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A multi-function grid-connected PV system based on fuzzy logic controller for power quality improvement

***Abstract**. This paper presents a multi-function grid-connected photovoltaic (PV) system based on shunt active power filter (APF). The proposed system is used to inject PV power into the utility grid to solve the power quality issues such as harmonic currents and poor power factor. The SRF theory is applied for reference currents extracting, while fuzzy logic controller is proposed for controlling the dc capacitor voltage and the harmonic currents. The P&O MPPT is used to extract the maximum PV power from the photovoltaic generator (PVG), hence increasing the system efficiency.*

Streszczenie.** W artykule zaprezentowano podłączony do sieci system fotowoltaiczny bazujący na bocznikowym filtrze aktywnym. System umożliwia poprawę parametrów jakości energii w sieci. System logiki rozmytej jest użyty do sterowania napięciem DC. **Wielofunkcyjny podłaczony do sieci system fotowoltaiczny z wykorzystniem logiki rozmytej do sterowania jakościa energii

Keywords: PV system, MPPT, Fuzzy Logic controller, power quality.
Słowa kluczowe: system fotowoltaiczny, logika rozmyta, jakość energii.

Introduction

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, which became a field of interest for many researches in the last decades [1, 2]. In order to improve the power quality, various traditional passive filter and modern active filter have been developed. Unlike the passive filters, the active filters have many advantages and functions such as harmonic filtering, reactive power compensation for power factor correction,.....etc [3-5]. The controller is one of the main parts of the APF. The conventional PI controller requires precise linear mathematical model of the system, which is difficult to obtain under parameter variations, nonlinearity, and load disturbances [6]. In last decades, Fuzzy logic (FL) controller has been successfully applied to many control problems, as they need no accurate mathematical models of the uncertain nonlinear systems under control [7]. FL can be considered as logic models that use such (If...Then) rules to establish qualitative relationships between model inputs/outputs.

On the other hand, the maximum output power from a PV system largely varies according to the changing atmospheric conditions [8, 9]. For more efficiency, it is very important to achieve the maximum power from PVG, by finding the optimal operating point of voltage and current under varying meteorological conditions. 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) and incremental conductance (IncCond) methods.

This paper proposes a combined system of a three-phase shunt APF, and photovoltaic generator (PVG) to solve the power quality problems by filtering harmonic currents generated by nonlinear load and compensating reactive power for power factor correction. The synchronous reference frame (SRF) theory is used to extracted the reference compensating currents while fuzzy logic controller is proposed for controlling the dc-side capacitor voltage and the harmonic currents of the PVG-APF (PVG and shunt APF). The P&O MPPT is used to increase the efficiency of the PVG and extract the maximum PV power from the PVG. The proposed PVG-APF is validated through numerical simulations using Matlab/Simulink environment.

Photovoltaic System modelling and characteristics

PV Cell equivalent circuit

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. In literature, various proposed models of the photovoltaic solar cell are presented, such as a single-diode model [8, 10], two-diode model [11]. In this paper, the used model is based on a single-diode equivalent circuit taking into account the series and parallel resistors as shown in Fig.1 this model consists of a photo-current I_{ph}, a diode in parallel with the current source, a shunt resistor R_{Sh}, and a series resistor R_S.

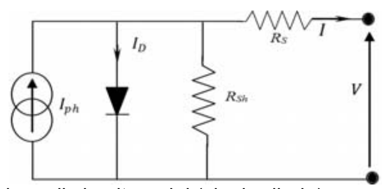

Fig. 1. PV Solar cell circuit model (single-diode).

The exponential equation which expresses the relationship between the PV cell current and its voltage, is given by the following equation [10, 12].

$$I = I_{ph} - I_S\left[\exp\left(\frac{q(V+IR_S)}{nKT} \quad -1\right)\right] - \frac{V+IR_S}{R_{Sh}} \tag{1}$$

where, I_S is the diode reverse saturation current, n is diode ideality factor, I is the cell output current, V is module output voltage, K is Boltzmann constant, T is module temperature and q is electron charge.

The PV cell produced only a few watts of power, since this power is insufficient to supply most devices, the voltage and current must be increased and therefore increasing the power. To increase the voltage, the cells are connected in series, and in parallel to increase the current. The combination of these cells in series and in parallel is called PV module.

In this study, the CS5P-220M module is used. The technical characteristics of the module are presented in the Table.1.

The *I-V* and *P-V* characteristics of the PV module under standard test conditions (STC, i.e., irradiance G =1000 W/m^2 and temperature T=25C°) are shown in Fig.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.

Table.1 Electrical characteristics of the CS5P-220M PV module.

Electrical characteristics	Symbols	Values
Maximum power at STC	P_{mpp}	219.72 W
Maximum power voltage	V_{mpp}	48.315 V
Maximum power current	I_{mpp}	4.5475 A
Open circuit voltage	V_{oc}	59.261 V
Short circuit current	I_{sc}	5.0926 A
Temperature coefficient of I_{sc}	α_{sc}	5.532 m A/C°
Temperature coefficient of V_{oc}	β_{oc}	-0.1110 V/C°

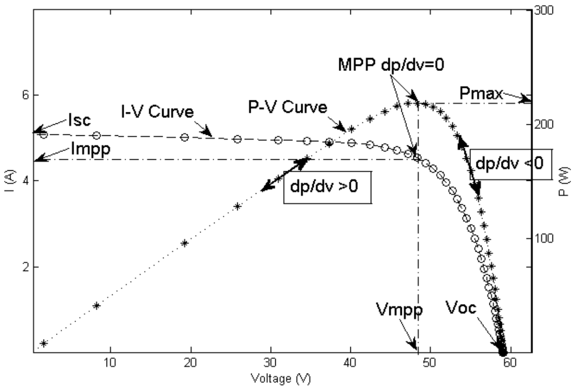

Fig. 2. *I–V* and *P–V* characteristics of a PV module at STC.

Perturb and observe (P&Q) MPPT technique

Perturb and Observe (P&O) is one of the most used MPPT techniques, because of its simplicity, low cost with an acceptable performance [13, 14]. The implementation of this technique requires voltage and current sensors to calculate the PV output power; ($P=I*V$) 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. Fig. 3 shows the flowchart of the P&O algorithm.

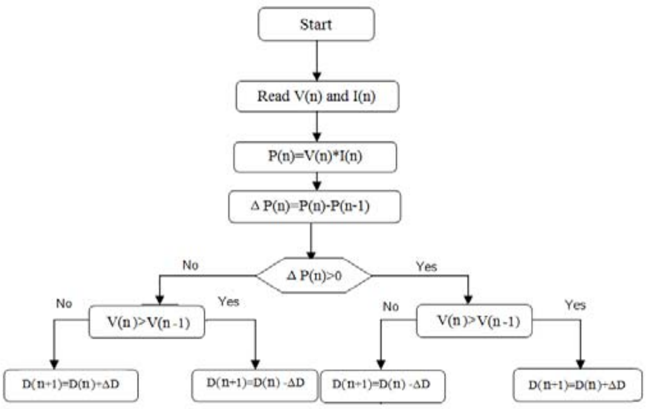

Fig 3. Flowchart of the P&O algorithm.

DC-DC boost converter

The DC-DC boost converter (Fig. 4) is used to interface between the PV array and the load for optimal system operation. The output voltage of the DC-DC boost converter (V_{out}) and the voltage of the PV array (V) are related to the duty cycle D by the following equation:

(2) $$\frac{V_{out}}{V}=\frac{1}{1-D}$$

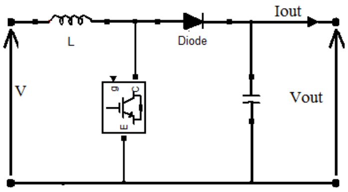

Fig. 4. DC-DC Boost converter circuit diagram.

Shunt active power filter topology

Fig. 5 shows the three-phase shunt APF topology based on two-level voltage source (VS) inverter fed by PVG and connected through an inductor to the utility grid at the point of common coupling (PCC), a DC–DC boost converter associated with P&O MPPT control, a dc side capacitor, a diode rectifier along with an RC load. The effectiveness of the shunt APF depends on the technique used for estim-ating of reference currents and generating 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 is used to extracted the reference compensating currents.

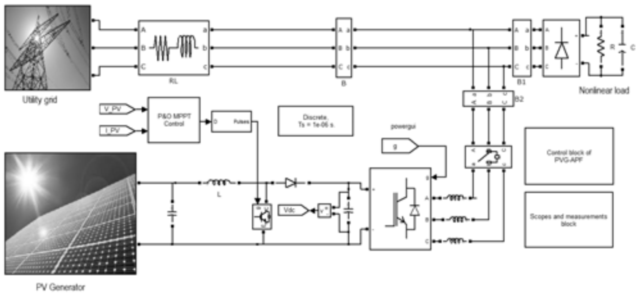

Fig. 5. Shunt APF fed by PVG configuration.

Synchronous reference frame theory

In the SRF theory [15-18], the three-phase instantaneous nonlinear load currents (i_{La}, i_{Lb} and i_{Lc}) are transformed from the *a-b-c* coordinates into *α-β* coordinates by the following equation;

(3) $$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\cdot\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

Then the transformation from α-β coordinates to d–q (direct, quadrature) coordinates is given by the following equation:

(4) $$\begin{bmatrix} i_d \\ i_q \end{bmatrix}=\begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}\cdot\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

The angle (θ) is obtained by using a PLL (Phase Locked Loop) from the three-phase voltage source v_{sa}, v_{sb} and v_{sc}. Each currents (i_d and i_q) includes an average value (DC component) corresponding to the fundamental current and oscillating value (AC component) corresponding to the harmonics current.

(5) $$\begin{cases} i_d=\bar{i}_d+\hat{i}_d \\ i_q=\bar{i}_q+\hat{i}_q \end{cases}$$

The DC value of i_d current is extracted out using a low pass filter, whereas the AC value of d and q are created from the harmonics component of the nonlinear load current.
Then the transformation from *d–q* coordinates to *α-β* coordinates is given by the following equation;

$$\begin{bmatrix} i_{\alpha\_ref} \\ i_{\beta\_ref} \end{bmatrix} = \begin{bmatrix} \cos(\hat{\theta}) & -\sin(\hat{\theta}) \\ \sin(\hat{\theta}) & \cos(\hat{\theta}) \end{bmatrix} . \begin{bmatrix} \hat{i}_d \\ i_q \end{bmatrix} \tag{6}$$

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

$$\begin{bmatrix} I_{a\_ref} \\ I_{b\_ref} \\ I_{c\_ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha\_ref} \\ i_{\beta\_ref} \end{bmatrix} \tag{7}$$

Finily the Simulink block diagram for the SRF theory is shown in Fig. 06.

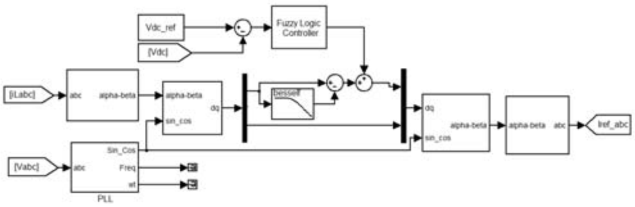

Fig 6. Simulink block diagram for SRF theory.

Fuzzy Logic Controller

Fuzzy logic (FL) control has been increasingly successful since the end of last century, particularly in the field of power electronics and industrial control. This logic realizes a relationship between the digital and linguistic variables through memberships functions [19]. In order to improve the performance of the proposed PVG-APF, FL controller is proposed for controlling the dc capacitor voltage and the harmonic currents. In this paper, the Mamdani type of FL controller is used for the APF control.

Table 2. Fuzzy control rule of the dc voltage.

E\ΔE	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

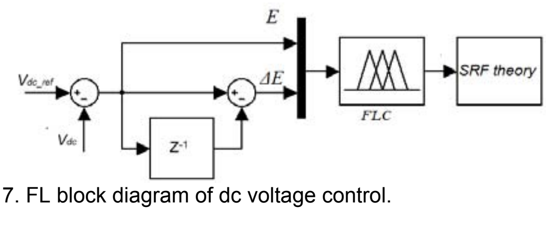

Fig 7. FL block diagram of dc voltage control.

FL controller-based dc Voltage

The FL controller of the dc capacitor voltage has tow inputs: the error (the difference between the reference voltage and the actual dc voltage $E=V_{dc\_ref} - V_{dc}$) and the variation of this error *ΔE*. These input variables are processed through the FL controller and then it gives the output as shown in Fig. 7. The used membership function for the inputs and output variables is expressed by linguistic variables such as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big). The fuzzy rules are summarized as following:

1- If (E is NB) and (ΔE is NB) then (D is NB)
2- If (E is NM) and (ΔE is NB) then (D is NB)
.
and so forth.

The rule matrix of the dc voltage is shown in Table 2.

FL controller-based harmonic currents

Fig. 8 shows the FL of harmonic currents control, the input variables are the error (the difference between reference current and the injected current $E= i_{ref} - i_f$) and its variation (*ΔE*), while the output signal is compared with the carrier signal to generate the gating signals for the switching VS inverter. Table. 2 shows the rule table of FL controller.

Table. 3. Fuzzy control rule table of current.

E\ΔE	NB	NS	ZO	PS	PB
NB	NB	NB	NS	NS	ZO
NS	NB	NS	NS	ZO	PS
ZO	NS	NS	ZO	PS	PS
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PS	PB	PB

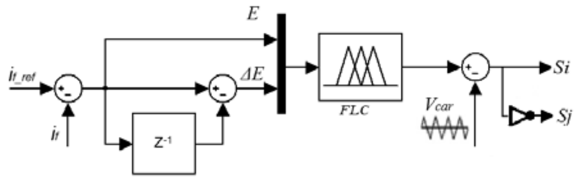

Fig 8. FL block diagram of currents control.

Simulation results and discussion

In this section, the proposed system is validated through numerical simulations using Matlab/Simulink environment. The PVG consists of eight series connected PV module from CS5P-220M panel model. The parameters used for the proposed PVG-APV system are presented in Table 4.

Table. 4: The parameters of the proposed PVG-APF.

parameters		Values
Power supply	Voltage *rms, frequency*	*220 V, 50 Hz*
	Line impedance *(R_s, L_s)*	*0.5 mΩ, 0.19µH*
Shunt APF	Inductance L_f	*0.3 mH*
DC capacitor	Capacitor C_{dc}	*4 mF*
DC voltage	V_{dc}	*750 V*
Nonlinear load	Load1 *(R_L, C_L)*	*2 Ω, 4mF*

Fig. 9.a shows the output voltage of the PVG, the duty cycle is initialized in the value of *D*=0.7. It can be observed that the P&O algorithm fallows rapidly the expected MPP within a very short time, and it manages to adjust the duty cycle D very quickly as shown in Fig. 9.b.

The nonlinear load absorb non-sinusoidal currents as shown in Fig. 10.a and the three-phase source currents are distorted and not in sync with the corresponding voltages. The PVG-APF can afford solar energy from the PVG into the utility grid, it injects at the PCC currents that are identical to the estimated reference currents (i_{fabc_ref} see Fig. 10.b), but opposite in corresponding phases as shown in Fig. 10.c. The monitoring of the PVG-APF trajectory of injected current and reference current is constructed with approximately zero error as shown in Fig. 10.d. The PVG-

APF has imposed sinusoidal waveform source currents as shown in Fig. 10.e. As can be observed the obtained source currents are in sync with the corresponding voltages as illustrated in Fig. 10.f.

Fig. 11. shows the dc voltage (V_{dc}) and its reference (V_{dc_ref}). This figure confirm that the FL controller operates very efficiently because the V_{dc} signal follows its reference signal V_{dc_ref} with very small oscillations, wich confirmed the effictivness of the PVG-APF with the FL controller.

Fig. 12 shows the FFT analysis of source current (phase_a (i_{sa})). It can be observed that the total harmonic distortion (THD) is reduced from 40.25% (before compensation) to 2.61% (after compensation) within the limit specified in the IEEE 519-1922.

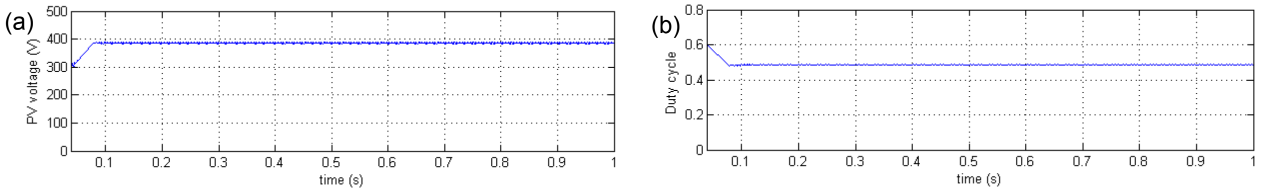

Fig. 9. (a) PV array voltage (V) and (b) duty cycle *D*.

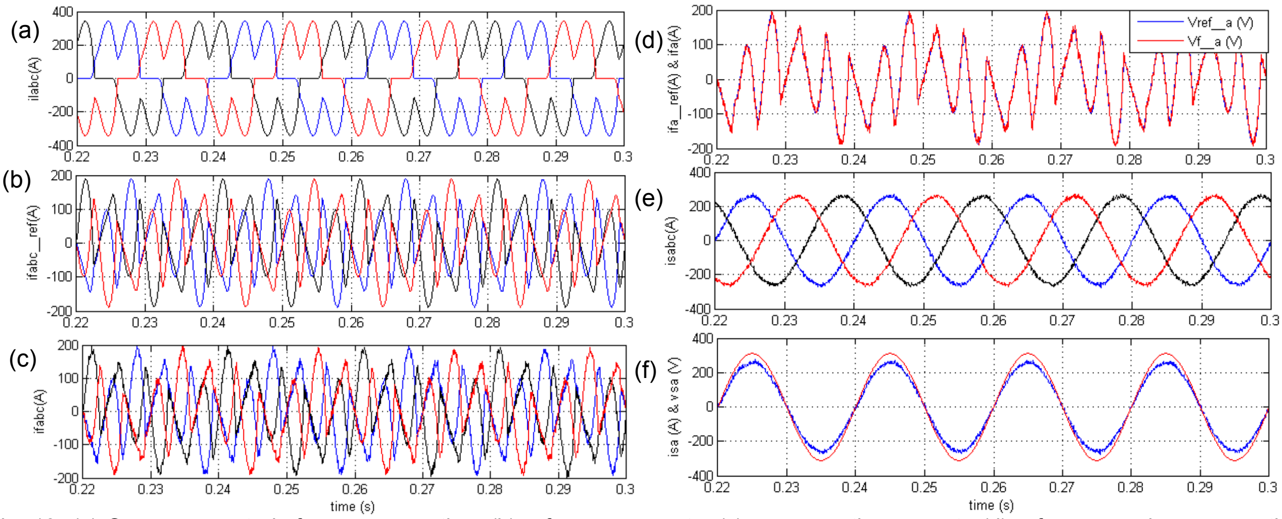

Fig. 10. (a) Source currents before compensation, (b) reference currents, (c) compensation currents (d) reference and com-pensation currents (phase a), (e) source currents after compensation, (f) power factor correction after compensation.

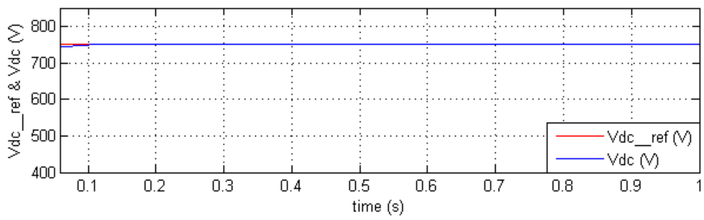

Fig. 11. (a) DC-link voltage.

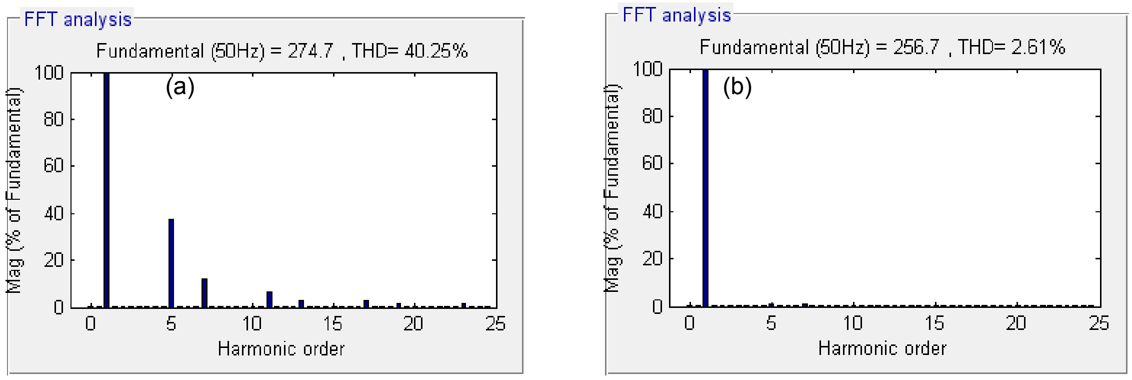

Fig. 12. FFT analysis of source current: (a) before compensation and (b) after compensation.

Conclusion

In this paper, a multi-function grid-connected PV system based on three-phase shunt APF is proposed to improve the power quality. The PVG-APF system can inject the issued energy from the PV array into the utility grid to solve the power quality problems by filtering harmonic currents and compensating reactive power for power factor correction. The SRF theory and fuzzy logic controller are evaluated under nonlinear load using shunt APF constructed by means of two-level VS inverter. A maximum power point tracking (MPPT) based on P&O is implemented in DC/DC boost converter to extract the maximum power from PV generator. The simulation of the proposed system has been carried out using

Matlab/Simulink environment. The obtained results show that the three-phase source currents have sinusoidal waveforms with low THD within the limit specified in the IEEE 519-1922. In addition, these currents are in sync with the corresponding voltages, which leads to improvement of the power quality. The results confirm the good filtering quality of the harmonic currents and the perfect compensation of reactive power for power factor correction. These results confirm the effectiveness of proposed PVG-APF for the improvement of the power quality.

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