Reactive power compensation and harmonic mitigation through quasi Z source converter for marine applications

Rajalakshmi Rajmohan, Dr. Rajasekaran Vairamani & Dr. S. Selvaperumal

1Department of Electrical and Electronics Engineering, Coimbatore Institute of Technology, Coimbatore, Tamil Nadu, India.
2Department of Electrical and Electronics Engineering, PSNA College of Engineering and Technology, Dindigul, Tamil Nadu, India.
3Department of Electrical and Electronics Engineering, Syed Ammal Engineering College, Ramanathapuram, Tamil Nadu, India.

*E-mail: perumal.om@gmail.com

Received 27 February 2015; revised 04 June 2015

This research work brings out the unique approach for attaining an efficient grid connected PV system with suppression of current harmonics by Shunt Active Power Filter (SAPF) as grid connected inverter. But the performance of SAPF is not consistent and is varied based on the control techniques. Filter currents are created using Phase Locked Loop (PLL) based park transformation. Control loops of SAPF are employed with Proportional Integral (PI) controllers. Tuning of PI controller is found to be crucial in improving the harmonic compensation of SAPF. Various optimization algorithms are used for obtaining optimized control parameters of PI controller. Self tuning of PI controller is proposed through Imperialist Competitive Algorithm (ICA) to get the optimal value of PI parameters. Simulation works are carried out in MATLAB/Simulink and the performance of this proposed approach is compared in minimizing Total Harmonic Distortion (THD), to maintain the quality of utility grid without distortion and thus increasing energy efficiency of the system.

[Keywords: Shunt Active Power Filter, Harmonic Mitigation, Renewable Energy Source (RES), Quasi Z Source Converter, Bacterial Forage Optimization, Shuffled Frog Leaping Algorithm, Imperialist Competitive Algorithm]

Introduction

In recent decades, the electric utilities and end users of electric power are concerned about meeting the growing energy demand. Seventy five percent of total global energy demand is supplied by the burning of fossil fuels. However, due to the increase in air pollution, global warming, diminishing fossil fuels and their increasing cost, renewable sources have become future sources of energy.

Photovoltaic energy is one of the purest forms of power generating technologies with very little influence on the environment producing no air pollution, waste, or noise. As a result, solar energy can be a valuable economic aspect as it reduces the impact on fossil fuels.

Alternatively, the growth and development of Nonlinear Loads (NL) has greatly depreciated the power quality in power transmission/distribution systems.

Non-linear loads are usual factors in industrial and marine applications, office buildings, homes, etc which in turn causes frequent power quality issues such as harmonics, flicker and resonance. Harmonic distortions are of greater concern in recent years due to the result of their distorted voltage waveforms which in turn causes overheat in building wiring, nuisance tripping, end-user utensils failures, etc. Thus, it is observed that harmonic distortion is the foremost reason for the increasing deterioration of the electrical power grid voltage and current waveforms. Harmonic currents through the line impedance generate distortion in the system voltages.

Moreover, voltage unbalance in three phase power systems is very frequent as most of the loads connected to the electrical systems are single-phase. These unbalanced system voltages results in a number of power quality issues which includes the erroneous operation of certain sensitive loads. Figure 1 presents a power system with sinusoidal source voltage (VS) operating with a non-linear load.

The scheme of the active filter considered in this
article is presented in Figure 1. It is a three-phase AC/DC converter, where the capacitor is acting as main energy storage element and the inductors are used for controlling the filter currents by means of converter voltages.

In Figure 1, \(v_{mabc}, i_{mabc}, i_{Fabc}, i_{Labc}\) are the source voltages, source currents, filter currents and load currents respectively and \(v_0\) is the capacitor voltage (DC Bus). Since the power lines have harmonic problems, the power quality at end user’s terminal is affected and it has become a great concern. Therefore, it is very essential to identify novel and efficient systems that would mitigate such disturbances in the electrical systems, improving their power quality. Normal filters such as LC, LCL, etc., are used to eliminate specified frequency range and thus, it can be only used for predetermined loads. Thus, Active Power Filters have been used for these types of harmonic mitigation concerns in transmission lines.

The utilization of SAPF provides significant advantages to the power system. Thus, developing new methodologies has become an active area of research to improve the performance of these SAPFs. In this paper, SAPF is used as a grid interfacing inverter to perform the function like transmission of active power yield from the PV system.

An efficient control strategy using \((i_d - i_q)\) control strategy and Pulse Width Modulation (PWM) is utilized here for the betterment of current quality by minimizing the Total Harmonic Distortion.

For compensating the harmonics efficiently, the DC voltage must be constant with minimum distortion. Generally, PI controllers have been extensively used to carry out this task. But, the optimization of PI regulator’s parameters becomes crucial in order to improve its performance.

In this work, the design of PI controller is formulated as an optimization problem. Two optimization approaches are presented in this paper to improve the current quality. Thus, this paper mainly focuses on the utilization of the optimization approaches such as SFLA and ICA and to tune the PI controller. These optimization approaches have been widely used to solve several non-linear variation problems and provided significant optimal results.

**Materials and Methods**

**Design of proposed system**

In this proposed approach, the SAPF is used for 3 phase 4 wire system to interface the Quasi Z Source Converter (QZSC) based PV system with the utility. The overall structure is given in Figure 2. In this approach, RES is been used as the alternative energy resource and a boost converter is used to maximize the voltage which is given as input to the inverter. In order to compensate the varying dc link voltage based on the impact of RES, this research work prefers the optimization algorithms.

The supply voltages \(v_{abc}\) are the co-sinusoidal of frequency \(f_s\) (50 Hz) balanced and equilibrated as shown in Figure 1.

\[
\begin{align*}
v_{a}(t) &= V_s \cos(2\pi f_s t) \\
v_{b}(t) &= V_s \cos(2\pi f_s t - \frac{2\pi}{3}) \\
v_{c}(t) &= -[v_{a}(t) + v_{b}(t)]
\end{align*}
\]

The PWM frequency \(f_{PWM}\) are already chosen. The peak to peak current ripple is given by...
\[ \Delta I_{p-k-pk} = \frac{V_s}{6 \times L \times f_{PWM}} \]  

(4)

where \( \Delta I_{p-k-pk} \) indicates ripples caused by the PWM technique. \( \Delta I_{p-k-pk} \) must be less than the maximum ripple chosen \( \Delta I_{Mpk-pk} \). Thus, the minimum Inductor value is given by the following equation:

\[ I_{minimum} = \frac{V_{max}}{6 \times f_{PWM} \times \Delta I_{Mpk-pk}} \]

(5)

\[ p^t_f(t) = \frac{d}{dt} \left( \frac{1}{2} C v^2_{0f}(t) \right) \]

(6)

This equation can be used to choose the capacitor value. The energy

\[ E^*(t) = \int_{t_0}^{t} p^t_f(\tau) d\tau \]

(7)

is periodic of frequency \( f_m \) by principle and its mean value is zero. Defining

Figure 2 – Proposed architecture of shunt active power filter
and imposing that the related voltage variation is \( (V_{\text{ref}} - V_{\text{min}}) \), it can be obtained the capacitor value design equation

\[
C = \frac{2E_{\max}}{V_{\text{ref}}^2 - V_{\text{min}}^2}
\]

Quasi Z Source Converter (QZSC) is a new promising power converter used for boosting up the output voltage of PV system and other RES also, like wind and fuel cells\(^6\). The QZSC has the following advantages:

- Boost-buck function by one-stage conversion;
- Continuous input current
- Excellent consistency due to the shoot-through withstanding capability;
- Low or no in-rush current during start up;
- Low common-mode noise.

So, this approach uses QZSC for improving the overall performance and its Current Conduction Mode (CCM) of operation is explained as follows.

The equivalent circuits of Mode 1 and Mode 2 are shown in Figure 3(a) and 3(b) respectively\(^7\). The required circuit equations are presented as follows:

\[
C \frac{dV_{c1}}{dt} = i_B - i_{L2} - \frac{dV_{c2}}{dt} - i_{L1}
\]

\[
L \frac{di_{L1}}{dt} = V_{in} - V_{c2}
\]

\[
L \frac{di_{L2}}{dt} = V_{c1} - V_{c2}
\]

where \( i_{L1}, i_{L2}, \) and \( i_B \) denote the currents of inductors \( L_1 \) and \( L_2 \) and the battery, respectively; \( V_{c1}, V_{c2} \) and \( V_{in} \) denote the voltages of capacitors \( C_1 \) and \( C_2 \) and the PV panel, respectively; \( C \) denotes the capacitance of capacitors \( C_1 \) and \( C_2 \); and \( L \) denotes the inductance of inductors \( L_1 \) and \( L_2 \).

The circuit equations for this Mode 2 are presented as follows:

\[
C \frac{dV_{c1}}{dt} = i_B + i_{L2} - i_d
\]

\[
C \frac{dV_{c2}}{dt} = i_{L2} + i_d
\]

\[
L \frac{di_{L1}}{dt} = V_{in} - V_{c2}
\]

\[
L \frac{di_{L2}}{dt} = -V_{c2}
\]

where \( i_d \) represents the load current going to the inverter.

\((i_d - i_q)\) Control Strategy

The \( \alpha - \beta \) orthogonal coordinates are obtained from phase voltages like \( V_{p_a}, V_{p_b} \) and \( V_{p_c} \) the load
currents $i_{d \alpha}$ and $i_{d \beta}$ as given in Equation (12 and 13) respectively.

\[
\begin{bmatrix}
V_0 \\
V_\alpha \\
V_\beta
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
V_{pa} \\
V_{pb} \\
V_{pc}
\end{bmatrix}
\]

\[
\begin{bmatrix}
l_0 \\
l_\alpha \\
l_\beta
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
l_{d \alpha} \\
l_{d \beta} \\
l_{d \beta}
\end{bmatrix}
\]

(12) (13)

The active and reactive currents $i_d$ and $i_q$ of the non linear load are attained through the orthogonal coordinates as given in equation (14).

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = \frac{1}{\sqrt{V_\alpha^2 + V_\beta^2}} \begin{bmatrix}
V_\alpha & V_\beta \\
V_\beta & V_\beta
\end{bmatrix} \begin{bmatrix}
i_\alpha \\
i_\beta
\end{bmatrix}
\]

(14)

where $i_\alpha$ and $i_\beta$ are the direct $\alpha-\beta$ axis current co-

This approach is significant as it frequency independent due to the fact that the angle theta is obtained from the main voltages.

Figure 4 and 5 show the reference current generation loop and overall proposed diagram for shunt active filter. In order to evade the direct current components in the $i_{d \alpha}$, the active and reactive currents attained from park transformation is then given to the Butterworth filter ($f_{\text{cutoff frequency}} = \frac{f_{\text{main}}}{2}$). There would be a little phase shift delay between dc component eliminated active and reactive current and active and reactive current.

Voltage Regulation of DC link Capacitance ($C_{dc}$)

The $i_d$ and $i_q$ are the active and reactive currents with positive and negative sequence. After the Butterworth filtering, positive sequence of active and reactive currents is obtained. Since the main aim of this work is to eliminate the negative sequence of reactive currents, the negative reference is set as zero. The active current is improved by tuning the active dc link voltage and the set dc link voltage with the help of PI controller. Now, the VSI gets the improved active power flow from the dc link side. PI controller tuning with traditional models resulted in degraded performance under non liner conditions. Optimal tuning of PI is needed to achieve the best performance of PI controllers. The problem formulation taken for consideration in this approach are proportional gain ($k_p$), integral gain ($k_i$) and saturation limit as the objective function to determine PI control parameters.

Figure 4 - Park transformation and harmonic current injection circuit
Background study on PI Control strategies

In general, PI controllers and their control mechanism are explained in many literatures for real time applications. PI controllers are applied in DC voltage control due to its ease. But, it necessitates accurate linear mathematical formulations, which are practically tough and also it fails to perform well under parameter variations, load disturbance, etc. This in turn would result in certain limitations, such as, great overshoot of DC voltage, large settling time and acute current impact. The THD obtained based on PI controller is 3.22%.

In order to overcome the drawbacks of the PI controller, hybrid fuzzy PI controller has been used. The fuzzy PI controllers provide better THD of about 3.00%. But, fuzzy PI controllers do not provide efficient results in certain conditions due to the manual setting of the input output voltage range.

The neural based PI controller provides better results than the hybrid fuzzy and conventional PI controller with a THD of 2.85%. Figure 6 shows the overall background study of PI controller.

Shuffled Frog Leaping Algorithm (SFLA) is a heuristic search algorithm for solving the optimization problems. The major advantage of this algorithm is to solve complex optimization problems without any use of conventional mathematical optimization apparatus. But, still there is space for improvement. To overcome these problems, this research work focuses on self tuning of the PI controller with Imperialist Competitive Algorithm (ICA).
Problem formulation and optimization algorithms

This research work uses ICA optimization algorithm to tune the PI controller. The objective function of this approach would be to minimize the THD of the model is

$$\text{Minimize } f(x) = \text{THD + Peak Overshoot + Settling Time} \quad (15)$$

The constraints used in the approach are equality constraint and inequality constraints. The parameters which have to be optimized in this approach are \(f(k_p, k_i, \text{sat})\). The subject of limits considered in this research work is

$$k_{p\text{min}} < k_p < k_{p\text{max}}$$
$$k_{i\text{min}} < k_i < k_{i\text{max}}$$
$$\text{sat}_{\text{min}} < \text{sat} < \text{sat}_{\text{upper}} \quad (16)$$

Imperialist Competitive Algorithm (ICA) is a well defined approach that is used to resolve optimization problems of various types. Figure 7 shows the flowchart of the ICA. ICA initiates with an initial population ‘IC’ countries. Each country is represented through the equation (17).

$$\text{Country}_i = [IC_1, IC_2, ..., IC_n] \quad (17)$$

where \(n\) is dimension of optimization problem. The significant countries are chosen as the imperialists and others are regarded as the colonies of these imperialists. The colonies are partitioned between imperialists depending on imperialist’s significance. The normalized cost \((\text{Cost}_{\text{nor}})\) of an imperialist to partition the colonies along with imperialists is given in the following equation:

$$\text{Cost}_{\text{nor}} = \text{cost}_n - \text{maximum(\text{cost}_i)} \quad (18)$$

where \(\text{cost}_n\) represents the cost of \(n\)th imperialist and \(\text{Cost}_{\text{nor}}\) denotes the normalized cost. The normalized power of each imperialist is given by the following equation:

$$P_{\text{nor}} = \left| \frac{\text{Cost}_{\text{nor}}}{\sum_{i=1}^{n_{\text{imp}}} C_{i}} \right| \quad (19)$$

The overall power \((\text{power}_n)\) of an empire is given by cost of the imperialists and the summation of the cost of the colonies of empires which is given as follows:

$$\text{power}_n = \text{cost(Imperialists)} + \text{mean(\text{cost(Colony of empire)} n)} \quad (20)$$

where \(\text{power}_n\) represents the overall cost of the \(n\)th empire and \(0 < \varepsilon < 1\). Any empire that is not victorious and cannot increase its power will be Ultimately, the approach will work for movement of colonies towards their appropriate imperialist.
Results and Discussion
The proposed SAPF approach has been simulated in MATLAB R 2011a. The simulation parameters used in this proposed approach is shown in Table 1. **ABC to \( \alpha, \beta \) conversion**

Transformation of the phase voltages \( v_a, v_b, \) and \( v_c \) and the load currents \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) into the \( \alpha - \beta \) orthogonal coordinates waveforms are shown in the Figure 8. The waveforms based on the transformation of the phase voltages and load currents are given in
### Table 1 – Simulation parameters

<table>
<thead>
<tr>
<th>System Parameters</th>
<th>Symbol Used</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Voltage</td>
<td>( V_{\text{max}} )</td>
<td>( 220 \text{ V} \times \sqrt{2} )</td>
</tr>
<tr>
<td>Supply Frequency</td>
<td>( f_s )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>( f_{\text{PWM}} )</td>
<td>28 KHz</td>
</tr>
<tr>
<td>Input Inductance</td>
<td>( L_s )</td>
<td>0.01 mH</td>
</tr>
<tr>
<td>Filter Inductance</td>
<td>( L_{\text{af}} )</td>
<td>0.5 mH</td>
</tr>
<tr>
<td>Dc-link capacitance</td>
<td>( C_{\text{dc}} )</td>
<td>3000 ( \mu \text{F} )</td>
</tr>
<tr>
<td>Reference Dc-Link</td>
<td>( V'_{\text{dc}} )</td>
<td>325 V</td>
</tr>
<tr>
<td>Voltage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Side Isolation</td>
<td>-</td>
<td>1:1, 50 Hz, 230 Vrms</td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
<td>( V_{\text{ms}} )</td>
</tr>
<tr>
<td>Injection Transformer</td>
<td>-</td>
<td>1:1, 50 Hz, 230 Vrms</td>
</tr>
<tr>
<td>Load Parameters</td>
<td>( R_L, L_L )</td>
<td>20 \Omega, 25 mH</td>
</tr>
</tbody>
</table>

Figure 8. The phase voltages namely \( V_x \) and \( V_\beta \) and moreover, load currents \( I_x \) and \( I_\beta \) are also indicated.

**\( i_d \) and \( i_q \) Current**

Figure 9 shows the active current and reactive currents extracted from equation (14) and the Figure 10 shows the ripple rejection of \( i_d \) and \( i_q \). Figure 11 shows the compensating current generated by the SAPF.

**Reference Current from Shunt Active filter and System Performance**

The set PWM value is 28 KHZ. For the designed configuration with respect to the NL and its Q value the circuit can be operated satisfactory upto 28 KHZ. If the carrier frequency is increased then with very less time interval we may get the switching pulses which may reduce the execution time and increases the speed of response. The frequent samples are taken with this increased frequency which will reduce the total harmonic distortion.

The THD of source current is a measure of the effective value of harmonic distortion and can be calculated as per equation (17) in which \( V_{\text{rms}} \) is the RMS value of fundamental frequency component of current and represents the RMS value of \( n^{\text{th}} \) order harmonic component of the current.

Figure 12 shows the response of SAPF on the system parameters in order to compensate the
current harmonics created by the NL in the source current and reactive power compensation also. Figure 12 (a) shows the source current after injecting the compensating current into the system. Figure 12 (b) demonstrates the nonlinear load current for the three phases and the compensated source current for the load current drawn by the nonlinear load for a single phase is given in the Figure 12 (c). Figure 12 (d) proves that the source voltage is also sinusoidal after the harmonic reduction in the system. Maintaining constant reference voltage at the DC link capacitor side is very important inorder to drive the SAPF for its maximum compensating performance. The constant DC link voltage is one of the key factors in improving the SAPF performance. Figure 12 (e) shows that the reference voltage is maintained at the value of 325 V throughout the operation of the system.

**Active and Reactive Power Analysis with Interconnected RES and SAPF**

RES with uneven output power is coupled on the dc-link of grid-interfacing inverter and it will generate an unbalanced nonlinear current which in turn will increase the reactive power. This uneven reactive power has to be compensated between Bus 1 and Bus 2.

In this proposed SAPF design, the reactive powers of grid, load and inverter are effectively compensated. The corresponding active-reactive powers of grid \( P_{grid}, Q_{grid} \), load \( P_{load}, Q_{load} \) and inverter \( P_{inv}, Q_{inv} \) are shown in Figure 13.
From the Figure 13, it is inferred that the positive signs of $(P_{grid}, Q_{grid})$ and $(P_{inv}, Q_{inv})$ clearly indicate that the power flow is from grid side and inverter towards Bus 2 respectively. Thus, $(P_{load}, Q_{load})$ are also denoted by positive signs. At the instant, when RES is connected with SAPF, active power generated from RES is injected by the inverter $(P_{RES} \approx P_{inv})$. The additional power is fed back to the grid as the generated power is more than the load demand. The negative sign of $P_{grid}$ denotes that it receives power from RES.

Figure 14 shows the DC link voltage response of the selftuning approach compared with the non-self tuning approach. When the output of the self tuning approach is considered, the settling time is attained at a lesser time without peak overshoot and rise time. But, non-self tuning approach produces a poor settling time, peak overshoot and higher rise time. The values are compared in Table 2.

Figure 15 clearly shows FFT analysis of source current harmonic reduction through various self tuned PI controllers. It is observed that, the proposed ICA based PI controller provides best minimized THD of about 1.89%.
Figure 15 (c) – THD of Neural PI controller

Figure 15 (d) – THD of SFLA PI controller

Figure 15 (e) – THD of ICA PI controller

Figure 16 – THD comparison of different approaches

Table 3 – THD values of various techniques

<table>
<thead>
<tr>
<th>S. No</th>
<th>Approaches</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yi Tang et al. [12]</td>
<td>3.49</td>
</tr>
<tr>
<td>2</td>
<td>Salem Rahmani et al.</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>Avik Bhattacharya et al.</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>Proposed PWM and L_p-L_q control Strategy</td>
<td>3.22</td>
</tr>
<tr>
<td>5</td>
<td>Proposed SLF based SAPF</td>
<td>1.99</td>
</tr>
<tr>
<td>6</td>
<td>Proposed ICA based SAPF</td>
<td>1.89</td>
</tr>
</tbody>
</table>

**Conclusion**

This paper proposes optimization based self-tuning PI controller to eliminate grid current harmonics. ICA optimization algorithm has been used in this approach for optimizing the controller parameters such as proportional gain ($k_p$) integral gain ($k_i$) and saturation limit to determine the optimal PI control parameters for a better performance. The proposed approach is simulated in MATLAB and the performances of the optimization algorithms are compared. It is observed from the results that the optimization approaches provides better results with minimal THD of IEEE standard. The proposed ICA based approach attains a THD of 1.82% where SLF attained THD of 2.12% respectively. Thus, the proposed ICA outperforms the other two.
optimization approaches and is very efficient in finding the optimal parameters such $k_p$, $k_i$ and saturation limits. Moreover, the proposed ICA based SAPF converges in lesser number of iterations when compared with SLF. Thus, the ICA based SAPF proves to be an proficient technique to improve the power quality by effective harmonic mitigation and hence increasing the energy efficiency of the system.

References