Shunt active power filter control based on Z-source inverter fed by PV system

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ABSTRACT

In this paper, an integration of a Z-source inverter (ZSI)-based shunt active power filter (SAPF) fed by a photovoltaic (PV) system for the enhancement of power quality is proposed. The ZSI provides substantial advantages including improved boost functionality, reduced harmonics, and superior performance compared to traditional inverters. In this paper, the SAPF control is based on instantaneous reactive power theory. A proportional-integral (PI) controller is implemented for DC-link voltage control, with the primary aim of this study being the elimination of total harmonic distortion (THD) in the source current. To demonstrate the effectiveness of the proposed approach, simulations were conducted using MATLAB/Simulink across various operating conditions. The outcomes substantiate and validate the efficacy of the proposed method.

Keywords: Instantaneous reactive power theory, Photovoltaic system, SAPF, Total harmonic distortion, Z-source inverter

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1. INTRODUCTION

The widespread use of non-linear loads in industrial applications has caused undesirable effects related to the power quality [1], [2]. This increase within the use of non-linear masses encompasses a vital impact on consumers, because the main issues in power quality consist current, voltage and frequency distortions. However, the need for consistent power quality is growing due to the increasing use of sensitive devices that rely on smooth sine waveforms [3], [4]. To eliminate harmonic currents and address the power issues caused by these non-linear loads, numerous studies have been conducted. Historically, passive filters have been used to reduce current harmonics and alleviate energy pollution in the network over an extended period. However, this type of filter has several drawbacks, such as being large in size, heavy, and sensitive to dynamic parameters, leading to resonance issues.

These challenges were successfully addressed by implementing an active filter, a concept that gained recognition around the 1970s [5], [6]. The shunt active power filter (SAPF) offers a versatile solution for reducing harmonic currents and improving power factor. Moreover, it can effectively adjust to various load types. The SAPF system consists of a voltage/current source inverter that interacts with a linked capacitor connected in parallel with non-linear loads [7], [8]. The electrical converter produces the required harmonic elements to mitigate the harmonic currents caused by non-linear loads. As a result, it aligns the main current to be sinusoidal and in phase with the supply voltage [9], [10]. Consequently, filters have become significantly important [11],

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The second option offers numerous benefits, such as the elimination of harmonic current, compensation of reactive power, and simultaneous injection of active power. However, it also has several drawbacks, including non-linear properties and a strong reliance on environmental conditions. There is an urgent need for accurate monitoring of the maximum energy harvested from photovoltaic sources [13]. Many approaches for maximum power point tracking (MPPT) have been suggested in the literature to address this issue. These include techniques like perturbation and observation (P&O), which involves perturbing the photovoltaic system and monitoring the changes in the output power. The conductance method utilizes the slope of the PV to determine the point of peak energy, and these approaches are reinforced by artificial intelligence [13], [14]. Additionally, Z-source inverter or ZSI features an additional state termed "shoot-through," which is created by concurrently operating the higher and lower switches of the same leg. Attributable to this extraneous state, the electrical phenomenon periodic voltage will be simply controlled employing a single-phase configuration [15], [16].

The aim of this article is to introduce a cost-effective solution for current compensation by proposing a three-phase active power filter connected to a PV system via ZSI [11] managed by instantaneous reactive power theory [17]. The DC side voltage control of the SAPF was achieved using a standard PI controller [18]. The effectiveness and performance of the system under study were evaluated through simulation using Simulink. The following sections of this paper are outlined. Section 2 details the SAPF topology based on the Z-source inverter, while section 3 covers the control of SAPF. Section 4 presents simulation results, and lastly, section 5 provides the conclusions of this work.

2. SAPF TOPOLOGY BASED ON Z-SOURCE INVERTER

2.1. PV power generating unit

Excess power generation from the PV power generation system can be routed through the DC-DC converter circuit. Also, it can be used in the energy storage unit and start providing the energy stored in the battery when a PV system is not powerful enough as shown in Figure 1 [19]. The subsequent are the essential equations of the PV module as shown in Figure 2. The modeling of the PV panel can be described as in (1) and (2).

\[ I_{ph} = I_d + I_{pv} = I_{ph} - I_d \]  \hspace{1cm} (1)

\[ V_{pv} = \frac{A_{kTc}}{e} \ln \left( \frac{l_{ph}+l_{dc}-l_c}{l_d} \right) - R_sl_c \]  \hspace{1cm} (2)

Where \( I_{pv} \) donates output current in amps. Photovoltaic cell voltage is displayed as Figure 2. The output of boost converter (12 V) is supplied to the Z-source inverter to boost. The equivalent ZSI circuit in shoot through state is presented in Figure 3(a). The voltage of inductor is equal to capacitor voltage \( V_L = V_C \) while \( T_{cycle} \) cycle.

The indicated ZSI circuits in the state of non-shoot through shown in Figure 3(b). The change pattern of ZSI is shown in Figure 4. During the non-shoot through state, the inductance voltage \( V_L \) and also the input voltage \( V_{in} \) may be described as (3)-(6).

\[ V_L = V_{dc} - V_C \]  \hspace{1cm} (3)

\[ V_{in} = \frac{1}{1-C} V_{dc} \]  \hspace{1cm} (4)

\[ V_L = BV_{dc} \]  \hspace{1cm} (5)

\[ B_L = \frac{1}{1-C} \]  \hspace{1cm} (6)

Where \( B \geq 1 \); the operation modes are: i) PV power generation mode, ii) battery backup mode, and iii) continuous supply mode as shown in Figures 5-7.

2.1.1. PV power generation mode

During daylight hours or when there is ample sunlight, the photovoltaic power generation mode is activated to produce sufficient energy. The PV sustained SAPF functions as a harmonics and reactive power controller, and any surplus power is stored in a battery. Refer to Figure 5, it is the current flow chart detailing the photovoltaic power generation mode.

2.1.2. Battery backup mode

Battery backup mode is supported overnight or in the absence of sunlight. In battery backup mode ZSI operates to hardly manage compensation continuity. Figure 6 indicates the output current flowchart for battery backup mode.
2.1.3. Continuous supply mode
During a voltage interruption, the PV-SAPF model ensures a consistent supply of power to critical and sensitive loads. In such instances, the solar PV power supply unit or battery backup unit serves as the power source for the connected load. Semiconductor switches are used to disconnect the power supply from the distribution network.

![General scheme of SAPF based on two-level ZSI](image1)

Figure 1. General scheme of SAPF based on two-level ZSI

![The proposed scheme of SPV array and DC-DC converter with MPPT control circuitry](image2)

Figure 2. The proposed scheme of SPV array and DC-DC converter with MPPT control circuitry

![Equivalent scheme of ZSI (a) shoot through state and (b) non-shoot through state](image3)

Figure 3. Equivalent scheme of ZSI (a) shoot through state and (b) non-shoot through state
Give the value 1 to each inverter control signal.

Figure 4. Switching cases for ZSI

During availability of PV source

Active state

Battery discharge

Energy storage by battery

Figure 5. Current flowchart for photovoltaic power generation mode

Figure 6. Current flowchart for battery backup mode
3. PV-SAPF CONTROL SCHEME

The current compensation is implemented in the control scheme based on currently reactive power theory for 3-phase PV-SAPF. This is one of the most popular theories that has been used. Not only in theory but also in practice can be considered as the first successfully implemented method based on the use of static converters [20].

3.1. Hysteresis control

The principle of hysteresis output control is to keep each of the generated currents within a band surrounding the reference currents. Any violation of this band gives a commutation command to stay within the band. The main function of the proposed model is to keep the output current within the standard limits.

3.2. Fixed band hysteresis regulation

With this kind of current control, the frequency essentially depends on the derivation of the target current as displayed in Figure 8. The latter depends on the size of the decoupling inductance and the voltage drop across it. The filter affects the switching frequency and the dynamic behavior of the active filter. Figure 9 displays the main promotion of this method is the simplicity of implementation, while the variable switching frequency, which cannot be properly controlled, can become its main disadvantage [21].

![Figure 7. Current flow chart for continuous supply mode](image)

**Figure 7. Current flow chart for continuous supply mode**

![Figure 8. Schematic diagram of the instantaneous power method](image)

**Figure 8. Schematic diagram of the instantaneous power method**

![Figure 9. Hysteresis band current controller](image)

**Figure 9. Hysteresis band current controller**
4. SIMULATION RESULTS

The elements of the PV-SAPF system are presented in Table 1. Modelling is carried out using MATLAB/Simulink. The results of the simulation study are presented before and after connecting the PV-SAPF system. It is noted that the initial state of the capacitors voltage in the system is zero as revealed in Figure 10.

4.1. DC voltage variation

First, the gain of proportional integral controller and its response to a stepwise disturbance in the DC bus voltage from 160 to 140 V is verified in Figure 11. Obviously, the traditional PI controller gives very satisfactory results. It can help in detecting the output current under control.

4.2. Continuous operation

The results of the state of the system before and after connecting of the filter are depicted as shown in Figures 12 to 14 [22]–[25]. Figure 15(a)-(c) shows the source current, filter current and DC bus voltage, respectively, which are the results obtained with the filter connected. Before the filter is connected, the load current is fully supplied from the network. The capacitors in the Z-source network are charged from the battery bank, which in turn is charged by the SPV, until the capacitors reach the line voltage level $V_{dc} = 80$ volts. Where we notice the elimination of ripple in the active and reactive powers after connecting the filter, and thus the reactive power was successfully compensated.

4.3. Load variation

In this case, the burden is suddenly reduced from $R_1 = 24 \ \Omega$ to $R_2 = 16 \ \Omega$ (with a change of 33%). A raise When the source current is increased, there is a minor reduction in voltage across the two terminals of the Z-source inverter (approximately 1 V). Figure 11 demonstrates the highly satisfactory outcomes. Table 2 presents a comparison showing the superiority of the proposed system over other methods.

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**Figure 10.** Control of switches by fixed band hysteresis

**Figure 11.** DC bus voltage response with conventional PI-based reference DC voltage variation
Shunt active power filter control based on Z-source inverter fed by PV system (Ahfouda Abdelkarim)
Table 1. Parameters of system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>System voltages (line to line) Vrms</td>
<td>57 V</td>
<td>Capacitance</td>
<td>$C_{source}$</td>
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<tr>
<td>Frequency</td>
<td>$f$</td>
<td>Switching frequency</td>
<td>$f_{source}$</td>
</tr>
<tr>
<td>Filter (series SAPF)</td>
<td>$L_s R_s$</td>
<td>$K_p$</td>
<td>$K_p$</td>
</tr>
<tr>
<td>Battery voltage</td>
<td>30 V</td>
<td>$K_i$</td>
<td>$K_i$</td>
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<tr>
<td>Battery capacity</td>
<td>33 Ah</td>
<td>Sample time</td>
<td>$1 e^{-4}$</td>
</tr>
<tr>
<td>Filter (shunt SAPF)</td>
<td>$L_f R_f$</td>
<td>Charge non-linéaire</td>
<td>$R_C$</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L_{source}$</td>
<td>5 mH</td>
<td></td>
</tr>
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Table 2. Comparison results between the proposed and different control strategies

<table>
<thead>
<tr>
<th>Topology</th>
<th>Control strategy</th>
<th>The output results of THD of proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAPF (p–q) method proposed in [3]</td>
<td>2.03%</td>
<td>1.76%</td>
</tr>
<tr>
<td>SAPF DPC strategy proposed in [3]</td>
<td>/</td>
<td>1.16%</td>
</tr>
<tr>
<td>SAPF Predictive-DPC-SVM strategy proposed in [3]</td>
<td>/</td>
<td>0.90%</td>
</tr>
<tr>
<td>SAPF Predictive control strategy proposed in [23]</td>
<td>22.60%</td>
<td>0.81%</td>
</tr>
<tr>
<td>ZSI-SAPF (p–q) method proposed in this paper</td>
<td>23.18%</td>
<td>0.72%</td>
</tr>
</tbody>
</table>

Figure 14. The results of the ZSI-SAPF: (a) before and (b) after
Figure 15. Simulation results of (a) source current $I_{sa}$, (b) filter $I_{fa}$, and (c) DC bus voltage $V_{dc}$, after the modelling of ZSI-SAPF.
5. CONCLUSION

In this paper, a three-phase shunt active filter design utilizing a Z-source inverter controlled by instantaneous reactive power theory and a PI hysteresis control algorithm is presented. Performance of the proposed structure was evaluated under different operating with a non-specific load. Simulation results using MATLAB/Simulink show satisfactory performance. Besides, to underscore the performance of the proposed structure, an improvement in efficiency was obtained as compared to the conventional structure. On the other hand, it is evident that the proposed structure achieves the best THDi in the simulation test by 0.72%. Furthermore, the system performance can be improved by extending the control algorithm to optimize the parameters of the PI controller. In addition, the power factor operation is improved since the reactive power is equal zero.

REFERENCES


BIOGRAPHIES OF AUTHORS

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