A New Control Approach for Shunt Hybrid Active Power Filter to Compensate Harmonics and Dynamic Reactive Power with Grid Interconnection

Tuğçe Demirdelen, Mustafa İnci, Mehmet Tümay

Çukurova University, Balcalı, Adana, Turkey

tdemirdelen@cu.edu.tr, minci@cu.edu.tr, ntumay@cu.edu.tr

Abstract—The grid interconnection of renewable energy source is a popular issue in the electric utilities. Different types of converter topology in grid interconnection have been improved by researchers to improve power quality and efficiency of the electrical system. The main contribution of this paper is that a shunt hybrid active power filter (SHAPF) with a DC-DC converter at dc link is to provide interconnection between renewable source and grid with linear dynamic loads. The other contribution of this paper is to present a novel control strategy for reactive power compensation and harmonics elimination in industrial networks using a hybrid active power filter as a combination of a three phase, two level voltage source converter connected in parallel with single tuned LC passive filter. In proposed control method, reactive power compensation is achieved successfully with perceptible amount. Besides, the performance results of harmonic compensation are satisfactory. Theoretical analyses and simulation results are obtained from an actual industrial network model in PSCAD. The simulation results are presented for proposed system in order to demonstrate that the harmonic compensation performance meets the IEEE-519 standard.

Keywords—Harmonics, grid interconnection, power quality, reactive power compensation, shunt hybrid active power filters (SHAPFs)

I. INTRODUCTION

By the development of technology, electric utilities and usage of electric power are increased. The majority part of energy demand is provided by fossil fuels. However, fossil fuels are finite resources and will eventually decrease. Due to this condition, they become too expensive or too environmentally damaging to retrieve. In the recent years, renewable energy in power generation has been emerging as an alternative energy source to mitigate the disadvantages of fossil fuels. Renewable energy source (RES) integrated at PCC[1]. The grid voltages and currents shape non sinusoidal form that is called harmonic distortion due to these types of loads. Harmonic distortions can not only increase power losses, but also reduce the lifetime of equipments. In order to reduce the current harmonic pollution, passive filter is one of the traditional solution ineffectively. These filters may cause unwanted resonance conditions. Their other limitation is unable to adapt to the changing conditions in the network and their size. With remarkable process in the speed and capacity of semiconductor switching devices, active filters have been studied and put into practical use, because they have the ability to overcome the disadvantages inherent in passive filters. These types of filters are more effective in harmonic compensation and improve performance [2]. However, active power filters have high initial cost, running cost and required comparatively high power converter ratings. To overcome the aforementioned disadvantages, passive and active filters can be combined into a single device called hybrid active power filters (HAPF). HAPFs effectively smooth the problems of the passive filter and an active power filter solution; hence ensure cost effective harmonic compensation. The passive filter in the system performs basic filtering action at the dominant harmonic frequencies, whereas the active filter part mitigates higher harmonics with precise control methods. This will effectively reduce the overall size and cost of active filtering. In addition, no fundamental voltage is applied to the active part. This results in a great reduction of the voltage rating of the active power filter part.

Several hybrid APF (HAPF) topologies [2-11,15-17] constitute active and passive parts in series and/or parallel have been proposed for reactive power and harmonic current filtering in [3-11]. The most common topologies are shunt HAPF (SHAPF) [3-10] consisting of an APF and passive filter connected in series with each other and series HAPF [11] which is a combined system of shunt passive filter and series APF. An extensive overview of the topological structures is explained in [2].

The controller design is a significant and challenging task due to its impact on the performance and stability of overall system. For this reason, numerous control methods such as pq theory [3-5], fast fourier transform [5], dq theory [6-7], fuzzy controller [8-9], proportional resonant current controller [10] are controller methods applied in literature.

Most studies about SHAPF in literature can not achieve dynamic reactive power compensation [7-9]. Furthermore, SHAPF can compensate the dynamic reactive power with
constant dc link voltage in [5]. In this article, direct current controlled pulse width modulation is used. In addition, the dc link is controlled as both active and reactive current component. The results are obtained for low voltage level with compensating small amount of reactive power. Besides, SHAPF can achieve the dynamic reactive power compensation with adaptive dc link voltage in [3]. Moreover, the dc link is controlled as active current component. The reference dc link voltage may be insufficient to track the new reference value when the adaptive dc link voltage may be changed from low level to high level [5]. In addition, when this dc link is controlled as active current component, an extra start up precharging control circuit is needed. In the last article [4], SHAPF can achieve the dynamic reactive power compensation with adaptive dc link voltage. Also, selective harmonic compensation is achieved. The dc link is controlled as both active and reactive current component as in [5]. The results are obtained for 220 V, 10 kVA system. However, SHAPF compensates small amount of reactive power.

The growing amount of electric energy generated from distributed or decentralized energy resources (DER), mainly of renewables, requires their appropriate grid integration. Thus, the renewable energy source interfacing with grid is the major issue in the electric utility side. Different types of converter topology in grid interconnection have been improved by researchers to develop power quality and efficiency of the electrical system [12-13]. This paper focuses on the shunt hybrid active filter interfaces for the renewable energy source with proposed controller.

On account of the limitations between existing literatures, the purpose of this paper is the following:

1. To provide interconnection between renewable source and grid by using shunt hybrid active power filter (SHAPF) with unidirectional isolated DC-DC converter at dc link.

2. To introduce a new control strategy for reactive power compensation and harmonics elimination.

3. To adaptively controlled dc link voltage as reactive current component.

4. To achieve reactive power compensation which is nearly equal to 99% of load reactive power capacity.

As this paper primarily focuses on the aforesaid four aspects of the shunt hybrid active power filter.

II. PROPOSED SYSTEM AND CONTROLLER

Figure 1 presents the proposed SHAPF system. As can be seen in Figure 1 inverter unit is connected to the grid through a LC filter tuned on the vicinity of the 5th harmonic.

As can be seen in Figure 2, the controller of proposed system consists of four main parts: harmonic reference generation, reactive current reference generation, dc link voltage controller, dc-dc converter controller and final reference compensation current pwm control block.

The harmonic current control, reactive current control and dc link control are achieved by indirect current control. With this control method, any extra start up precharging control process is not necessary for dc link. In addition, reactive power compensation is achieved successfully with perceptible amount. Besides, the harmonic compensation performance is satisfactory.

A. Harmonic Current Control

The harmonic control of SHAPF is shown in Figure 2. The first step is to isolate the harmonic components from the fundamental component of the grid currents. This is achieved through dq transformation (1), synchronized with the PCC voltage vector, and a first order low pass filter with cut off frequency of 10 Hz. Then the dq inverse transformation (2) produces the harmonic reference currents in abc referential frame.

\[
\begin{bmatrix}
    i_{d} \\
    i_{q}
\end{bmatrix} =
\begin{bmatrix}
    \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\
    -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3})
\end{bmatrix}
\begin{bmatrix}
    i_{ref} \\
    i_{ref} \\
    i_{ref}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    l_{a} \\
    l_{b} \\
    l_{c}
\end{bmatrix} =
\begin{bmatrix}
    \frac{2}{3} & \frac{2}{3} & \frac{2}{3} \\
    \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
    \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
    \frac{2}{3} & \frac{2}{3} & \frac{2}{3} \\
    \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
    \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
    i_{a} \\
    i_{b} \\
    i_{c}
\end{bmatrix}
\]

B. Reactive Power Control

Dynamic reactive power variations in approximately 20% occurred in load are compensated by inverter side of SHAPF. In this way, the dynamic reactive power compensation characteristics of SHAPF firstly provides at high levels in this article. The system responds to instantaneous load changes immediately. The reference
current provided essential reactive power is produced. In order to achieve the reactive power compensation of SHAPF, the reference current having 90° phase difference among the PCC point should be produced. To produce this reference current, the output voltage of SHAPF inverter should be generated in phase with PCC voltage vector. The block diagram of reactive power control is shown in Figure 2.

The reference currents should be calculated to compensate reactive power in the system. The reference currents are generated by the dq method. The first step is to isolate the fundamental components from the harmonic components of the grid currents. This is achieved through the dq transformation (3). The quadrature component of the source current which is taken from dq transformation is directly passed through the LPF. Thus, the 50 Hz component of the source current is generated. Then, this signal is applied to produce the reactive power compensation current by inversing dq transformation. However, this reference current is in quadrature axis. To achieve reactive power compensation by voltage controlled voltage source SHAPF, the reference current must be in phase with source voltage. Thus, the reference current is transformed by using only d component inverse dq transformation (4).

\[
\begin{align*}
    i_d &= \begin{bmatrix}
        \cos \theta_p & \cos(\theta_p - \frac{2\pi}{3}) & \cos(\theta_p + \frac{2\pi}{3}) \\
        -\sin \theta_p & \sin(\theta_p - \frac{2\pi}{3}) & \sin(\theta_p + \frac{2\pi}{3})
    \end{bmatrix} i_{sc} \\
    i_q &= \frac{\sqrt{2}}{2} \begin{bmatrix}
        \cos(\theta_p - \frac{2\pi}{3}) & \cos(\theta_p + \frac{2\pi}{3}) \\
        \sin(\theta_p - \frac{2\pi}{3}) & \sin(\theta_p + \frac{2\pi}{3})
    \end{bmatrix} i_{sc}
\end{align*}
\]  

(3)

\[
\begin{align*}
    i_{sc \_ref} &= \begin{bmatrix}
        \cos \theta_q & -\sin \theta_q \\
        \cos(\theta_q - \frac{2\pi}{3}) & \cos(\theta_q + \frac{2\pi}{3}) \\
        \sin(\theta_q - \frac{2\pi}{3}) & \sin(\theta_q + \frac{2\pi}{3})
    \end{bmatrix} \begin{bmatrix}
        i_{dc} \\
        0 \\
        0
    \end{bmatrix}
\end{align*}
\]  

(4)

C. DC Link Voltage Controller

Figure 2 shows the block diagram of the dc link voltage controller. The first step is to calculate the instantaneous load reactive power. This is achieved through dq transformation synchronized with the PCC voltage vector.

Then using the d and q component both three phase grid voltage and current, the instantaneous load reactive power is calculated. In next process, the reference dc link voltage is determined with the equation [3] shown in Figure 2.

Figure 2 illustrates the control of the error signal. The error signal is controlled by conventional PI controller [6].

---

**Figure 2. Proposed Controller Block Diagram**
D. DC DC Converter Controller

Single phase shift (SPS) control method which is the most widely used is applied for the proposed system. In SPS control, the cross-connected switch pairs in both full bridges are switched in turn to generate phase-shifted square waves with 50% duty ratio to the transformer’s primary and secondary sides. Only a phase-shift ratio (or angle) D can be controlled. Through adjusting the phase-shift ratio the equal-voltage ac output voltages of full-bridges, the voltage across the transformer’s leakage inductors will change then, the power flow direction and magnitude can be easily controlled. An extensive overview of this control method is explained in [14].

For the proposed system, the power flow is realized from RES to SHAPF. Thus, dc-dc converter generate negative phase-shift angle for this power flow direction. This phase shift angle is controlled by simple PI controller.

This converter only performs when PRES>0 where PRES is the power generated from RES shown in Figure 3.

First mode of operation considers a case where PRES>0, the SHAPF injects RES active power into grid and also enhanced the quality of power at PCC. Before time t=1 s, RES is not connected to the network. The source, SHAPF and load active power are shown in Figure 5(a). At t=1 s, RES connected to the network. The SHAPF starts injecting active power generated from RES as shown in Figure 5 (b). Besides, SHAPF compensates harmonics successfully as shown in Figure 4 (b).

E. Final Reference Compensation Current and PWM Control Block

The final reference current consists of three phase harmonic reference current signals, three phase reactive reference current signals and dc link control signals. The reference signal (In_harmonic_ref + In_reactive_ref + Vcappi_n) is generated using these signals together. Then, the reference signals are compared with carrier signal to generate switching signals shown in in Figure 2.

III. SIMULATION RESULTS

Simulation studies are carried out using PSCAD/EMTDC. The main purpose of the simulation is to evaluate the effectiveness and correctness of the control strategy used in the SHAPF with variations of linear loads. Parameters used in simulations are given in Table I. In simulation, the nominal frequency of the power grid is 50 Hz and the harmonic current source is generated by the three phase diode rectifier. Also, the dynamic reactive power changing is generated by linear loads shown in Table II. The phase to phase grid voltage is selected as 380 V (peak-peak). Passive filters are tuned at 5th and the control signals of IGBTs are generated through the pulse width modulation generator whose amplitude and frequency of carrier wave are ±1 and 20 kHz, respectively. The passive filter part supports a fixed reactive power which is equal to 10 kVAR. The reactive power capacity of the nonlinear load is 2 kVAR.

In this section, two mode of operation are discussed in simulation cases. A renewable energy source (RES) is connected on the dc link of grid interface SHAPF. The main aim of proposed approach is to regulate the power at PCC during: 1) PRES>0 and 2) PRES=0 where PRES is the power generated from RES. While performing the power management operation, the SHAPF is actively controlled in such a way that it always draws/supplies fundamental active power from/to the grid. Initially, the SHAPF is not connected to the network. Before time t=0.5 s, the source, load and SHAPF currents are illustrated in Figure 4 (a).

First mode of operation considers a case where PRES>0, the SHAPF injects RES active power into grid and also enhanced the quality of power at PCC. Before time t=1 s, RES is not connected to the network. The source, SHAPF and load active power are shown in Figure 5(a). At t=1 s, RES connected to the network. The SHAPF starts injecting active power generated from RES as shown in Figure 5 (b). Besides, SHAPF compensates harmonics successfully as shown in Figure 4 (b).

Second mode of operation considers a case when there is no power generation from RES. The SHAPF is to enhance the quality of power at PCC. The proposed control method for dynamic reactive power compensation with adjustable dc link voltage will be verified by simulations. When the loading reactive power consumption is greater than provided by the passive filter part, the inverter side of the SHAPF can compensate the remainder reactive power of the passive filter. At time t= 2 s, the 4th load is connected to the system. The reactive power rating of loads is increased 12 kVAR. The reactive power rating of loads is increased 12 kVAR. The reactive power rating of loads is increased 12 kVAR. When the loads are connected to the system, the system gives a dynamic response. Thus, the inverter side is compensated the reactive power remained by passive filter capacity. The source reactive power is nearly equal to zero shown in Figure 5 (c). The reduced THD of the source current, while compensating these loads variations, working balanced supply means in all the cases, sinusoidal current is drawn from the source shown in Figure 4 (c). SHAPF dc link voltage is adaptively changed from 160 to 225V shown in Figure 5 (e). The amount of source side reactive power remains nearly zero. In 2.5 s, the 5th load is connected to the system. The reactive power rating of loads is increased 13 kVAR. The inverter side is compensated remained by passive filter capacity. The amount of source side reactive power also remains nearly zero shown in Figure 5 (d).

The dc link voltage of SHAPF is adaptively changed from 225 to 290V shown in Figure 5 (d). The reduced THD of the source current, while compensating these loads variations, working balanced supply means in all the cases, sinusoidal current is drawn from the source shown in Figure 4 (d).
Figure 4. Three phase Source Voltages, Source - SHAPF - Load Currents (a) when SHAPF is not operated, (b) when PRES $>$ 0, (c) when PRES $= 0$ and 1 kVAR loads are connected (d) when PRES $= 0$ and another 1 kVAR loads are connected.

Compared the simulation results with dynamic load changes, the proposed method can:
1) Interconnect between renewable source by using shunt hybrid active power filter (SHAPF)
2) Provide dynamic reactive power compensation
3) Reduce the THD of source side current
4) Adaptively change the dc link voltage value

<table>
<thead>
<tr>
<th>TABLE I. SIMULATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Line frequency</td>
</tr>
<tr>
<td>Filter Capacitor (CF)</td>
</tr>
<tr>
<td>Filter Inductance (LF)</td>
</tr>
<tr>
<td>Tuned freq. of series filter (ftuned)</td>
</tr>
<tr>
<td>Filter Capacitor (CP)</td>
</tr>
<tr>
<td>Load Inductance (Lac1)</td>
</tr>
<tr>
<td>Switching frequency (fswitching)</td>
</tr>
<tr>
<td>Simulation Step Time</td>
</tr>
<tr>
<td>DC Link Reference Value</td>
</tr>
<tr>
<td>DC link Capacitors</td>
</tr>
</tbody>
</table>
Figure 5. Source - SHAPF - Load Active power and SHAPF DC link voltage when PRES=0, (b) Source - SHAPF - Load Active power and SHAPF DC link voltage when PRES>0, (c) Source - SHAPF - Load Reactive power and SHAPF DC link voltage when PRES=0 and 1 kVAR loads are connected, (d) Source - SHAPF - Load Reactive power and SHAPF DC link voltage when PRES=0 and another 1 kVAR loads are connected
TABLE II. SIMULATION PARAMETERS FOR TESTING LOADING

<table>
<thead>
<tr>
<th>Inductive Loads</th>
<th>Physical Value</th>
<th>Reactive Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Load (Rload1)</td>
<td>5 Ω 90 mH</td>
<td>5 kVAR</td>
</tr>
<tr>
<td>2nd Load (Rload2)</td>
<td>10 Ω 225 mH</td>
<td>2 kVAR</td>
</tr>
<tr>
<td>3rd Load (Rload3)</td>
<td>10 Ω 225 mH</td>
<td>2 kVAR</td>
</tr>
<tr>
<td>4th Load (Rload4)</td>
<td>20 Ω 450 mH</td>
<td>1 kVAR</td>
</tr>
<tr>
<td>5th Load (Rload5)</td>
<td>20 Ω 450 mH</td>
<td>1 kVAR</td>
</tr>
</tbody>
</table>

As a result, it is clearly shown that shunt hybrid active power filter (SHAPF) with a DC-DC converter at dc link achieves interconnection between renewable source and grid with linear dynamic loads. Besides, SHAPF using the proposed method can provide better compensation performance both harmonic and dynamic reactive power compensation.

IV. CONCLUSION

In this paper, SHAPF provides interconnection between renewable source and grid with linear dynamic loads. Besides, the novel control scheme for SHAPF is proposed in order to compensate both harmonic and dynamic reactive power with adaptive dc link voltage. The main contributions of this paper are:

- The grid interconnection is supplied by SHAPF for the renewable energy source.
- To introduce a new control strategy for reactive power compensation and harmonics elimination.
- To adaptively controlled dc link voltage.
- To achieve reactive power compensation which is nearly equal to 100% of load reactive power capacity.

The harmonic current control, the dc link control and reactive current control are achieved by indirect current control. With this control method, any extra start up precharging control process is not necessary for dc link. In addition, reactive power compensation is achieved successfully with perceptible amount. Besides, the harmonic compensation performance is satisfactory.

In a conclusion, the SHAPF injects RES active power into grid and also enhances the quality of power at PCC. Simulation results of the three-phase three-wire SHAPF in dynamic reactive power compensation.

REFERENCES


