effectiveness of the control algorithm. The proposed algorithm is found quite satisfactory to compensate the reactive power and harmonics under non-ideal mains voltage conditions. The increased performance of the active power filter under different non-sinusoidal mains voltage and dynamic load conditions are extensively demonstrated.

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Keywords: Active power filter; Non-ideal mains voltage; Instantaneous power ($p-q$) theory

1. Introduction

In a modern power system, increasing of loads and non-linear equipment’s have been demanding the compensation of the disturbances caused for them. These non-linear loads may cause poor power factor and high degree of harmonics. Active power filter (APF) can solve problems of harmonic and reactive power simultaneously. APF’s consisting of voltage-source inverters and a dc capacitor have been researched and developed for improving the power factor and stability of transmission systems. APF’s have the ability to adjust the amplitude of the synthesized ac voltage of the inverters by means of pulse width modulation or by control of the dc-link voltage, thus drawing either leading or lagging reactive power from the supply. APF’s are an up-to-date solution to power quality problems. Shunt APF’s allow the compensation of current harmonics and unbalance, together with power factor correction, and can be a much better solution than conventional approach (capacitors and passive filters). The simplest method of eliminating line current harmonics and improving the system power factor is to use passive LC filters. However, bulk passive components, series and parallel resonance and a fixed compensation characteristic are the main drawbacks of passive LC filters.

In APF design and control, instantaneous reactive power theory was often served as the basis for the calculation of compensation current [1,10,11]. In this theory, the mains voltage was assumed to be an ideal source in the calculation process. However, in most of time and most of industry power systems, mains voltage may be unbalanced and/or distorted. For improving APF performance under non-ideal mains voltages, new control methods are proposed by Komatsu and Kawabata [2] and Huang et al. [3] and Chen and Hsu [4]. In this paper, the proposed control algorithm
3. Instantaneous power theory

In three-phase circuits, instantaneous currents and voltages are converted to instantaneous space vectors. In instantaneous power theory, the instantaneous three-phase currents and voltages are calculated as follows equations. These space vectors are easily converted into the $\alpha-\beta$ orthogonal coordinates [5].

$$p = \frac{1}{2} (v_a i_a + v_b i_b + v_c i_c)$$

Considering only the three-phase three-wire system, the three-phase currents can be expressed in terms of harmonic positive, negative and zero sequence currents. In Equations (1) and (2), $\alpha$ and $\beta$ are orthogonal coordinates. $v_\alpha$ and $i_\alpha$ are on $\alpha$ axis, $v_\beta$ and $i_\beta$ are on $\beta$ axis. In three-phase conventional instantaneous power is calculated as follows:

$$p = v_\alpha i_\alpha + v_\beta i_\beta$$

In fact, instantaneous real power ($p$) is equal to following equation:

$$p = v_a i_a + v_b i_b + v_c i_c$$

Instantaneous real and imaginary powers are calculated as Equations (5):

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_a & v_b & v_c \\ -v_b & v_a & v_c \\ -v_c & v_b & v_a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

In Equation (5), $v_a i_a$ and $v_b i_b$ are instantaneous real ($p$) and imaginary ($q$) powers. Since these equations are products of instantaneous current and voltages in the same axis. In three-phase circuits, instantaneous real power is $p$ and its unit is watt. In contrast $v_\alpha i_\alpha$ and $v_\beta i_\beta$ are not instantaneous powers. Since these are products of instantaneous current and voltages in two orthogonal axes, $q$ is not conventional electric unit like W or Var. $q$ is instantaneous imaginary power and its unit is Imaginer Volt Ampere (IVA) [1]. These power quantities given above for an electrical system represented in $a-b-c$ coordinates and have the following physical meaning [6].

$\bar{p}$, the mean value of the instantaneous real power—corresponds to the energy per time unity which is transferred from the power supply to the load, through $a-b-c$ coordinates, in a balanced way.

$\bar{q}$, the mean value of the instantaneous real power—it is the energy per time unity that is exchanged between the phases of the load. This component does not imply any exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases.

$\bar{q}$, the mean value of the instantaneous imaginary power that is equal to the conventional reactive power.
The instantaneous active and reactive power includes ac and dc values and can be expressed as follows:

\[ p = \tilde{p} + \overline{p} \]
\[ q = \tilde{q} + \overline{q} \]  

(6)

dc values of the \( p \) and \( q \) (\( \overline{p}, \overline{q} \)) are created from positive-sequence component of the load current. ac values of the \( p \) and \( q \) (\( \tilde{p}, \tilde{q} \)) are produced from harmonic components of the load current [6].

Equation (5) can be written as Equation (7):

\[
\begin{bmatrix}
\tilde{i}_c \\
\tilde{i}_d
\end{bmatrix} = 
\begin{bmatrix}
\tilde{v}_a & \tilde{v}_b \\
-\tilde{v}_b & \tilde{v}_a
\end{bmatrix}^{-1} \begin{bmatrix}
p \\
q
\end{bmatrix}
\]

(7)

From Equation (7), in order to compensate harmonics and reactive power instantaneous compensating currents (\( \tilde{i}_{ca} \) and \( \tilde{i}_{cd} \)) on \( \alpha \) and \( \beta \) coordinates are calculated by using \( -\tilde{p} \) and \( -\tilde{q} \) as given below:

\[
\begin{bmatrix}
\tilde{i}_{ca} \\
\tilde{i}_{cd}
\end{bmatrix} = 
\begin{bmatrix}
\tilde{v}_a & \tilde{v}_b \\
-\tilde{v}_b & \tilde{v}_a
\end{bmatrix}^{-1} \begin{bmatrix}
-\tilde{p} \\
-\tilde{q}
\end{bmatrix}
\]

(8)

In order to obtain the reference compensation currents in the \( a-b-c \) coordinates the inverse of the transformation given in expression (9) is applied [6]:

\[
\begin{bmatrix}
\tilde{i}_{ca} \\
\tilde{i}_{cb} \\
\tilde{i}_{cc}
\end{bmatrix} = 
\begin{bmatrix}
1 & 1 & \frac{\sqrt{3}}{2} \\
-\frac{1}{2} & \frac{3}{2} & -\frac{\sqrt{3}}{2} \\
-\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
\tilde{i}_{ca} \\
\tilde{i}_{cd}
\end{bmatrix}
\]

(9)

4. Hysteresis band current controller

The actual active power filter line currents are monitored instantaneously, and then compared to the reference currents generated by the control algorithm. In order to get precise instantaneous current control, the current control method must supply quick current controllability, thus quick response. For this reason, hysteresis band current control for active power filter line currents can be implemented to generate the switching pattern in the inverter. There are various current control methods proposed for such active power filter configurations, but in terms of quick current controllability and easy implementation hysteresis band current control method has the highest rate among other current control methods such as sinusoidal PWM. Hysteresis band current control is the fastest control with minimum hardware and software but even switching frequency is its main drawback.

The hysteresis band current control scheme, used for the control of active power filter line current, is shown in Fig. 2, composed of a hysteresis around the reference line current. The reference line current of the active power filter is referred to as \( i_{a} \) and actual line current of the active power filter is referred to as \( i_{c} \). The hysteresis band current controller decides the switching pattern of active power filter [7,8]. The switching logic is formulated as follows:

If \( i_{ca} > (i_{ca}^* + HB) \) upper switch is OFF and lower switch is ON for leg “a” (\( SA = 1 \)).
If \( i_{ca} < (i_{ca}^* - HB) \) upper switch is ON and lower switch is OFF for leg “a” (\( SA = 0 \)).

The switching functions SB and SC for phases “b” and “c” are determined similarly, using corresponding reference and measured currents and hysteresis bandwidth (HB).

5. The proposed method

The conventional instantaneous reactive power (\( p-q \)) theory is inadequate under non-ideal mains voltage scenarios. In order to improve the performance, the new algorithm is developed. Alternating value (\( \tilde{p} \)) of instantaneous real power (\( p \)) and instantaneous imaginary power (\( q \)) are unwanted components of the power system. The shunt active power filter is controlled as it gives the negatives of these components. If the mains voltages are distorted and/or unbalanced, alternating values of the instantaneous real and imaginary power have current harmonics and voltage harmonics. The shunt APF does not generate compensation current equal to current harmonics, since the APF compensating currents include mains and load harmonics. Consequently, APF gives to mains more than load harmonics than required. In order to eliminate this drawback and to decrease total harmonic distortion to desired level, the instantaneous reactive and active powers have to be calculated after filtering of mains voltages. In the proposed method, in order to reduce numbers of filters \( d-q \) reference coordinate transformation is used. In order to increase the performance of the instantaneous power theory to a distorted and unbalanced mains voltage, the measured mains voltage is low-pass filtered in a rotating reference frame. Hence, the non-ideal mains voltages are converted to ideal sinusoidal shape by using the fifth-order 50 Hz cutoff frequency low-pass filters in \( d-q \) coordinates.

The proposed method block diagram, that presents the calculations required in this method, is shown in Fig. 3. The filtered \( d-q \) components of the voltages (\( \tilde{v}_a \) and \( \tilde{v}_c \)) are converted to voltages in \( a-b \) coordinates as given in Fig. 3. These voltages are used in Equation (5) in order to calculate real and imaginary powers. The proposed method can be used when the voltages are distorted or unbalanced and sinusoidal currents are desired. Schematic block diagram of proposed method controlled shunt APF is shown in Fig. 4.
In the proposed method, instantaneous voltages are first converted to $\alpha-\beta$ coordinates and then to stationary $d-q$ coordinates. The produced $d-q$ components of voltages are filtered and reverse converted $\alpha-\beta$ coordinates (as expressed in Equation (10)). These filtered $\alpha-\beta$ components of voltages are used in conventional instantaneous power theory (Equation (7)). Hence, the non-ideal mains voltages are converted to ideal sinusoidal shape by using low pass filter in $d-q$ coordinates. The time constant of the low pass filter is $12e^{-3}$. So, the mains voltages assumed to be an ideal source in the calculation process.

\[
\begin{bmatrix}
V_{\alpha} \\
V_{\beta}
\end{bmatrix} =
\begin{bmatrix}
\cos \phi & -\sin \phi \\
\sin \phi & \cos \phi
\end{bmatrix}
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix}
\]  
\[
(10)
\]

The three-phase reference currents, which the active power filter configuration should supply to the three-phase actual power system, should be obtained. These reference currents, calculated by the control algorithm equations should be supplied to the power system by switching of the power transistors of the inverter. The hysteresis band current controller as mentioned above section IV achieves the method for generation of the switching pattern.

6. Simulation results

The presented simulation results were obtained by using Matlab-Simulink Power System Toolbox software, for a three-phase power system with a shunt APF. The proposed method has been simulated under four scenarios, including ideal mains voltage, unbalanced three-phase mains voltage, distorted mains voltage and unbalanced—distorted mains voltage conditions. In order to evaluate dynamic performance of the proposed method, in 1.5-s thyristor rectifier firing angle are changed from $15^\circ$ to $30^\circ$. The proposed algorithm dynamic performances under such dynamic conditions are investigated by detailed simulation study. The simulation results are discussed below.


6.1. Ideal mains voltages

Fig. 5 shows the simulation results of this algorithm under ideal mains voltages when ohmic-inductive loaded three-phase thyristor bridge rectifier is connected. The three-phase mains currents after compensation are balanced, sinusoidal and in phase with three-phase mains voltages. The instantaneous reactive power theory and proposed method are feasible. After compensation the THD of source current is reduced to 3.7 from 26.7%.

6.2. Unbalanced mains voltages

When the three-phase mains voltages are unbalanced, the mains voltage can be expressed as positive and negative sequence components. The negative sequence currents, produced by unbalanced loads, will cause additional generator, transmission line and transformer losses. The negative sequence voltage caused by negative sequence currents, which is one of power quality disturbance, will induce extra motor losses and ripple in rectifiers [9]. For this case, the unbalanced three-phase mains voltages \(v_u\) are:

\[
\begin{align*}
  v_{ua} &= 311 \sin(\omega t) + 31 \sin(\omega t) \\
  v_{ub} &= 311 \sin(\omega t - 120^\circ) + 31 \sin(\omega t - 240^\circ) \\
  v_{uc} &= 311 \sin(\omega t - 240^\circ) + 31 \sin(\omega t - 120^\circ)
\end{align*}
\]

(11)

Figs. 6 and 7 show simulation results of 10% unbalanced mains voltages scenario with \(p-q\) theory and the proposed method, respectively. The three-phase compensated mains currents are not sinusoidal in instantaneous power theory and are sinusoidal in the proposed method in unbalanced mains voltage case. THD levels of source current after compensation are 11.2 and 3.6% in phase “a” with conventional \((p-q\) theory) and the proposed methods, respectively. The proposed method has very good harmonic limit imposed by the IEEE-519 standard. From these figures, mains currents are balanced and sinusoidal after compensation. The voltage unbalanced in a three-phase system will not affect the APF performance.

6.3. Distorted mains voltages

In Turkish electrical energy distribution system, harmonic problems caused by power electronic devices are very important. Inherently, mains voltages usually have non-ideal waveforms, and have different levels of harmonics. When the three-phase mains voltages are distorted, the mains voltages have harmonic components. In order to simulate a real case distortion level, mains voltages are measured with a harmonic analyzer. The measured real mains voltage, THD level and its harmonic spectrum is shown in Fig. 8. As shown in Fig. 8, mains voltage has 3, 5, 7 and 11 harmonics. The mains voltage has dominant fifth harmonic component. For this case, the distorted three-phase mains voltages \(v_d\) are expressed
as:

\[ v_{da} = 311 \sin(\omega t) + 4 \sin(3\omega t) + 18 \sin(5\omega t - 120^\circ) + 4.6 \sin(7\omega t) + 3.1 \sin(11\omega t - 120^\circ) \]
\[ v_{db} = 311 \sin(\omega t - 120^\circ) + 4 \sin(3\omega t - 120^\circ) + 18 \sin(5\omega t) + 4.6 \sin(7\omega t - 120^\circ) + 3.1 \sin(11\omega t) \]
\[ v_{dc} = 311 \sin(\omega t - 240^\circ) + 4 \sin(3\omega t - 240^\circ) + 18 \sin(5\omega t - 240^\circ) + 4.6 \sin(7\omega t - 240^\circ) + 3.1 \sin(11\omega t - 240^\circ) \]

(12)

Figs. 9 and 10 show simulation results of distorted mains voltages scenario with \(p-q\) theory and the proposed algorithm, respectively. The performance of the instantaneous power algorithm for this case is shown not qualified. The three-phase compensated mains currents have 7% THD level in phase “a” in instantaneous power theory. After compensation, these currents have sinusoidal waveform and 3.6% THD level for the proposed method in distorted mains voltages scenario, a smaller value than that is regulated by any power quality standard. There is a significant reduction in harmonic distortion level. Therefore, the performance of the proposed method is better than that of the conventional \(p-q\) theory.

6.4. Distorted-unbalanced mains voltages

When the three-phase mains voltages are distorted and unbalanced \((v_{da})\), the mains voltages have harmonic components and unbalanced. For this case, the distorted and unbalanced three-phase mains voltages are expressed as:

\[ v_{da} = 311 \sin(\omega t) + 31 \sin(\pi t) + 4 \sin(3\omega t) + 18 \sin(5\omega t - 120^\circ) + 4.6 \sin(7\omega t) + 3.1 \sin(11\omega t - 120^\circ) \]
\[ v_{db} = 311 \sin(\omega t - 120^\circ) + 31 \sin(\omega t - 240^\circ) + 4 \sin(3\omega t - 120^\circ) + 18 \sin(5\omega t) + 4.6 \sin(7\omega t - 120^\circ) \]
\[ v_{dc} = 311 \sin(\omega t - 240^\circ) + 31 \sin(\omega t - 120^\circ) + 4 \sin(3\omega t - 240^\circ) + 18 \sin(5\omega t - 240^\circ) + 4.6 \sin(7\omega t - 240^\circ) + 3.1 \sin(11\omega t - 240^\circ) \]

(13)

Figs. 11 and 12 show simulation results of distorted-unbalanced mains voltage scenario with \(p-q\) theory and the proposed algorithm, respectively. The performance of the instantaneous power algorithm for this case is shown not qualified. The three-phase compensated mains...
Fig. 11. Distorted-unbalanced mains voltage simulation results with \( p-q \) theory.

currents have 13\% THD level in phase “a” in instantaneous power theory. After compensation, these currents have sinusoidal waveform and have 3.6\% THD level for the proposed method in distorted mains voltage scenario. There is a significant reduction in harmonic distortion level. Average switching frequency is about 12.5 kHz with both methods. The unsymmetrical distorted voltage system is the most severe condition. However, good results can be obtained by the proposed theory.

The design specifications and the essential parameters of the system used in the simulation are indicated in Table 1. THD levels of a, b and c phase currents in load and different operating conditions are shown in Tables 3 and 4. The results from above comparisons are summarized in Tables 2–4. From system control block diagram in simulation study, it can be seen that the hardware of the proposed algorithm is simpler than that of the conventional \( (p-q) \) theory and earlier proposed algorithms [2–4] and that in addition its compensation performance is better.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_s ) (rms/phase) (V)</td>
<td>220</td>
</tr>
<tr>
<td>( f ) (Hz)</td>
<td>50</td>
</tr>
<tr>
<td>( R_L ) (ohm)</td>
<td>10</td>
</tr>
<tr>
<td>( L_L ) (mH)</td>
<td>10</td>
</tr>
<tr>
<td>( C_d ) (\mu F)</td>
<td>1500</td>
</tr>
<tr>
<td>( L_e ) (mH)</td>
<td>1</td>
</tr>
<tr>
<td>( V_{dc} ) (V)</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>Load THD level (%)</th>
<th>The ( p-q ) theory THD level (%)</th>
<th>The proposed approach THD level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase “a”</td>
<td>Phase “b”</td>
<td>Phase “c”</td>
</tr>
<tr>
<td>Ideal mains voltage</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>Distorted mains voltage</td>
<td>25.77</td>
<td>25.77</td>
<td>25.77</td>
</tr>
<tr>
<td>Unbalanced mains voltage</td>
<td>22.26</td>
<td>28.41</td>
<td>29.71</td>
</tr>
<tr>
<td>Unbalanced-distorted mains voltage</td>
<td>22</td>
<td>27.8</td>
<td>28.47</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>1 Fundamental current magnitude (A)</th>
<th>3 Harmonic current magnitude (A)</th>
<th>5 Harmonic current magnitude (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load ( p-q ) Proposed</td>
<td>Load ( p-q ) Proposed</td>
<td>Load ( p-q ) Proposed</td>
</tr>
<tr>
<td>Ideal mains voltage</td>
<td>93.06</td>
<td>76.30</td>
<td>20.38</td>
</tr>
<tr>
<td>Distorted mains voltage</td>
<td>93.84</td>
<td>77.76</td>
<td>19.90</td>
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<tr>
<td>Unbalanced mains voltage</td>
<td>101.57</td>
<td>76.08</td>
<td>14.72</td>
</tr>
<tr>
<td>Unbalanced-distorted mains voltage</td>
<td>102.68</td>
<td>78.80</td>
<td>13.76</td>
</tr>
</tbody>
</table>

Fig. 12. Distorted-unbalanced mains voltage simulation results with the proposed method.
Table 4

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>7th harmonic current magnitude (A)</th>
<th>9th harmonic current magnitude (A)</th>
<th>11th harmonic current magnitude (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load p-q</td>
<td>Prop.</td>
<td>Load p-q</td>
<td>Prop.</td>
</tr>
<tr>
<td>Ideal mains voltage</td>
<td>10.57 0.63</td>
<td>0 0</td>
<td>7.97 0.88</td>
</tr>
<tr>
<td>Distorted mains voltage</td>
<td>10.93 4.84 1.91</td>
<td>0 0</td>
<td>6.98 0.9</td>
</tr>
<tr>
<td>Unbalanced mains voltage</td>
<td>12.06 0.71 0.24</td>
<td>6.64 0.67 0.34</td>
<td>1.41 0.63 0.24</td>
</tr>
<tr>
<td>Unbalance-d distorted mains voltage</td>
<td>13.22 4.08 0.34</td>
<td>6.87 1.10 0.75</td>
<td>1.76 1.11 0.34</td>
</tr>
</tbody>
</table>

All figures show that the actual currents are almost agrees with the reference currents. The above figures indicate that after compensation the mains currents are still sinusoidal even when the mains voltages are distorted and/or unbalanced. In an unsymmetrical or distorted voltage system, the results obtained by the p-q theory are not good. However, the proposed theory gives good results for both non-ideal and distorted voltage system. In the proposed method, the distorted mains voltages do not affect the compensated mains current.

7. Conclusion

In this paper, a new APF control scheme has been proposed to improve the performance of APF under non-ideal mains voltage conditions. The computer simulations have verified the effectiveness of the proposed control scheme. From the simulation results, the proposed approach was very successful and easily implemented. Active power filters, based on the proposed theory, give satisfactory operation even when the system phase voltages are unsymmetrical and distorted, because no distortion appears in the line currents. In non-ideal mains voltage condition, the source currents by the instantaneous power (p-q) theory are distorted, but the source currents by the proposed method have no distortion. The increased performance of the APF under different non-sinusoidal mains voltage conditions is extensively demonstrated. The APF is found effective to meet IEEE 519 standard recommendations on harmonics levels in all of the non-ideal voltage conditions. The performance of the proposed algorithm is therefore superior to that of conventional three-phase APF control algorithm. Its control circuit is also simpler that those of published non-ideal mains voltage algorithms.

The unsymmetrical distorted voltage system is the most severe condition. However, good results can be obtained by the proposed theory.

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