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Direct Power Control of a PWM-Inverter for Grid Connected Photovoltaic System

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***Abstract*— In this paper, direct power control (DPC) in view of instantaneous control of active and reactive power is proposed for controlling the three-phase PWM-inverter powered by a Photovoltaic Panel connected to grid. The control system is applied for improving the energy quality produced by a photovoltaic (PV) cell and the performance of PWM-inverter. The simulation results demonstrated a good performance of the proposed controller. The decoupled power control is achieved with success and low total harmonic distortion (THD) currents.**

***Keywords*—** Direct Power Control; Maximum power point Tracking (MPPT); PV-grid connected system; PWM-Inverter ; total harmonic distortion (THD).

I. INTRODUCTION

The utilization of sustainable energy source has encountered reliable development because of the restricted supply of petroleum product based energy and the continually developing natural concerns related with consuming non-renewable energy sources [1-8]. Solar energy as a sustainable power source is specifically noteworthy because of their lower support, the wealth of the energy source, zero post-production contamination and the progressions in semiconductor and influence electronic devices [9-13]. The photovoltaic system is a standout amongst the most encouraging sustainable power sources, as it has the upsides of being green, limitless, safe, contamination free and requiring little support [14,15]. The photovoltaic (PV) systems are utilized today in numerous applications which can be grouped into two fundamental classes: the stand-alone PV system and the grid-connected PV system. In remote country regions where the association is outlandish, the stand-alone PV systems are utilized with a battery bank for the energy stockpiling [16]. On the other hand, for the grid-connected PV systems, the PV boards are associated with the utility network without the utilize of battery bank to such an extent that the accessible PV control is conveyed to the electric grid [17].

The measure of power produced by photovoltaic board depends generally on the barometrical conditions (sun based light and air temperature). So to achieve the most extreme PV generation point for a given working conditions, a Maximum Power Point Tracker (MPPT) is utilized empowering the control of PV module's working point. An extensive assortment of MPPT techniques have been proposed in the literature so as to enhance the solar system proficiency, for example, Hill-Climbing strategy, Perturb and Observe technique and its enhanced rendition, incremental conductance technique, and other enhanced intelligent strategies [18-22].

In the grid-connected PV systems, the DC voltage delivered by a PV system is generally converted to an AC voltage using power electronics converter (Pulse Width Modulated PWM-inverter), the system performance is based on the control technique of the PWM-inverters. Diverse power management setups for grid associated PV systems interface exist, for example, the single stage and the two-stage structures. The quantity of stages associated with the grid-connected PV system is an imperative issue, since it decides the general proficiency, unwavering quality and complexity of control in such systems. In a double stage grid-connected Photovoltaic (GCPV) framework, the elements of the DC– DC and DC– AC control converters are free that influences the worldwide control to assignment less demanding than the one-stage design. However, the general productivity of the inverter diminishes because of the association of two converters. So as to accomplish an effective energy generation, the grid associated PV inverter is controlled in order to infuse an unadulterated sinusoidal current (AC) synchronized with the utility voltage. The power conditioning interface between the photovoltaic generator and the grid can turn out to be more proficient by picking a suitable control procedure. As a rule, the control structure of voltage-source inverters (VSI) involves an internal current loop that influences altogether the performance of the system. Empowering the power quality control, a few current control

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systems have been proposed in the literature [23– 26], for example, hysteresis current control (CHC), predictive direct control (PDC), dead-band based controller, and voltage oriented control (VOC) with PWM modulator.

Voltage oriented control (VOC) is the most popular method of control [27-29]. This strategy utilizes an external dc connect voltage control loop and an internal current control loop to accomplish quick unique reaction. The execution of the power stream relies upon the nature of the connected current control strategy. Direct Power Control depends on the dynamic active and reactive power control [30-32]. In this control method, there is no interior loop of current control and no Pulse Width Modulator, as the exchanging states of the inverter are properly chosen by a look-up table in light of the momentary errors of the power segments [31]. Contrasted with voltage oriented control, direct power control has a less complex calculation, no loops of current control, no different PWM voltage modulator, no requirement for decoupling between the control of the active and reactive power parts, and it has better flow execution. Then again, the variable and higher exchanging frequency are the notable disservices of the direct power control conspire [32]. Additionally, the angular data of the grid voltage is required, in light of the fact that the choice of the inverter output vectors basically relies upon this angle. At that angle PLL (Phase Locked Loop) is required to remove this data as in the VOC. In this work, the direct power control is applied to a PWM-inverter powered by a photovoltaic panel and connected to the electrical grid for improving the energy quality.

This paper is organized as follows: Section II presents the direct power control of PWM inverter. Section III gives an overview about the MPPT algorithm used in this study. The simulation results and discussion are described in Section IV. Finally, conclusion is presented in Section V.

II. DIRECT POWER CONTROL OF PWM INVERTER

The system diagram shown in Fig. 1 illustrates the overall operating principle of the proposed system.

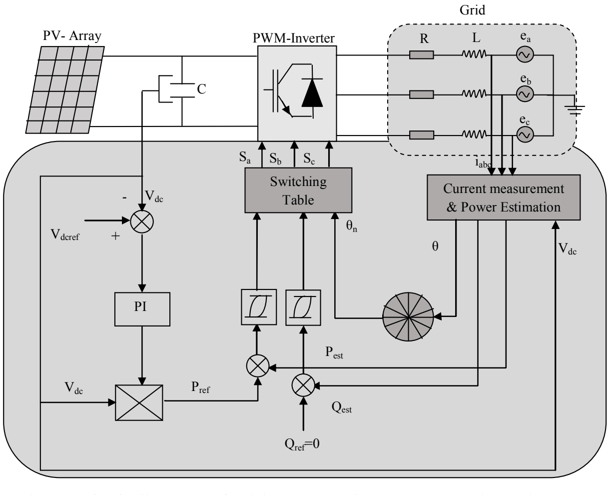

Fig. 1. Block diagram of grid connected PV system using Direct Power Control

The proposed system consists of a photovoltaic panel, a three-phase PWM-inverter connected with the grid; and the direct power controller. The Q_{ref} reactive power and P_{ref} active power commands are contrasted with the evaluated reactive (Q_{est}) and active (P_{est}) values in the reactive and active power hysteresis controllers. The output signal S_p of the active power controller is defined as follows:

$$\begin{cases} S_p = 1 \Rightarrow P_{est} \prec P_{ref} - h_p \\ S_p = 0 \Rightarrow P_{est} \succ P_{ref} - h_p \end{cases} \tag{1}$$

Similarly, the output signal S_p of the reactive power controller is defined as follows:

$$\begin{cases} S_q = 1 \Rightarrow Q_{est} \prec Q_{ref} - h_q \\ S_q = 0 \Rightarrow Q_{est} \succ Q_{ref} - h_q \end{cases} \tag{2}$$

The area of the voltage vector can be divided into twelve or six sectors, as shown in Fig. 2. These sectors can be defined numerically as follows [33-34]:

$$(n-2)\frac{\pi}{6} < \theta_n < (n-1)\frac{\pi}{6} \tag{3}$$

Where n=1,2,3…12 indicating the sector number. It is instantaneously given by the voltage vector position and is computed as follows :

$$\theta_n = arctg(\frac{v_\beta}{v_\alpha}) \tag{4}$$

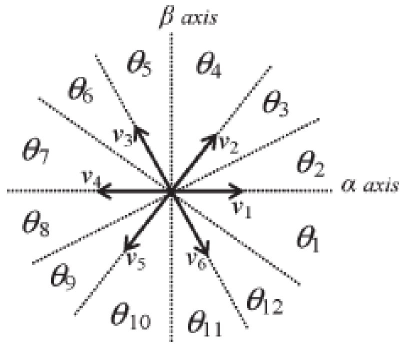

Fig. 2. voltage vector position in fixed frame

A. *DPC based on voltage estimation*

In order to remove the sensors from the alternating voltage, an instantaneous active and reactive power estimate has been proposed as a function of the switching states and the DC voltage as indicated by [33-34]:

$$\hat{P} = L(\frac{di_a}{dt} + \frac{di_b}{dt} + \frac{di_C}{dt}) + V_{dc}(S_a i_a + S_b i_b + S_c i_c) \tag{5}$$

$$\hat{Q} = \frac{1}{\sqrt{3}}[L(\frac{di_a}{dt} i_c - \frac{di_c}{dt} i_a) + V_{dc}(S_a(i_b - i_c) + S_b(i_c - i_a) + S_c(i_a - i_b))]$$

The first parts of the two expressions shown in Eqn. (5) show the power in the line inductors, noting here that the internal resistances of these inductances are negligible because the active power dissipated in these resistors is in fact much lower in comparison with the power involved. Other parts represent the power in the converter.

B. *Estimated voltage*

The working area of the line voltage is required to determine the commands. Moreover, it is important to estimate the line voltage correctly, even with the existence of harmonics, in order to obtain a high-power factor. The voltage drop across the inductor can be calculated by deriving the current. Thus, the voltage can be calculated by summing the reference voltage at the input of the converter with the voltage drop already calculated [33-34]. On the other hand, this approach has a disadvantage which is the derivative of the current, where the noise is amplified. To avoid this drawback, a voltage estimate based on the power calculation can be applied

The following expression (Eqn. 6) gives the line currents i_a, i_b, i_c in the stationary coordinates α, β.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{6}$$

The expressions of the active and reactive powers can be written as follows:

$$\begin{aligned} \hat{p} &= v_\alpha i_\alpha + v_\beta i_\beta \\ \hat{p} &= v_\alpha i_\beta - v_\beta i_\alpha \end{aligned} \tag{7}$$

The matrix writing of the preceding expressions is:

$$\begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8}$$

The matrix equation (Eqn. 8) can be rewritten as a function of the line current (measured) and the (estimated) power as follows:

$$\begin{bmatrix} \hat{v}_\alpha \\ \hat{v}_\beta \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \hat{P} \\ \hat{Q} \end{bmatrix} \tag{9}$$

Concordia's inverse transform of line tensions is written as:

$$\begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} \hat{v}_\alpha \\ \hat{v}_\beta \end{bmatrix} \tag{10}$$

C. *Switching Table*

Table.1 gives the switch-board of the direct power control. The digitized errors S_p, S_q and the working sector θ_n are the inputs of this table, where the switching states S_a, S_b and S_c of the converter are stored. The optimum switching state of the converter is chosen in each switching state according to the combination of the digital signals S_p, S_q and number of sector. That is to say that the choice is made where the error of the active power can be restricted in a band with hysteresis of width $2\Delta h_p$ and the same for the error of the reactive power with a Band of width $2\Delta h_q$.

Table.1 Switching Table

S_P	S_q	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
0	0	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
0	1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
1	0	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5
1	1	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_1
$V_1(100)$, $V_2(110)$, $V_3(010)$, $V_4(011)$, $V_5(001)$, $V_6(101)$													

III. MAXIMUM POWER POINT TRACKING

Maximum power point tracking control strategies assume an essential part in PV system since they increase the power output from a PV system for a given arrangement of conditions, and hence expand the array effectiveness. There are distinctive strategies used to track the most extreme power point. Perturb and Observe (P&O) strategy is the most generally traditional technique in PV MPPTs [35].

Perturb and Observe Algorithm

The P&O calculation works by perturbing the working voltage point (V) [18-22]. This bother makes the power of the PV module be changed. On the off chance that the power increments because of the perturbation then the perturbation is proceeded toward that path [14]. After the power peak is achieved, the power at the following moment diminishes and henceforth after that the perturbation switches. At the point when the steady state is achieved, the technique oscillates around the peak point. So as to keep the power variety little, the perturbation size is kept little. The strategy is created in such a way, to the point that it sets a reference voltage of the module relating to the peak voltage of the module. Flowchart of the P&O MPPT algorithm is shown in Fig. 3. With this method, the working voltage V is perturbed at each MPPT cycle. When the MPP is achieved, V will sway around the perfect working voltage V_{mpp}. This causes a power misfortune which relies upon the perturbation step width, C_P.

IV. SIMULATION RESULTS

The photovoltaic system is connected to the grid and all the control systems are simulated using the MATLAB / SIMULINK software. Two simulation tests have been done: keeping the active power constant and variation of reactive power of reference.

A. *Constant active Power Test*

In this test the active and reactive power are kept constant.

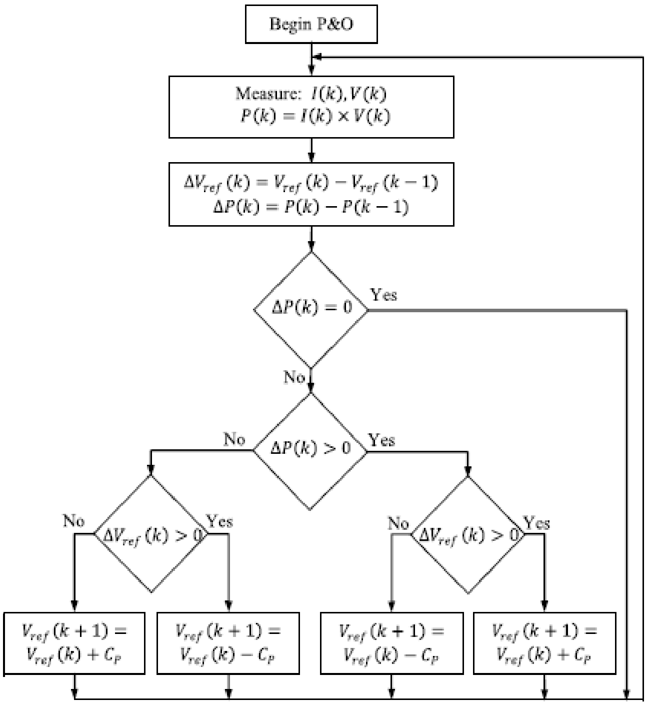

Fig. 3. Flowchart of the Perturb and Observe algorithm (C_P is the perturbation step width) [35].

Figure 4 shows the DC supply voltage of the PWM-inverter delivered by the Photovoltaic Panels; this voltage is kept at a desired reference voltage.

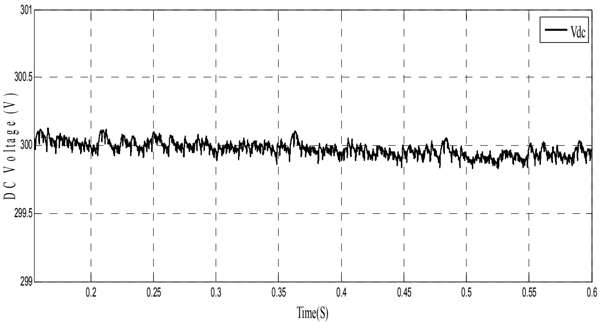

Fig. 4. DC voltage

Figure 5 illustrates the active reference power (red) and the estimated value (black). The estimated active power follows well its reference calculated from a proportional integral (PI) controller which regulates the direct voltage delivered by the solar panels.

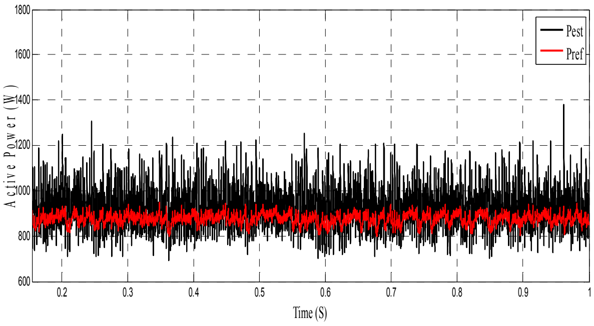

Fig. 5. Active Power

Figure 6 illustrates the reactive reference power (red) and the estimated value (black); The estimated reactive power follows its imposed reference equal to zero, which makes it possible to have a unit power factor.

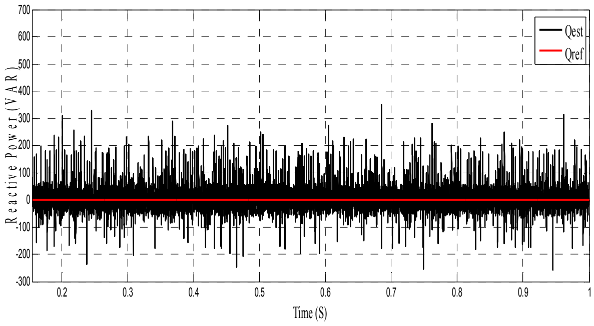

Fig. 6. Reactive Power

Figure 7 illustrates the line currents, which are almost sinusoidal, which gives a very good quality of energy and a low THD of the current transmitted to the network by the solar panels.

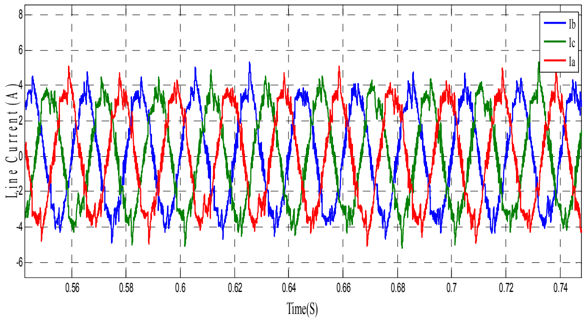

Fig.7. Line Current

B. Variation of Reactive Power of Reference Test

In this test the active power is kept constant and the reference reactive power is varied. Figure 8 shows that the DC voltage delivered by the photovoltaic system is maintained at its desired reference.

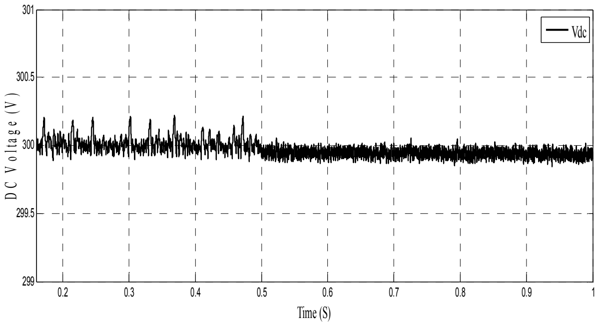

Fig.8. DC Voltage

It can be noted from Fig. 9 that the estimated active power follows its reference calculated by regulating the DC voltage of the solar panels even when the reactive power is varied (as indicated in Fig. 10), which confirms the active and reactive powers decoupling control.

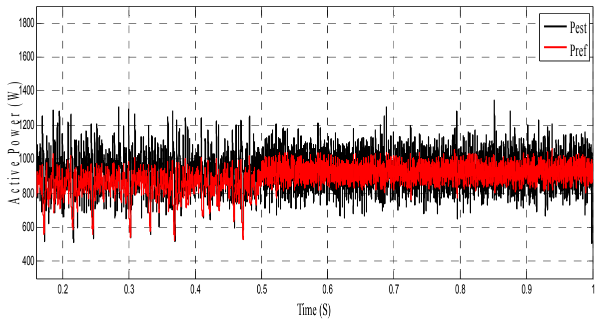

Fig.10. Active Power

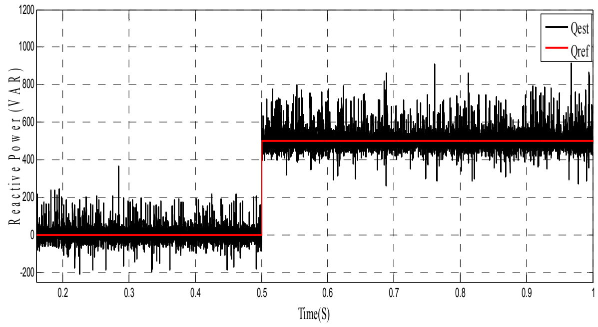

Fig. 10. Reactive Power

It can be noted from Fig. 11 that the line currents injected into the PWM-inverter network are almost sinusoidal in shape. Therefore, a low THD of the current is obtained and a very good quality of energy is transferred to the grid which confirms a system of Non-polluting energy conversion.

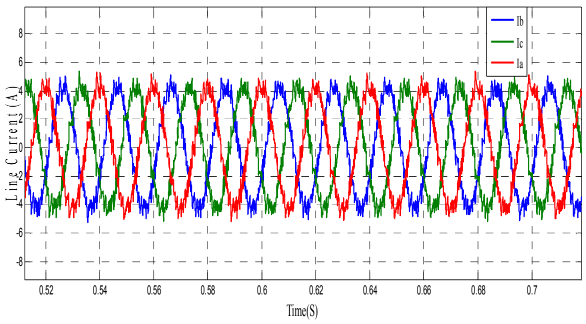

Fig. 11. Line Current

V. CONCLUSION

In this work, a direct power control (DPC) in perspective of prompt control of active and reactive power is proposed for controlling the three-stage PWM-inverter powered by a PV Panel associated with grid. The active and reactive power decoupled control is accomplished without utilizing a decoupling system and without coordinate change. The DC voltage is controlled to a consistent incentive under all conditions. The experimental results and simulation tests demonstrated that the great dynamic exhibitions and additionally the decoupled control of the active and reactive power are successfully achieved. Low THD of the currents is obtained which affirms a nature of transferred energy to the grid by the PV boards through PWM - inverter control using the proposed direct power control.

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