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COMBINED OPERATION OF PHOTOVOLTAIC AND ACTIVE POWER FILTER SYSTEM CONNECTED TO NONLINEAR LOAD

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Key words: Photovoltaic system (PV), Active power filter (APF), Grid connected, Instantaneous power theory, Maximum power point tracking (MMPT).

Currently, photovoltaic inverters are used in electricity production. They must therefore meet the requirements and needs of the electricity grid. They are not only used to provide active and reactive power, but also contribute to other tasks such as power quality, frequency and voltage regulation. This paper presents a photovoltaic system connected to the grid via an inverter combined with a parallel active filter. The model aims to provide active power to the grid as well as reactive power with a higher power quality. Thus, this model can compensate for harmonics caused by the grid or non-linear loads. The command of this model requires a robust and reliable control system to perform the three above-mentioned tasks (quality, frequency and voltage regulation). Consequently, the instantaneous power method was chosen for this model. This system was simulated in the Matlab/Simulink program to validate its function.

1. INTRODUCTION

In recent years, renewable energy sources (RES) have required more auxiliary services on the grid such as conventional power stations. In addition, these renewable energy sources must provide clean energy to the grid with minimum total harmonic distortion (THD).

Photovoltaic power plants are currently being developed in global electricity generation through the development of solar panels and PV inverters for the main equipment [1]. Unfortunately, photovoltaic systems only operate during the day and they are switched off during the night. Therefore, they will not provide continuous active power to the grid and their availability rate is low compared to the conventional power plant [2].

Several studies [3–26] have been carried out to improve the quality of the PV energy system. These studies are based on the combination of an active filter with photovoltaic systems to inject active power with low levels of total harmonic distortion.

The inverter is the key equipment in a photovoltaic system because it can control and provide several options such as active and reactive power supply [9]. The PV system can also contribute to improve power quality, voltage and frequency regulation [6]. In addition, its main role is to transform direct current (dc) energy into (ac) to adapt the PV parameters to the grid [10].

Two types of inverters are commonly used in the PV system, the voltage source inverter (VSI) and the current source inverter (CSI). The first converter VSI needs dc link capacitor to generate a constant dc voltage and requires an ac filter inductor to generate ac voltage.

In this work, a voltage source inverter (VSI) is used instead of the current source inverter (CSI) to provide reactive power supply [7]. To perform the filtration function, the PV inverter must inject the opposite current to compensate for the non-linear current [11].This function also requires a source to supply the voltage source inverter. Two condensers dc are used in the proposed system [12]. The filter control must take into account the dc voltage control.

When a photovoltaic system becomes unavailable at night or during low illumination days, the installation remains functional and compensates for grid harmonics [2]. This is considered as another advantage of the proposed model. Several methods have been used to control PV inverters [13–15]. The majority of these methods can inject active and reactive power into the grid, with low or high harmonics.

This paper presents an analysis and a simulation of a grid connected PV system with an active power filter (APF). The advantage of this topology is that it operates with one voltage source inverter to control active and reactive power and it compensates for harmonics, unlike the conventional topologies that need two inverters for this function. The control of the proposed system is based on the instantaneous power theory applied to this system.

The reminder of the paper is organized as follows: Section 2 describes the proposed model and the equipment. Section 3 introduces the controller used in the model. The results are presented in Section 4, while Section 5 draws conclusions and presents some future work.

2. SYSTEM DESCRIPTION

The system consists of a photovoltaic array, a capacitor, a boost converter with a maximum power point tracker (MPPT), an input dc capacitor, a voltage source inverter (VSI) and an inductive filter (Fig. 1). The global system is connected to the grid and the nonlinear load. In addition, it uses an alternative solution with a proportional resonant controller [8]. With an infinite gain at the resonant frequency, the proportional resonant (PR) controller can achieve high performance both in the elimination of steady-state errors in the stationary frame and in the minimization of load current distortion.

The simple model of a PV cell includes a dc power source I_L, a bypass diode, a shunt resistance R_{sh} and a series resistance R_s (Fig. 2) [10]. Two parameters influence the dc current, the ambient temperature T_a and the solar irradiation G_a. The mathematical model of the

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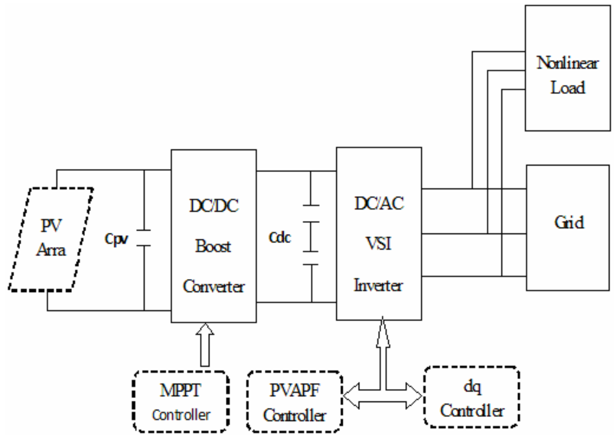

Fig. 1 – The proposed system model.

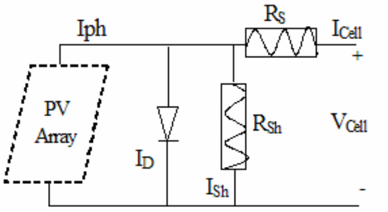

Fig. 2 – Equivalent circuit of a PV cell.

photovoltaic cell is given by equation (1). Many PV cells are connected in parallel or in series to produce a photovoltaic module.

$$I = I_{pv} - I_0 \left[\exp\left(\frac{q(V + R_s.I)}{N_s K.T_a} \right) - 1 \right] - \frac{V + R_s.I}{R_{sh}} \ , \qquad (1)$$

where

- I_{pv} - PV current, I_0 - diode saturation current;
- N_s - number of series-connected cells;
- k - Boltzmann constant (1.3806503 × 10^{-23} J/K);
- T_a (Kelvin) - temperature of the p-n junction of the diode;
- q (1.60217646 × 10^{-19} C) is the electron charge;
- R_s and R_{sh} are the equivalent series and shunt resistances of the module.

To achieve the desired power, several photovoltaic modules are connected in series N_{ss} and parallel N_{pp} to form a PV array (2) and (3).

$$I = I_{pv} N_{pp} - I_0 N_{pp} \left[\exp\left(\frac{q\left(V + R_s.\left(N_{ss}/N_{pp}\right)I\right)}{N_s K.T_a} \right) - 1 \right] - \frac{V + R_s.\left(N_{ss}/N_{pp}\right)I}{R_{sh}.\left(N_{ss}/N_{pp}\right)}, \qquad (2)$$

$$V = N_s.N_{ss}.V_{cell}\ , \quad P_{pv} = I.V \ . \qquad (3)$$

3. PROPOSED CONTROLLERS

In this work, two controllers were used to manage the PV inverter [11]. The first one was the dq current; its role is to inject only an active and reactive power from the PV array. The second one was a photovoltaic active power filter that was used to compensate for harmonics and reactive power in addition to the first controller [17]. The utility of each controller was compared in the simulation section.

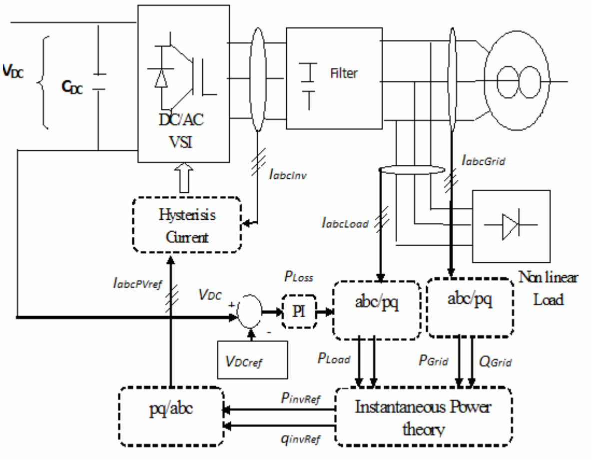

Fig. 3 – Control block diagram of the proposed system.

The PV inverter is a three-phase voltage source inverter compound type: insulated gate bipolar transistor (IGBT) semiconductor switch; it has a better efficiency and a fast dynamic response. The voltage source inverter acts on the IGBT switches to transit the active and reactive power [26].

In this mode, the active power filter function is integrated with the voltage source current inverter to provide maximum power generated by the PV system. It compensates for harmonics and reactive power [1]. The input variables of the controller's active photovoltaic power filter are the active output power of photovoltaic arrays P_{PV}, the dc input voltage V_{dc}, the main voltages of the grid $V_{abcGrid}$, the output current of the PV inverter I_{abcInv} and the load currents $I_{abcLoad}$. The p-q theory is used to control the active and reactive power. Figure 3 shows a simplified diagram of the controller bloc of this system [21].

In this mode, the control strategy of this system must have two abilities. The first is the dc voltage regulation to balance the power between the PV units, grid and the load [19]. The second one is the ability to produce the reference current to generate the harmonics and reactive power compensation.

The instantaneous reactive power theory [20] was used to generate the reference current [11]. This method is based on voltage transformation and current variables to the αβ coordinate based on (4):

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \left[\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \right] \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (4)$$

The instantaneous active and reactive power [6] can be calculated on α β coordinates using (5):

$$\begin{aligned} p(t) &= v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \\ q(t) &= v_\beta \cdot i_\alpha + v_\alpha \cdot i_\beta \end{aligned} . \qquad (5)$$

In terms of instantaneous power [18], the currents value i_α and i_β can be written as follows:

$$\begin{bmatrix} i_{\alpha Inv-ref} \\ i_{\beta Inv-ref} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p(t) \\ q(t) \end{bmatrix} , \qquad (6)$$

where, p and q can be considered as the sum of dc and ac components using (7) :

$$\begin{cases} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{cases}, \qquad (7)$$

where

- $\bar{p}$ and $\tilde{p}$ are dc and ac components of instantaneous active power;
- $\bar{q}$ and $\tilde{q}$ are dc and ac components of instantaneous reactive power.

A grid reference current system must involve $\tilde{p}$, $\bar{q}$ and $\tilde{q}$ and supply the utility with clean energy without harmonics and eliminate all harmonics caused by the non-linear load. In addition, the control system must provide the grid with the maximum active power produced by the PV system. The last task has the role of the maximum power point tracker (MPPT) control.

To perform both functions, the reference currents must be calculated with the coordinates α and β. Equation (5) can be rewritten using (8):

$$\begin{bmatrix} i_{\alpha Inv-ref} \\ i_{\beta Inv-ref} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_{Inv-ref} \\ q_{Inv-ref} \end{bmatrix}, \qquad (8)$$

where $i_{\alpha Inv-ref}$ and $i_{\beta Inv-ref}$ are reference currents and v_α and v_β are the grid voltage of the system at α β.

$$P_{PV_{ref}} = P_{load} - \bar{P}_{grid} + \bar{P}_{loss}, \qquad (9)$$

$$q_{Inv-ref} = q_{load} - q_{grid} . \qquad (10)$$

Finally, to control the switches of the voltage source inverter, the above equations must be transformed into the *abc* system that coordinates as follows:

$$\begin{bmatrix} i_{aPVref} \\ i_{bPVref} \\ i_{cPVref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha ref} \\ i_{\beta ref} \end{bmatrix}. \qquad (11)$$

4. RESULTS AND DISCUSSION

The system's performance was tested by simulating the dq-current and photovoltaic active power filter (PVAPF) modes in Matlab/Simulink. The objective was to show the benefits and advantages of the combined system. A three phase diode bridge rectifier was implemented as a non-linear load to generate current harmonics in the system. Table 1 presents the system parameters used in this study.

The system operated in dq current mode during the first period (0 to 0.1 µs) and as a photovoltaic active power filter (PVAPF) function during the last second (0.1 µs to 0.2 µs). The photovoltaic model used in this work is the First Solar FS -272.

Figure 4 shows that the PV unit can produce 13 kW during dq current function, but when the photovoltaic power filter mode is activated, the active power decrease at 10 kW to supply the power necessary for the APF function. Therefore, this function cannot be use during the day because the priority is to inject the active power to ensure the stability and balance of the grid. The APF function can only be used according to the request of grid dispatcher or at night to compensate for harmonics and reactive power.

Table 1

System parameters

PV array	Maximum power output $P_{\max}$ Output current rating I_{pv} Output voltage rating V_{pv}	13000 kW 35 A 368 V
Dc/ac voltage source inverter	Output capacitor C_{pv} Dc link capacitor Dc link voltage *L* filter *R* filter	78.6 µF 154.69 µF 425 V 5 mH 10 Ω
Non-linear load	*R* non-linear Three-phase bridge rectifier	10 Ω
Grid	Voltage rms Frequency	220 V 50 Hz

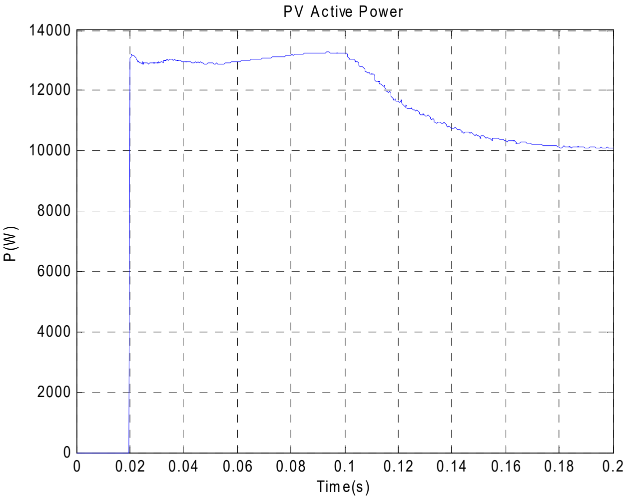

Fig. 4 – Variation of the PV output power.

On the other hand, the photovoltaic substation is still occupied by the MPPT controller to extract the maximum power from the PV array, thus, it is not logical to use the active power for other tasks. In this case, the active power must be retained to supply only the grid and the load

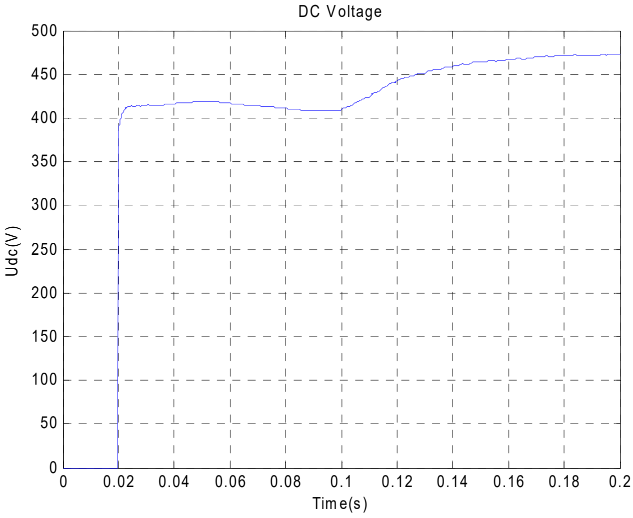

Fig. 5 – Input dc voltage of PV inverter.

because the price of kW and equipment are expensive. Therefore the dispatcher's grid promotes the renewable energy compared to classical energy. Figure 5 shows the variation of dc voltage.

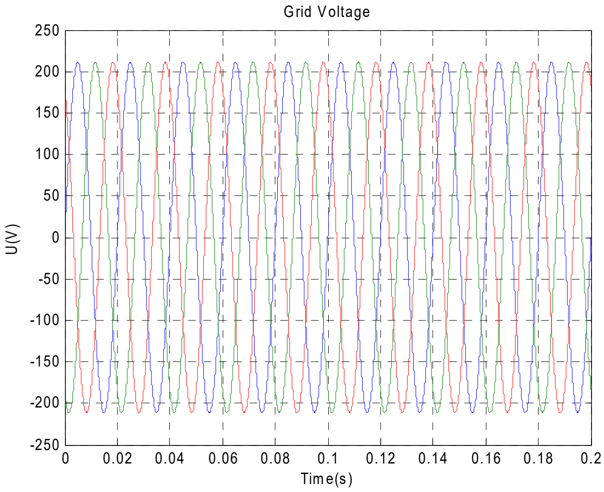

Fig.6. a –Grid supplied voltage waveform.

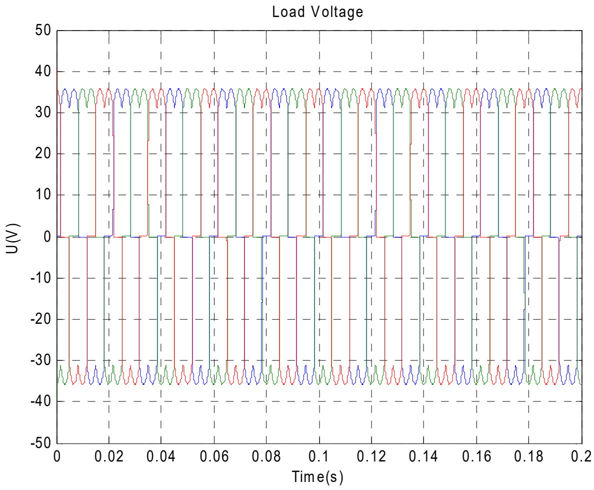

Fig. 6. b – Load voltage waveform.

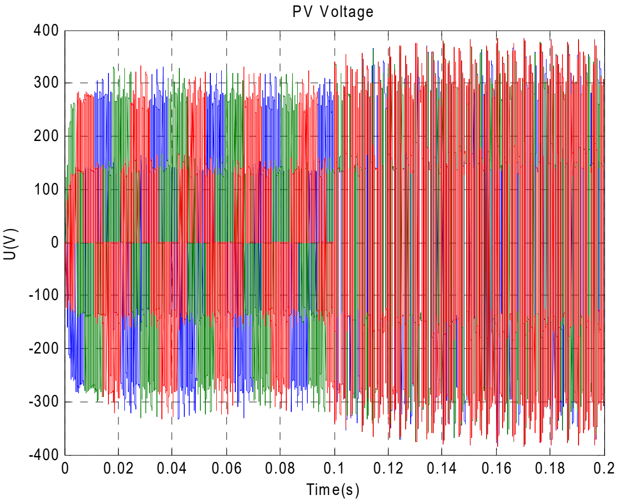

Fig. 6.c – PV voltage waveform.

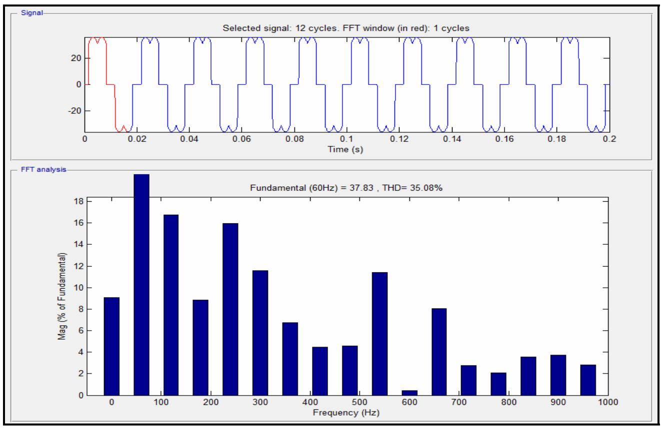

Fig. 7. a – Load current waveform with fast Fourier transform (FFT) analysis tool.

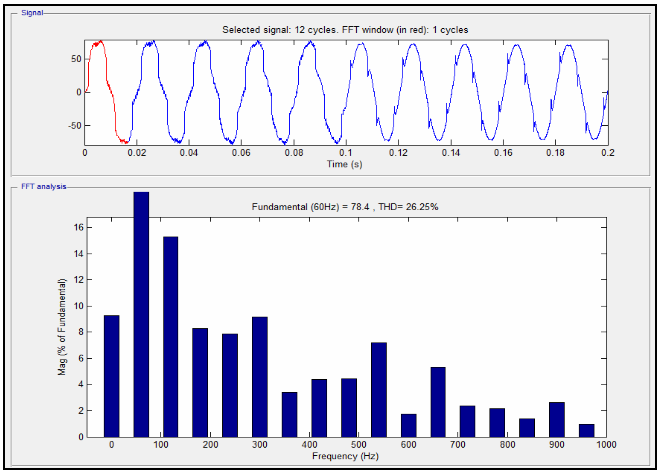

Fig. 7. b – Grid current waveform with FFT analysis tool.

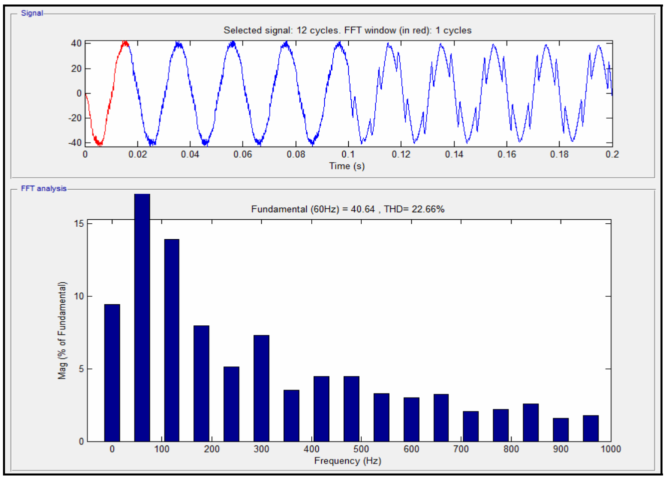

Fig. 7. c – PV supplied current waveform with FFT analysis tool.

Figures 6 and 7 show the load, utility, PV voltage and current waveform. It can be observed that the PV inverter injects the compensating current into the grid system; this current overlaps the load current to improve the grid current.

In addition, Fig. 6 shows that the grid current waveforms are in bad shape due to the nature of the load that generates harmonics in the grid. From t = 0.1 µs, the photovoltaic active power filter controller is activated and it begins to reduce the harmonics.

Figure 7 also indicates the fast Fourier transform (FFT) analysis tool for each current. The total harmonic distortion (THD) of the load current is 34.08 % and it is higher than the utility. PV is equal to 26.25 % and 22.66 %, respectively.

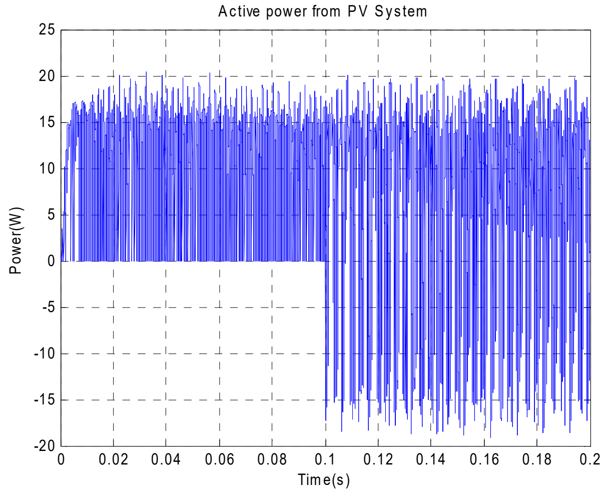

Fig. 8. a – Active power from PV unit.

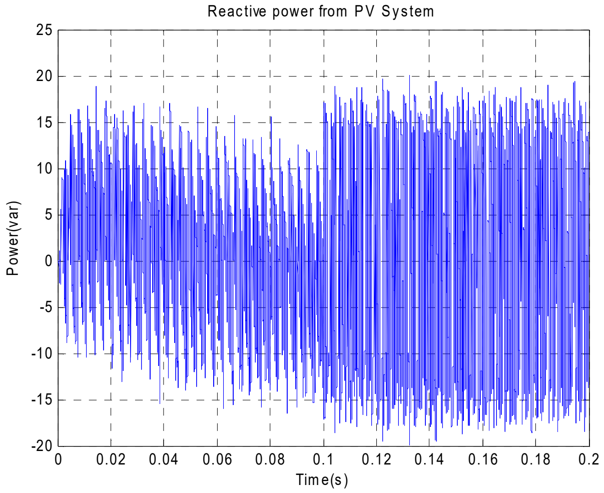

Fig. 8. b – Reactive power from PV unit.

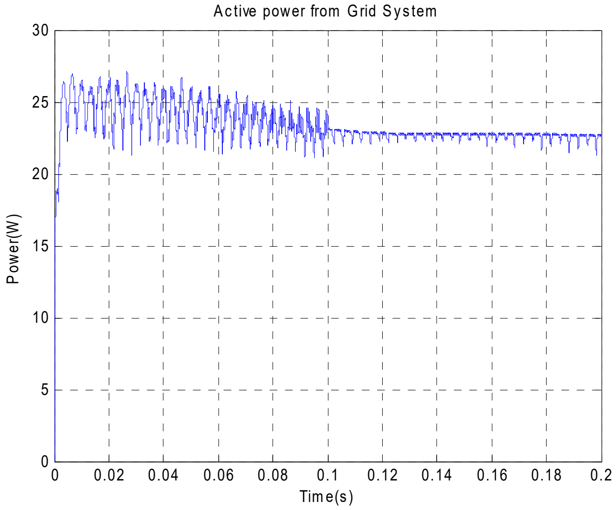

Fig. 9. a – Active power from utility.

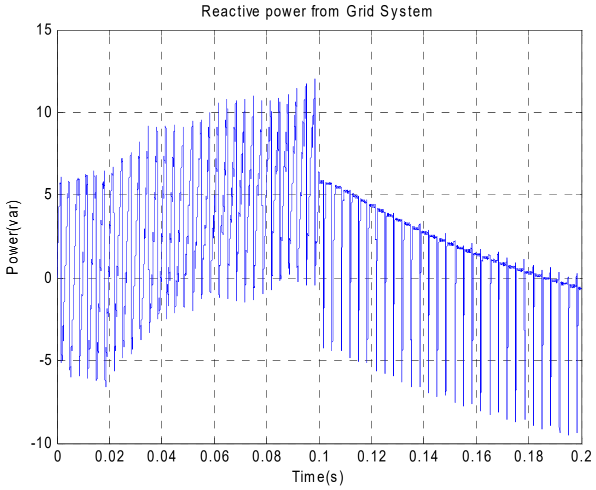

Fig. 9. b – Reactive power from utility.

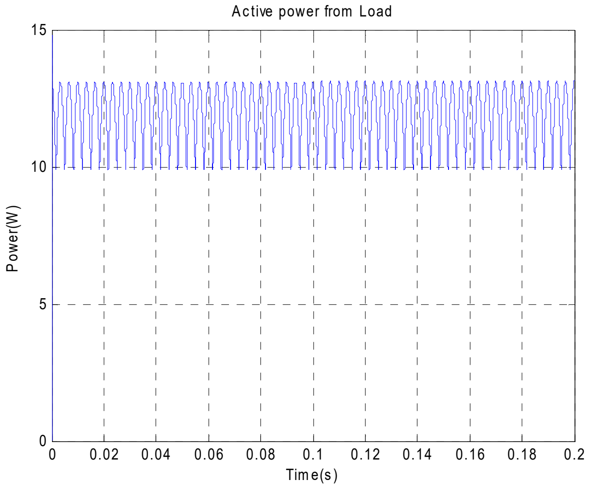

Fig. 10. a – Active power from load.

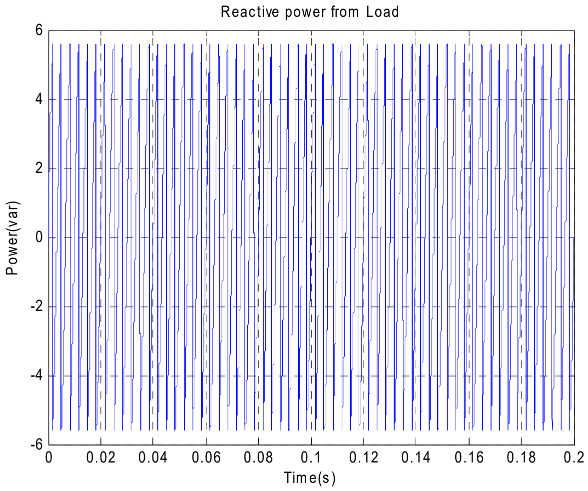

Fig. 10. b – Reactive power from load.

The reactive power from the PV inverter is required to compensate the reactive power from the grid, as shown in Fig. 8. From 0.1 µs, the PV system provides the active and reactive power. In this case, a part of the power is consumed by the dc capacitor for the APF function. Figure 9 shows that the reactive power is fully compensated by the APF controller PV.

5. **CONCLUSION**

This paper presented the combination of a grid-connected PV system connected with a parallel active filter. The proposed system aimed to provide more options for a photovoltaic inverter.

In recent years, the photovoltaic inverter has undergone a major evolution and has become more attractive in the energy system. Therefore, the combined system can provide active and reactive power and at the same time it compensates for harmonics and reactive power generated by the nonlinear load.

Based on the simulations, it can be noted that the photovoltaic active power filter (PVAPF) controller is able to compensate for harmonics and reactive power compared to the dq-current controller, which can only inject active and reactive power into the grid.

The control strategy based on the instantaneous p-q power theory was used in this system to control the voltage source inverter. The results of the Matlab simulation demonstrated that the proposed control is more feasible and effective.

Consequently, other tasks for the PV inverter, such as voltage and frequency regulation, can be introduced in future work.

NOMENCLATURE

RnE : renewable energy,
THD : total harmonic distortion,
dc : direct current,
CSI : current source inverter,
VSI : voltage source inverter,
IGBT : insulated gate bipolar transistor,
PVAPF : photovoltaic active power filter,
FFT : fast Fourier transform.

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