A Three-Phase Grid-Connected PV System Based on SAPF for Power Quality Improvement

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Abstract
This paper proposes a combined system of three-phase four-wire shunt active power filter (SAPF), and photovoltaic generator (PVG), to solve the power quality problems such as harmonic currents, poor power factor, and unbalanced load. In addition, the proposed system can inject the issued energy from the PVG into the utility grid. To increase the efficiency of the PVG and extract the maximum photovoltaic (PV) power under variable atmospheric conditions, a maximum power point tracking (MPPT) technique based on perturb and observe (P&O) is implemented in the DC/DC boost converter. The effectiveness of the proposed PVG-SAPF (PVG and SAPF) based on the use of synchronous reference frame theory (SRF theory) under unbalanced nonlinear load. The proposed PVG-SAPF is validated through numerical simulations using Matlab/Simulink software. The simulation results show the effectiveness of the proposed PVG-SAPF.

Keywords: Power quality, shunt active power filter, SRF theory, PV system and MPPT.

1. Introduction
In the last decades, renewable energy sources have attracted much more attention due to the advantages such as less environmental impact and offer clean and abundant energy. Solar energy is one of the most famous sources of renewable energy, with the development of control tools, photovoltaic systems are no longer limited to active power generators in the utility grid, but they also contribute to the improvement of the power quality. In order to improve the power quality, various traditional passive filter and modern active filter have been developed [1-6]. The traditional passive filters, using capacitors (C), inductors (L) and/or resistors(R) [4], it was a popular solution for harmonics mitigation [7, 8], because it has some advantages such as simplicity, reliability and low cost. However, in practical applications, it presents many disadvantages such as fixed compensation, large size, and parallel and series resonance with load and utility impedances [4, 9]. Modern active filters are superior in filtering performance, smaller in physical size, and more flexible in application. Unlike the passive filters, the active filters have many advantages and functions such as harmonic filtering, reactive power compensation for power factor correction, load balancing,.....etc [4, 9].

To extract the maximum solar energy from the photovoltaic generator, during the variations of atmospheric conditions, many MPPT techniques have been proposed in the literature, the most widely used algorithms are perturb and observe (P&O) [10-12] and incremental conductance (IncCond) methods [13, 14].

This paper proposes a combined system of a three-phase four-wire SAPF, and PVG to solve the power quality problems. The PVG-SAPF controller generates reference currents using SRF theory under unbalanced nonlinear load. the DC-DC boost converter is controlled using a P&O-based MPPT technique.

The remainder of the paper is organized as follows: the next section presents the modeling of the PV system, its I-V and P-V characteristics, MPPT and (P&O) technique. The third section presents the design and control of PVG-SAPF. The fourth section displays simulation results and discussion and the last section of this paper consists of a conclusion.
2. PV System
2.1. PV Model and Characteristics

A photovoltaic cell is a sensor consisting of a semiconductor material (PN junction) that absorbs light energy and transforms it to electrical power. When the junction is illuminated, it has the particularity that it can function as a generator, producing a photocurrent proportional to irradiance [15]. In literature, various proposed models of the photovoltaic solar cell are presented, such as a single-diode model [10], two-diode model [16].

In this paper, the used model is based on two diodes equivalent circuit, taking into account the series and parallel resistors as shown in Figure 1. This model consists of a photocurrent \( I_{ph} \), two diodes in parallel with the current source, a shunt resistor \( R_{sh} \), and a series resistor \( R_S \).

The exponential equation between the PV cell current and its voltage, is given by the following equation:

\[
I = I_{ph} - I_{s1}(e^{\frac{q(V-Ir_1)}{n_1kT}} - 1) - I_{s2}(e^{\frac{q(V-Ir_2)}{n_2kT}} - 1) - \frac{(V + IR_s)}{R_{sh}}
\]

(1)

Where \( V \) and \( I \) represent the output voltage and current of the PV cell, \( I_{s1} \) and \( I_{s2} \) are diodes saturation currents; \( q \) is coulomb constant, \( K \) is Boltzman's constant, \( T \) is cell temperature (K); \( n_1 \) and \( n_2 \) are P-N junction ideality factor.

In this study, the CS5P-220M module is used, the technical characteristics of the module are presented in the Table 1. The \( P-V \) and \( I-V \) characteristics of the PV module under standard test conditions (STC, i.e., irradiance \( G=1000 \text{ W/m}^2 \) and temperature \( T=25 \text{ C}^\circ \)) are shown in Figure 2. In this figure, the PV module has nonlinear voltage-current characteristics, and there is only one unique operating point for a PV generation system with a maximum output power under constant condition of temperature and irradiance.

![Figure 1. Model of a PV cell with two diodes](image)

![Figure 2. \( P-V \) and \( I-V \) characteristics of a PV module at STC](image)

![Figure 3. \( I-V \) and \( P-V \) characteristics of a PV module with different irradiations and at a constant temperature (\( T=25 \text{ C}^\circ \)).](image)

![Figure 4. \( P-V \) and \( I-V \) characteristics of a PV module with different temperature and at a constant irradiations (\( G=1000 \text{ W/m}^2 \)).](image)
As shown in these figures, the PV power increases with the increasing of irradiance. Thus, the maximum power point (MPP) decreases with the decreases of irradiance. On the other hand, the PV power decreases with the increasing of temperature. Therefore, the MPP increases with the decrease of temperature.

![Figure 3: P–V and I–V characteristics of a PV module under different irradiations and at a constant temperature T= 25 C°](image1)

![Figure 4: I–V and P–V characteristics of a PV module under different temperature and at a constant irradiation G=1000 W/m²](image2)

2.2. Perturb and Observe (P&O) MPPT Technique

The main function of the MPPT techniques is to obtain the optimal operating point of voltage and current to increase the efficiency of the PV system and extract the maximum PV power under variable atmospheric conditions [10]. Perturb and Observe (P&O) is one of the most used MPPT techniques, because of its simplicity, low cost with an acceptable performance [17]. The implementation of this technique requires voltage and current sensors to calculate the PV output power; \(P=I\times V\) and causes a perturbation on the duty cycle \(D\). This duty cycle is updated during each sampling period as a function of the power variation. Figure 5 shows the flowchart of the P&O algorithm, while Figure 6 shows the Simulink block of P&O algorithm.

2.3. DC-DC Boost Converter

The DC-DC boost converter is used to interface between the PVG and the load for optimal system operation. The output voltage of the DC-DC boost converter \(V_{\text{out}}\) and the voltage of the PVG \(V\) are related to the duty cycle \(D\) by the following equation:

\[
\frac{V_{\text{out}}}{V} = \frac{1}{1-D}
\]
3. Shunt Active Power Filter Topology

The proposed system (PVG-SAPF) consists of photovoltaic generator, a DC/DC boost converter connected in parallel with a DC side capacitor, a three-phase four-wire shunt active power filter based on two-level voltage source (VS) inverter, and connected through an inductor to the utility grid at the point of common coupling (PCC) in parallel with three nonlinear loads.

The effectiveness of the proposed PVG-SAPF depends on the technique used for estimating of reference currents and generation of switching pulses. Many conventional time-domain control algorithms are reported in the literature for the extraction of reference currents, in this paper, SRF theory [18-20] is used under unbalanced nonlinear load.

3.1. Synchronous Reference Frame (SRF) Theory

Synchronous reference frame theory is used first for three-phase three-wire active power filter (APF) and gave good results. Then this theory is generalized for three-phase four-wire APF based on the modification of the cross-vector theory of dqo-axes [21, 22]. The three-phase instantaneous nonlinear load currents \(i_{L_a}, i_{L_b} \text{ and } i_{L_c}\) are transformed from the \((a-b-c)\) coordinates into \((\alpha-\beta-0)\) coordinates as follows:

\[
\begin{bmatrix}
    i_d \\
    i_q \\
    i_0 \\
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    0 & \frac{1}{2} & \frac{1}{2} \\
    0 & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
    i_{L_a} \\
    i_{L_b} \\
    i_{L_c} \\
\end{bmatrix}
\]

In this theory the PLL (phase locked loop) is used to generate \(\cos(\theta)\) and \(\sin(\theta)\) from the three-phase voltage source \(v_{sa}, v_{sb} \text{ and } v_{sc}\). Then the cross-vector theory gives:

\[
\begin{bmatrix}
    i_d \\
    i_q \\
    i_{0_{apf}} \\
\end{bmatrix} = \begin{bmatrix}
    0 & \sin(\theta) & -\cos(\theta) \\
    0 & \cos(\theta) & \sin(\theta) \\
    -\cos(\theta) & 0 & 0 \\
    -\sin(\theta) & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
    i_d \\
    i_q \\
    i_{0_{apf}} \\
\end{bmatrix}
\]

The \(i_d\) and \(i_q\) currents include DC and AC values corresponding to the fundamental and harmonic currents respectively;
\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = \begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = \begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
\]

(5)

The DC value of \( i_d \) currents is extracted out using a low pass filter. Then the currents in \( \alpha-\beta-\theta \) by the following equation:

\[
\begin{bmatrix}
i_{\alpha\_ref} \\
i_{\beta\_ref}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & -\cos(\theta) & -\sin(\theta) \\
\sin(\theta) & \cos(\theta) & 0 & 0 \\
-\cos(\theta) & \sin(\theta) & 0 & 0 \\
i_d & i_q & i_d & i_q
\end{bmatrix}
\]

(6)

Then the reference current in the a-b-c coordinates can be obtained as follows:

\[
\begin{bmatrix}
i_{\beta\_\_ref} \\
i_{\phi\_\_ref} \\
i_{\kappa\_\_ref}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & 0 & \frac{1}{\sqrt{2}} \\
-\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} \\
-\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
i_{u\_ref} \\
i_{\alpha\_ref} \\
i_{\beta\_ref}
\end{bmatrix}
\]

(7)

The reference currents are compared with their actual compensating currents in a hysteresis controller to generate the required switching pulses for the SAPF. Figure 7 shows the Simulink block diagram for the SRF theory.

**Figure 7.** SRF Theory under Matlab/Simulink

4. Simulation Results and Discussion

Figure 8 shows the design of the developed PVG-SAPF under Matlab/Simulink software environment. The parameters used for the proposed model are presented in Table 2. The PVG consists of eight series connected PV module from CS5P-220M panel model.
Table 2. The parameters of the proposed PVG-SAPF

| parameters                  | Values                  |
|-----------------------------|-------------------------|
| Voltage rms, frequency      | 220 V, 50 Hz            |
| Line impedance ($R_s$, $L_s$)| 0.5 mΩ, 0.19 µH         |
| Inductance $L_i$            | 0.3 mH                  |
| Capacitor $C_{dc}$          | 4.0 µF                  |
| $V_{dc}$                    | 750 V                   |
| Load1 ($R_1$, $L_1$)        | 6 Ω, 0.012 H            |
| Load2 ($R_2$, $L_2$)        | 4.5 Ω, 0.09 H           |
| Load3 ($R_3$, $L_3$)        | 3.8 Ω, 0.01 H           |

Figure 8. Matlab/Simulink based simulation of the designed PVG-SAPF

Figure 9(a) shows the different variations of irradiance, the P&O algorithm follows rapidly the expected maximum power point within a very short time, and it manages to adjust the duty cycle $D$ very quickly as shown in Figure 9(b). The P&O MPPT algorithm is robust against fast variation in atmospheric conditions, with few oscillations around MPP, and with high efficiency (up to 92%). Figure 10(a) shows the output voltage of the PVG, while Figure 10(b) shows the dc-bus voltage ($V_{dc}$) and its reference ($V_{dc\_ref}$). The results confirm that the system operates very well because the $V_{dc}$ signal follows the reference signal $V_{dc\_ref}$ under variable irradiance.

The simulation results for the PVG-SAPF performing the current compensation and considering the three loads presented in Table 2 are illustrated in Figures 11-16. Without PVG-SAPF, the three nonlinear loads absorb non-sinusoidal currents and the three-phase source currents are distorted, unbalanced and they are not in sync with the corresponding voltages as shown in Figure 11(a). With PVG-SAPF, the PVG-SAPF can afford solar energy from the PVG into the utility grid, it injects at the PCC a current that is identical to the estimated reference current ($i_{abc\_ref}$, see Figure 12(a)), but opposite in phase as shown in Figure 11(b). The monitoring of the PVG-SAPF trajectory of injected currents $i_{abc}$ and reference currents $i_{ref\_abc}$ is constructed with approximately zero error for the SRF theory as shown in Figure 12(b). The PVG-SAPF has imposed sinusoidal waveform source currents as shown in Figure 11(c), as can be observed the source currents are balanced. Moreover, the obtained current and the source voltage are in phase as illustrated in Figure 12(c). Without PVG-SAPF, the form of the neutral current has a maximum value 55 A as shown in Figure 13(a). With PVG-SAPF, the source neutral current is approximately equal to zero as shown in Figure 13(b). Figure 14-16 show the FFT analysis of three-phase source currents ($i_{sa}$, $i_{sb}$, $i_{sc}$) without PVG-SAPF and with PVG-SAPF. The THD’s are given in Table 3. It can be observed that these THD’s values without PVG-SAPF are very high and unacceptable. The THD’s are reduced with PVG-SAPF and SRF theory gives very good results under unbalanced nonlinear loads. The results confirm the good
quality of filtering of the proposed PVG-SAPF, a perfect compensation of reactive power for power factor correction, and also the reduction of the neutral current magnitude.

![Figure 9](image)

**Table 3. THD (%) values after and before filtering**

| Phases | THD% before filtering | THD% after filtering |
|--------|-----------------------|----------------------|
| Phase a | 21.11%                | 2.98%                |
| Phase b | 24.46%                | 2.67%                |
| Phase c | 29.97%                | 2.50%                |

![Figure 10](image)

![Figure 11](image)

![Figure 12](image)

*A Three-Phase Grid-Connected PV System Based on SAPF for Power... (Rachid Belaidi)*
5. Conclusion

In this paper, a combined system of a three-phase four-wire SAPF and PVG is proposed. The PVG-SAPF allows harmonics filtering, reactive power compensation for power factor correction, and load balancing, as well as injecting the issued energy from the PVG into the utility grid. The SRF theory is evaluated under unbalanced nonlinear load using a PVG-SAPF constructed by means of two-level VS inverter. In order to increase the efficiency of maximum power point tracking, an MPPT control based on P&O is implemented in DC/DC converter. The simulation of the proposed system has been carried out using Matlab/Simulink software. The obtained results show that the three-phase source currents have sinusoidal waveform with low THDs with the proposed PVG-SAPF. In addition, these currents are in sync with the corresponding voltages and balanced, which leads to improvement of the power quality. The results confirm the good filtering quality of harmonic currents, the perfect compensation of reactive power for power factor correction and the neutral current magnitude reduction. These
results confirm the effectiveness of proposed PVG-SAPF for the improvement of the power quality under unbalanced non linear load.

References

[1] Park TJ, Jeong GY, Kwon BH. Shunt active filter for reactive power compensation. International Journal of Electronics. 2001; 88: 1257-1269.
[2] Jain SK, Agarwal P, Gupta H. A Dedicated Microcontroller based Fuzzy Controlled Shunt Active Power Filter. Intelligent Automation & Soft Computing. 2005; 11: 33-46.
[3] Srikanth K, Mohan TK, Vishnuvardhan P. Improvement of power quality for microgrid using fuzzy based UPQC controller. Electrical, Electronics, Signals, Communication and Optimization (EESCO), 2015 International Conference on: IEEE. 2015: 1-6.
[4] Akagi H. Modern active filters and traditional passive filters. Bulletin of the Polish Academy of sciences, Technical sciences. 2006; 54.
[5] PitchaiVijaya K, Mahapatra K. Adaptive-fuzzy controller based shunt active filter for power line conditioners. TELKOMNIKA (Telecommunication Computing Electronics and Control). 2013; 9: 203-210.
[6] Amirullah A, Penangsang O, Soeprijanto A. Power Quality Analysis of Integration Photovoltaic Generator to Three Phase Grid under Variable Solar Irradiance Level. TELKOMNIKA (Telecommunication Computing Electronics and Control). 2016; 14: 29-38.
[7] Tali M, Obbadi A, Elfajri A, Errami Y. Passive filter for harmonics mitigation in standalone PV system for non linear load. 2014 International Renewable and Sustainable Energy Conference (IRSEC): IEEE. 2014: 499-504.
[8] Hong YY, Chiu CS, Huang SW. Multi-scenario passive filter planning in factory distribution system by using Markov model and probabilistic Sugeno fuzzy reasoning. Applied Soft Computing. 2016; 41: 352-361.
[9] Mahela OP, Shaik AG. Topological aspects of power quality improvement techniques: A comprehensive overview. Renewable and Sustainable Energy Reviews. 2016; 58: 1129-1142.
[10] Bendib B, Belmilhi H, Krim F. A survey of the most used MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems. Renewable and Sustainable Energy Reviews. 2015; 45: 637-648.
[11] Libo W, Zhengming Z, Jianzheng L. A single-stage three-phase grid-connected photovoltaic system with modified MPPT method and reactive power compensation. IEEE Transactions on Energy Conversion. 2007; 22: 881-886.
[12] Alik R, Jusoh A, Sutikno T. A Review on Perturb and Observe Maximum Power Point Tracking in Photovoltaic System. TELKOMNIKA (Telecommunication Computing Electronics and Control). 2015; 13: 745-751.
[13] Safari A, Mekhilef S. Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter. IEEE Transactions on Industrial Electronics. 2011; 58: 1154-1161.
[14] Rezk H, Eltamaly AM. A comprehensive comparison of different MPPT techniques for photovoltaic systems. Solar Energy. 2015; 112: 1-11.
[15] Salmi T, Bouguendia M, Gastli A, Masmoudi A. Matlab/simulink based modeling of photovoltaic cell. International Journal of Renewable Energy Research (IJRER). 2012; 2: 213-218.
[16] Boumaraaf H, Talha A, Bouhali O. A three-phase NPC grid-connected inverter for photovoltaic applications using neural network MPPT. Renewable and Sustainable Energy Reviews. 2015; 49: 1171-1179.
[17] Reisi AR, Moradi MH, Jamsab S. Classification and comparison of maximum power point tracking techniques for photovoltaic system: a review. Renewable and Sustainable Energy Reviews. 2013; 19: 433-443.
[18] Mahela OP, Shaik AG. Power quality improvement in distribution network using DSTATCOM with battery energy storage system. International Journal of Electrical Power & Energy Systems. 2016; 83: 229-240.
[19] Belaidi R, Fathi M, Larafi MM, Kaci GM, Haddouche A. Power quality improvement based on shunt active power filter connected to a photovoltaic array. 2015 3rd International Renewable and Sustainable Energy Conference (IRSEC): IEEE. 2015: 1-6.
[20] Sundaram E, Venugopal M. On design and implementation of three phase three level shunt active power filter for harmonic reduction using synchronous reference frame theory. International Journal of Electrical Power & Energy Systems. 2016; 81: 40-47.
[21] Benhabib M, Saadate S. New control approach for four-wire active power filter based on the use of synchronous reference frame. Electric Power Systems Research. 2005; 73: 353-362.
[22] Chebabhi A, Fellah M, Kessal A, Benkhoris M. Comparative study of reference currents and DC bus voltage control for Three-Phase Four-Wire Four-Leg SAPF to compensate harmonics and reactive power with 3D SVM. ISA transactions. 2015; 57: 360-372.