

Reactive Power Controller Design for Single-Phase Grid-Connected Photovoltaic Systems

EhsanRezapour, Md. Tavakoli Bina, Amin Hajizadeh

Abstract-Lack of adequate transmission capacity is a major impediment in connecting more of renewable energy sources (wind, solar) into the transmission grid. This paper at first presents a control algorithm for a single-phase grid-connected photovoltaic system in which an inverter designed for grid-connected photovoltaic arrays can synchronize a sinusoidal current output with a voltage grid. The power provided by the PV panels is controlled by a Maximum Power Point Tracking (MPPT) algorithm based on the incremental conductance method specifically modified to control the phase of the PV inverter voltage. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power injected into the grid. Simulation results show that the control system has good performances.

Index Terms — grid connected, photovoltaic system, reactive power, MPTT Algorithm

I. INTRODUCTION

PHOTOVOLTAIC (PV) solar energy as an alternative resource has been becoming feasible due to enormous researches and development work being conducted over a wide area (Bahu, 1996), (Chiang, 1998), (Hirachi, 1996) and (Yamaguchi, 1994). Some researchers spent efforts in developing PV inverter systems with grid connection and active power filtering features using sensors to measure the load current (Wu, 2005), (Kim, 1996), (Cheng, 1997) and (Kuo, 2001). This paper presents a single-phase topology, without load current sensor, composed by a dc-dc converter in cascaded with an inverter, as shown in Fig. 1. The system aims transferring the photovoltaic (PV) power to the ac load and paralleled with the utility. The dc-dc converter is used to boost the PV voltage to a level higher than the peak of the voltage utility such that the inverter can provide the ac voltage without requiring the transformer. The dc-dc converter is also responsible for tracking the maximum power point (Koutroulis, 2001) and (Zhang, 2000) of the PV modules to fully utilize the PV power. The shortage of load power from the PV module is supplemented by the utility. On the contrary, the excessive power from the PV module to the load can be fed to the utility. The balance of power flow is controlled through the inverter. The inverter also is used to act always as an active power filter to compensate the load harmonics and reactive power such that the input power factor is unity (Fig. 2). It converts the DC output voltage of the solar modules into the AC system.

The grid-connected photovoltaic (PV) system extracts maximum power from the PV arrays. The maximum power point tracking (MPPT) technique is usually associated with a DC-DC converter. The DC-AC inverter injects the sinusoidal current to the grid and controls the power factor. An important aspect related to the photovoltaic system connected to the electric grid is that it can operate the double functions of active power generator and reactive power compensator. The proper power factor is selected according to active power and reactive power that the grid demands. At the same time, it can supply reactive power to the electrical grid when there is little or no solar radiation. This is important for compensating the reactive power at peak hours, when the main grid needs a amount of reactive power higher than average consumption. Although the photovoltaic system does not generate active power in such period of time, it can supply reactive power up to its maximum. This inverter control strategy is not only capable to control the active power, but also dynamically reconfigured to change the magnitude of the reactive power injected into the grid. Some solutions are proposed [1-6], [10], to obtain a high reliability inverter. The basic idea of the proposed control is to obtain a low cost and simple controller. In this method, the active power is controlled by load angle and the reactive power is controlled by inverter output voltage magnitude. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power fed into the grid.

II. OPERATIONAL PRINCIPLES

The power stage of the single phase inverter connected to the grid in the Fig.1 explains the inverter output current.

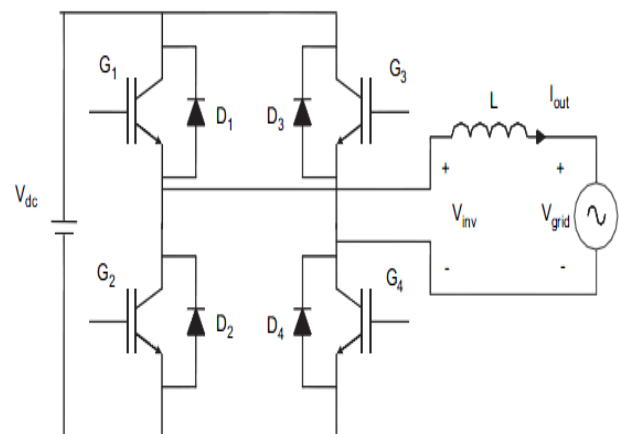


Fig.1. Single-phase inverter connected to the grid

The current of the inverter connected to the grid must be generated from a PV panel. The analysis is based on inductor coupling and applied for other types of output filter configurations, such as L, LC, LCL, etc [1,4,9].

In order to explain the circuit characteristics, the Fig.2



Manuscript received March 15, 2014.

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represents the phase diagram of the undamentalcomponents, including the inverter output voltage (E), the inverter output current (I), the drop voltage on the inductance L ($jX_s I = j\omega LI$), and the fundamental component of the grid voltage (U). [8].

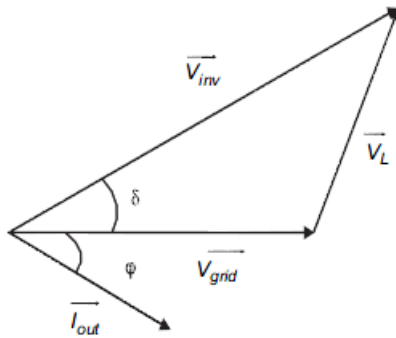


Fig.2. Phase diagram with V_{inv} , V_L , V_{grid} and I_{out} .

φ is represented as the power angle between the grid voltage and the inverter output current. And, δ is represented as the load angle between the grid voltage and the inverter output voltage. The phase diagram is shown in Fig. 3. The following relations can be represented:

The active power (P) provided by the converter to the grid can be expressed as:

$$P = UI \cos(\varphi) = \frac{UE}{X_s} \sin(\delta) \quad (3)$$

And the reactive power (Q) provided by the converter to the grid, can be expressed as:

$$Q = \frac{UE}{X_s} \cos(\varphi) - \frac{U^2}{X_s} = \frac{U}{X_s} (E \cos(\delta) - U) \quad (4)$$

According to figure 3, equations (3) and (4), the power flow adjustment of the inverter is parallel connected to the main grid, can be performed by controlling the inverter output voltage magnitude (E) and load angle (δ). On the other hand, to inject power to the grid, the value of the DC voltage must be high enough so that the output voltage E can get a value which is equal or greater than the grid peak voltage. From equation (3) and (4), the active and reactive power depend on both the inverter output voltage magnitude E and the load angle δ [6]. So, the active power injected into the grid can be controlled by the phase difference between grid voltage and inverter output voltage δ . At the same time, the reactive power can be controlled by the inverter output voltage magnitude E.

III. PROPOSED CONTROL IMPLEMENTATION

The proposed control structure for a single-phase inverter connected to the grid is shown in Fig.4. The photovoltaic system consists of photovoltaic generator (PV array), DC/DC converter with maximum power point tracking (MPPT), a single phase inverter and an active and reactive power controller. The control circuit has two parts: the first one controls the active power injected into the grid by the load angle δ , and the second one controls the reactive power through the inverter output voltage magnitude E.

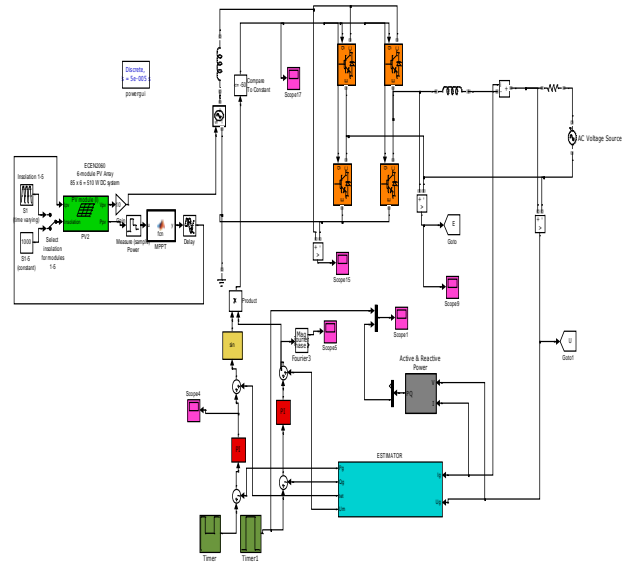


Fig.3. Simulink diagram of case study system

As shown in figure 3, the controller compensates the reactive power injected into the grid (Q_g) and compares it with its reference (Q_r), originating an reactive power error. This error passes through a PI controller and it is added to grid voltage amplitude ($U_m \approx \text{const}$), resulting in the inverter output voltage amplitude (E_m) in the X -axis and (U_m) in the Y -axis. The controller produces the active power generated by the inverter (P_g) and compares it with a reference signal (P_r), generating an active power error. This error passes through another PI controller, originating reference load angle (δ). The load angle is added to grid voltage phase angle (θ_u), generating inverter output voltage phase angle ($\delta + \theta_u$). The inverter output voltage amplitude (E_m) is multiplied by $\sin(\delta + \theta_u)$, resulting in the instantaneous value of the inverter output voltage (e) – the DC/AC inverter reference signal. The grid voltage:

$$u = U_m \sin(\omega t) = U_m \sin(\theta_u) \quad (5)$$

And $\delta \sim P$ and $\Delta E \sim Q$

Inverter output voltage:

$$e = E_m \sin(\theta_u + \delta) \quad (6)$$

Where:

$$E_m = \Delta E + U_m \quad (7)$$

The main advantage of this control strategy is its simplicity related to the computational requirements of the control circuit and hardware implementation. By another way, it allows controlling not only an active power needs to be injected but also a reactive component. When the reactive power reference is zero, the power factor will approach to the unity.

IV. SIMULATION RESULTS

MATLAB/Simulink software were used in all simulations accomplished here which show the results obtained for voltage and current waveforms, active, reactive and apparent powers on the AC side supplied to the grid. The rate value of grid voltage ($U = 220 \text{ V}_{rms}$) and the inverter is connected to the grid through a coupling inductance $L = 10 \text{ mH}$. Simulations at low-power scale (1 kVA) is implemented in predicting the behaviour of the



system for the experiments to be performed on the laboratory testbench.

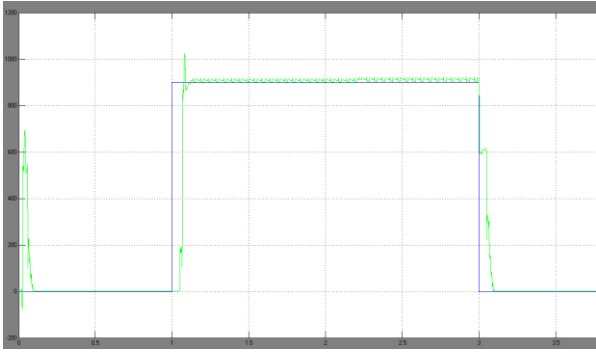


Fig. 4: Reactive Power supplied by the inverter with 100%-50%-100% of photovoltaic system power.

The simulation results obtained for steady-state operation are shown in Fig. 4. Active and reactive power response has good performance. The active power and reactive power injected into the grid for four generation conditions: $[P,Q]=[0\%, 0\%]$, $[100\%, 0\%]$, $[50\%, 0\%]$, $[50\%, 87\%]$.

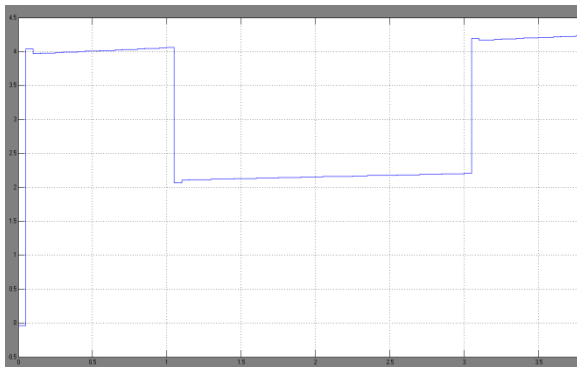


Fig.5.Load angle δ [degree]

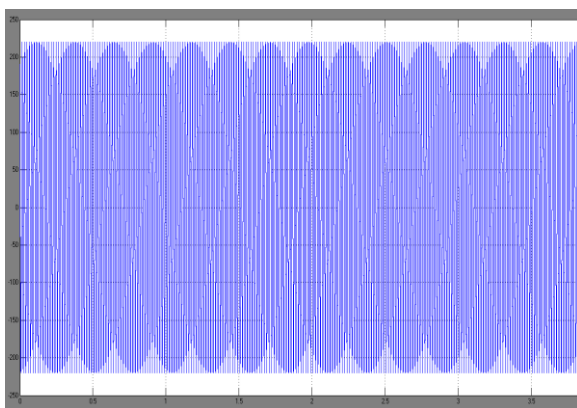


Fig. 6. Inverter output voltage E [Vrms].

As observed in figures 4 to 6, when the active power is reduced, the control is adjusted to increase the reactive power supplied capacity. Hence, the values of inverter current and the apparent power injected into the grid can get the rate values whereas the solar radiation is low. [7]. The active power supplied by the photovoltaic system to the grid presented a agreeable performance, due to a reasonable system response. When there is sunstroke variation, the system adjusts to a new reference of active power with a good performance. Moreover, it was observed an interaction between the active and reactive powers delivered to the grid. So, the system takes advantage of the

moments of little active power generation to accomplish the compensation of reactive power.

V. CONCLUSION

GPL shows its effectiveness and attraction when it draws areal interest of students majoring in Power Engineering. Students are really interested in new concepts, new technologies introduced into the curriculum. In addition, the introduction of micro electronics and DSP techniques into the renewable energy field really makes the subject state-of-the-art and more interdisciplinary. Power electronics, electrical machines, dsp, microelectronics, control techniques, all integrated in the discipline gives even more attractiveness to students.

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