Control Strategies for Grid-Tied Inverters Based on Photovoltaic Solar Systems

A Q Almousawi¹, A Aldair²

¹Electrical Engineering Department, Faculty of Engineering, University of Kufa, Iraq
²Electrical Engineering Department, College of Engineering, University of Basra, Iraq

E-mail: ¹ ali.almousawi@uokufa.edu.iq (Corresponding author), ² mmr.ali2@googlemail.com

Abstract. A two control strategy for a photovoltaic grid-tied system is proposed in this paper. A microgrid (MG) can be operated in a grid-tied mode or be disconnected from the grid (in an islanded mode). To interface renewable energy sources with low-voltage distribution systems, grid-tied inverters are more commonly used, however. When a MG operates in conjunction with the grid, various control techniques have been proposed based on current control (power control) in single or triple loops. In this paper, the proposed controller enables the PV solar system to run based on voltage-control (frequency/ voltage) to regulate both active and reactive power injected into the grid. The MG consists of a photovoltaic (PV) array; a DC/DC boost converter to interface the PV array to a common DC-link with double loop strategy; a 3-phase inverter controlled using a triple loop strategy; an LCL output filter; and an impedance feeder used to connect the output of the inverter to the busbar of the grid. A dq-frame for voltage and current control structure is also used. A Phase-Locked Loop (PLL) mechanism is used to provide current control in order to extract (θ), while it is extracted from the frequency control in the voltage control structure. Additionally, the control strategy uses feed-forward techniques to reduce the impacts of the inherent nonlinearity of the control system and inter-couplings. Two control strategies were thus designed, analysed, and validated through simulations under several operating scenarios using detailed switching models of a 23.5 kW a PV unit in PSCAD/EMTDC software.

Keywords: Microgrid, Grid-Tied, MPPT controller, PV array, Voltage control, Current control

1. Introduction

In distributed generation (DG) applications, solar photovoltaic (PV) panel are considered to be an attractive choice due to their low emissions, decreased cost based on higher volume production of solar panels and improvements in technology, low maintenance requirements, high reliability, and increased efficiency [1]. PV solar systems can be classified according to their operating or control mode as either grid connected (grid-tied) or autonomous (standalone or islanded) configurations. In microgrids, PV units are generally controlled for use as a power source or current source to inject available PV power into the large-scale grid, and a similar control methodology is utilised in grid-tied applications [2].

In a grid-tied PV array, a droop controller and the Maximum Power Point Tracking (MPPT) controller are essential. The production power of PV panels changes constantly with atmospheric temperature and solar radiation; thus, an MPPT to extract maximum power from the PV panels in real time is necessary to the efficiency of the PV system. The MPPT controller, tracks the maximum power production of the PV panel, while the droop controller sets the production power of the PV panel overall [3]. There are many methods using to implement MPPT controllers in PV systems, including the use of a Perturb and Observe (P&O) method, incremental conductance, and hill climbing. The P&O method is
considered most suitable for regulating PV output voltage and obtaining fast dynamic performance, however [4].

A voltage source converter (VSC) requires a coupling filter in order for it to be connected correctly to feed AC local loads or the main grid. The high-frequency switching noise generating by VSC can be attenuated by using filters to supply a voltage with minimum distortion at the point of common coupling (PCC) [5]. There are three types of coupling filters that are generally utilised in a MG L, LC (used in islanded modes), and LCL. The type of filter installed affects the performance of the VSC and can cause instability or resonance, among the various elements of the MG, however [6]. The LCL filter has higher-order dynamics than the L filter, and thus, requires more advanced control; however, it offers the best total harmonic distortion and greater reliability [7]. In this paper, the LCL filter is thus used in all controllers presented.

There are three key state variables for using an LCL filter, represented by the current of inductance (currents from both the inverter side and grid side) and the voltage of capacitance; these variables offer feedback and can thus be used as a closed loop controller to ensure predefined reference tracking performance. Various cascade control constructions have emerged in the literature, and these can be classified as single, double, and triple loops without computation of any variable feedforward as a loop. Control using proportional integral (PI) is also common in grid-tied PV applications, as this allows control of the parameters of the system under disturbances. The main features of a PI regulator are good performance characteristics and a straightforward structure strategy [8].

The basic technique used to preserve stability in a MG is droop control. Reactive power-voltage (Q-V) and real power-frequency (P-f) droop controls are the most popular methods, with droops represented as linear relationships between reactive power and voltage, or between real power and frequency [9]. Different control strategies for a grid-tied PV unit have been reported in several papers [10-15].

In [10], the design of a double loop current controller and the parameters for a PV grid-tied inverter with LCL filter are offered. Stationary-frame generalized integrators are used instead of feed-forward grid compensation in order to control the fundamental current, while to control the grid current, a repetitive control dependent on an IIR filter is proposed in [11]. Analysis of the dynamic performance and MPPT control technique will are also used for the half bridge dc–dc converter, and single-phase full bridge inverter with LCL filter used for a PV grid-tied. multi-loop feedback current control with analysis of the dynamic performance proposed in [12]. In [13], a VSC and current source converter (CSC) with LC filters is used for a grid-tied PV system, allowing the design and tuning processes for single and multiloop control structures for a VSC and CSC to be examined. A double loop control structure with tuning procedures, robustness, performance, and limitations is discussed for a grid-tied PV unit using an LCL filter in [14], while in [15], a control method for grid-tied PV systems is proposed with a boost converter used as the DC-DC converter and MPPT performed using an incremental conductance technique.

In this paper, a power management strategy for grid-tied PV units is proposed. As opposed to the PV units control techniques proposed in previous the works, where the PV arrays are controlled as a power control, the proposed control strategy enables the PV unit to work as a voltage source utilising a droop control. The PV systems ability to track and feed the maximum extraction power to the main grid, is thus harnessed. The PV array controlled as a power control is also simulated, however.

The remainder of this paper is arranged as follows. Section 2 describes the structure of the grid-tied PV units for both power control and voltage control. The modelling and control strategy of the PV array, boost converter, and VSC are analysed in section 3. While section 4 presents the simulation results for both transient and steady states. Finally, the simulation results and conclusions are given in Sections 4 and 5, respectively.

2. System Structure
The general structure of grid-tied inverter based on photovoltaic (PV) array is illustrated in Figures 1 and 2 for the power and voltage controllers, respectively. The simplified diagram of a grid-tied system shows the PV array, a boost converter that connects the PV array with the DC link input inverter, a three-phase voltage source converter (VSC), a three-phase LCL filter, feeder, and a transformer for isolating the main grid. The PV array consists of an aggregate of solar panel arranged in parallel and
series to obtain the required voltage and current to be extracted. Each solar panel has a number of solar cells, and the solar panel output power is determined by the environment temperature and solar radiation.

A boost converter is used to regulate the output voltage and current in the solar panels based on the maximum power point tracking (MPPT) controller in order to allow the PV units to work at their optimal point during variations in temperature and radiation. The VSC DC side is paralleled by the output boost converter DC-link capacitor and a VSC controls the DC link. Increasing the voltage of the DC link requires increasing the real power transfer from the output inverter to the grid. \( L_{\text{in}}, C_f \) and \( L_o \) represent the inductance input, capacitance, and inductance output of the filter, respectively. \( R_t \) and \( L_t \) represent the resistance and inductance of the feeder.

Figures 1 and 2 illustrate the fact that the VSC is controlled in a rotating dq reference frame, and \( \Theta \) is obtained from a PLL for power controller, as shown in Figure 1, which constitutes an essential part of a dq-transformation while obtained from a frequency controller, as shown in Figure 2. The control objective is to regulate the real and reactive power injected into the grid using power regulation or voltage regulation of the output inverter unit. Ideally, both methods should be accomplished in a stable manner to permit droop control. In the three-phase VSC, there are six switches (S1 to S6), and each switch is connected in parallel with a diode.

\( V_{\text{DC}} \) represents the direct output voltage from the converter PV units, \( C_o \) represents the filter capacitor, \( i_{\text{abc}} \) is the output currents of the inverter, \( V_{\text{abc}} \) represents the output voltages of the inverter, and \( i_{o\text{abc}} \) represents the output currents of the inverter grid side.

![Diagram](image)

**Figure 1.** Grid-tied PV unit using the power controller.
3. Modelling and Control
Mathematical models and control designs for the PV array, unidirectional boost converter, and the VSC with power and voltage control are offered below. The key electrical parameters of the system are presented in Table 1.

Table 1. Electrical parameters for simulation

| symbol | Description                      | Value     |
|--------|----------------------------------|-----------|
| $C_{in}$ | PV input capacitor              | 1500 µF   |
| $C_o$   | Output capacitor                | 9600 µF   |
| $L_{pv}$ | PV Inductor                     | 550 µH    |
| $L_{in}$ | Filter inductance inverter side | 2.5 mH    |
| $C_f$   | Filter capacitance              | 75 µF     |
| $L_o$   | Filter inductance grid side     | 2.5 mH    |
| $V_{dc}$ | Solar array open circuit voltage | 575 V     |
| $I_{sc}$ | Solar array short circuit current | 69 A     |
| $V_{dc}$ | Nominal DC-Link voltage         | 1 kV      |
| $R_t$   | Feeder resistance               | 0.8 Ω     |
| $L_t$   | Feeder inductance               | 5 mH      |
| $Y - \Delta$ | Transformer         | 0.48:11 kV |

3.1 PV Model
The equivalent circuit of a PV panel is shown in Figure 3. A single diode model is utilised to depict the I-V characteristics of the PV panel used in this paper, and equations 1 to 3 show the modelling of the I-V relationship for a PV panel [16]
Figure 3. Equivalent circuit of a solar cell

\[ I_{pv} = n_p I_{pv} - n_p I_{sat} \times \left[ \exp \left( \frac{q}{A k T} \left( \frac{V_{pv}}{n_s} + I_{pv} R_s \right) \right) - 1 \right] \]  
(1)

\[ I_{ph} = (I_{ss0} + k_i (T - T_r)) \cdot \frac{S}{1000} \]  
(2)

\[ I_{sat} = I_{rr} \left( \frac{T}{T_r} \right)^{3/2} \exp \left( -\frac{E_{gap}}{A k} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right) \]  
(3)

where \( V_{pv} \) and \( I_{pv} \) are the PV array voltage and current, respectively; \( T \) is the surface temperature of the PV in Kelvin; \( T_r \) is the reference temperature; \( I_{ph} \) is the photocurrent; \( I_{sat} \) is saturation current; \( I_{ss0} \) is the short-circuit current at \( T_r \); \( A \) is the diode quality ideality factor (1.5); \( q \) is the electron charge (1.602 * \( 10^{-19} \) C); \( k \) is Boltzmann constant (1.38*10^{-23} J/K); \( R_s \) and \( R_p \) are the cell series and parallel resistances of the PV cell; \( k_i \) is the short-circuit current temperature coefficient; \( n_s \) is the number of cells in series; \( n_p \) is the number of cells in parallel; \( E_{gap} \) is the energy of the bandgap for silicon (1.1 e.v); and \( S \) is the solar radiation level. These parameters were estimated by using a method similar to that developed in [17].

In this work, each panel included 36 cells connected in series. The PV array thus consisted of 49 strings connected in parallel, with each string containing 24 panels in series to obtain a power of 23.5 kW.

3.2 Boost Converter Control Design

The PV panels include a DC/DC converter that joins the panels and the inverter. In a grid-tied PV system, the boost converter is commonly modulated in MPPT mode to achieve maximum utilisation of renewable energy; the PV converter input voltage is thus controlled to track MPP using a P&O algorithm, and the output voltage of the boost converter is stabilised using VSC. The output of the voltage control acts as a reference current for the PV converter input current, with limited PI control between zero and maximum PV current, as shown in Figure 4. The time constant of the LPF is 5 * \( 10^{-5} \) seconds and the switching frequency of the boost converter is 20 kHz.

Figure 4. Control Strategy Structure for Boost Converter

According to the control strategy proposed for the boost converter, the PV panel voltage must be controlled with MPPT modes. Small signal stability can be used to create a linear model around MPP, and a linear model for PV panel is equivalent to the voltage source connected in series with a resistor [18]. Current loop and voltage loop transfer functions for a PV unidirectional boost converter are derived.
by applying the averaged state-space equations obtained in switching off and switching on states, as shown in Figure 5.

\[ G_{id}(s) = \frac{d_{i}}{d} = \frac{V_{DC}(1+Rs_{eq}C_{in})}{sC_{in}L_{PV}R_{eq}+sL_{PV}+R_{eq}} \]  

\[ G_{v}(s) = \frac{V_{PV}}{i_{L}} = \frac{G_{id}(s)C_{i}(s)}{1+G_{id}(s)C_{i}(s)} \]  

\[ G_{v}(s) = \frac{V_{PV}}{i_{L}} = -\frac{R_{eq}}{sC_{in}+(R_{eq})^{-1}} = -\frac{R_{eq}}{sC_{in}R_{eq}+1} \]  

where \( R_{eq} \) is the equivalent linear model resistor of PV panel, \( C_{i}(s) \) represents the current controller, and \( C_{v}(s) \) represents the voltage controller. Figure 6 shows the closed loop control model of the PV converter.

The PI controllers were designed using the frequency response method and selected as follows:

\[ C_{v}(s) = \frac{s+20}{s} \]

\[ C_{i}(s) = \frac{s+50}{s} \]

### 3.3 VSC Control Design

#### 3.3.1 VSC Power Control

As shown in Figure 1, the power control loops were designed as in [19]. As indicated, feedback signals \( I_{oabc} \) and \( V_{abc} \) can be utilised in order to compute the output power of the VSC for the PV control system, allowing the droop controller to deliver a reference signal to regulate the current of the microgrid. At this point, the reference signals are sent to the current PI regulator loop as shown in Figure 7. The three-phase current and voltage of the VSC on conversion into the current and voltage of the q-
axis and d-axis has a coupling effect; decoupling terms ($wL_i o_q$, $wL_i o_d$) are therefore included in the control loop [19].

![Current Tracking Loop for Power Control Grid-Tied PV Units](image)

**Figure 7.** Current Tracking Loop for Power Control Grid-Tied PV Units

To clarify Figures 1 and 7, the PI regulators are presented in full in Table 2. The time constant of the LPF for the reactive power is $5 \times 10^{-4}$ seconds and the switching frequency of the VSC is 10 kHz.

| parameters                  | Value   |
|-----------------------------|---------|
| symbol                      | Description | Value   |
| PLL                         | PLL proportional term | 950      |
|                             | PLL integral term     | 1500     |
| PI$Q$                       | Reactive power proportional term | 0.3      |
|                             | Reactive power integral term | 50       |
| PI$_{dc}$                   | Voltage DC link proportional term | 0.2      |
|                             | Voltage DC link integral term     | 50       |
| PI$_i$                      | Current proportional term       | 0.17     |
|                             | Current integral term           | 11       |

### 3.3.2 VSC Voltage Control

As shown in Figure 2, the dynamics of the PCC are defined by the space-phasor equation

$$\frac{d}{dt} \vec{v} = \vec{i} - \vec{i}_0$$  \hspace{1cm} (7)

The generic condition used to characterize every space phasor is

$$\vec{x}(t) = \left( \frac{2}{3} \left( \vec{x}_a(t) e^{j0} + \vec{x}_b(t) e^{j2\pi/3} + \vec{x}_c(t) e^{j4\pi/3} \right) \right)$$  \hspace{1cm} (8)

where $x_a(t)$, $x_b(t)$, and $x_c(t)$ establish a three-phase waveform or voltage/current signal. By substituting

$$\vec{x}(t) = (x_d(t) + jx_q(t)) e^{j\theta(t)}$$

into (7), the dq-frame equivalent of (7) can be determined as

$$\frac{d}{dt} \left[ (v_d + jv_q) e^{j\theta} \right] = \left( i_d + ji_q \right) e^{j\theta} - \left( i_{od} + ji_{oq} \right) e^{j\theta}$$  \hspace{1cm} (9)

where $\theta(t)$ represents the angle of the dq-frame. This can be simplified by using a partial $(u.dv)$ integral and separated into
\[ C_f \frac{dv_d}{dt} = (C_f w)v_q + i_d - i_{od} \]  \hspace{1cm} \text{(10)}

\[ C_f \frac{dv_q}{dt} = -(C_f w)v_d + i_q - i_{oq} \]  \hspace{1cm} \text{(11)}

where

\[ \frac{d\theta}{dt} = w \]  \hspace{1cm} \text{(12)}

which is the output of the frequency control. In grid-tied mode, in a steady state, \( w \) is equal to \( w_o \) (377 rad/sec when the frequency is 60 Hz).

As shown in Figure 2, feedback signals \( I_{abc} \), \( I_{oabc} \), and \( V_{abc} \) can be utilised to compute the output power of the VSC for the PV control system, allowing the droop controller to deliver a reference signal so that the frequency and voltage of microgrid can be regulated. At this point, the reference frequency and voltage signals are sent to the double loop PI regulator, with the voltage representing the outer loop and the current representing the inner loop. The structure of the double PI regulator is shown in Figure 8. The three-phase of two currents and voltage in the VSC has coupling effect when converted into the current and voltage of the q-axis and d-axis, so the decoupling terms \( wL_i q \), \( wL_i d \), \( wC_f v_d \), and \( wC_f v_q \) are included in the control loop [20].

![Figure 8. Voltage Tracking Loop for Voltage Control Grid-Tied PV Units.](image)

The PI regulators shown in Figures 2 and 8 are presented in detail in Table 3. The time constant of the LPF for the reactive power is \( 5 \times 10^{-4} \) seconds, with a nominal frequency of 60 Hz, nominal voltage of 0.48 kV, and switching frequency of the VSC of 10 kHz. A modified V-f droop control and the PI controller of the DC link are used, limited with a plus-minus PV rating; the minus term is necessary in order to charge the DC link capacitor at the beginning of the system operation.

| Table 3. Control Parameters for Voltage Control |
|-----------------------------------------------|
| symbol | Description                     | Value |
| PiQ    | Reactive power proportional term | 0.8   |
|        | Reactive power integral term    | 200   |
| Pi_{dc} | Voltage DC link proportional term | 0.1   |
|        | Voltage DC link integral term   | 2.5   |
4. Simulation Results

In this work, power control and voltage control were simulated with PSCAD/EMTDC software. In term of power control, the active power export was examined, while with regard to voltage control (proposed control), all controllers were examined.

4.1 Simulation Results for Power Control

The current control system was simulated for 50 seconds; the local load was connected with the system at a time equal to 15 sec, and the responses of active power, reactive power and DC link voltage are shown in Figure 9. The rating of PV units was set to supply 22.5 kW, 10 kVAR from the beginning of the simulation; when the local load was connected at 15 sec 12.5 kW, 8 kVAR, notice that the active power slightly increased before returning to the rating value. The DC link voltage also suddenly increased at that point then returned to the reference value. The solar irradiation decreased from 1000 to 800 w/m^2 then returned to 1000 w/m^2 at 20 sec. In all graphs, currents are expressed in kA, voltages in kV, active power in MW, and reactive power in MVAR.
Figure 9. Plots of (a) Active Power (b) Reactive Power (c) DC link voltage

4.2 Simulation Result for Voltage Control
The solar radiation was assumed to control the rating of the PV units from the beginning of the simulation, in this test, with six sequential actions, each lasting 15 seconds; the solar irradiation thus changed from 1000 w/m² to 400 w/m² in three steps, each equal to 200 w/m², before returning back to 1000 w/m² in an inverse manner.

Initially, the active power, reactive power, voltage dc link, output inverter voltage and current required 0.5 seconds to reach a steady state. During this period the system can be operated as a rectifier to charge the capacitors of the PV converter. The response of voltage, current, and solar irradiation for the PV converter are shown in Figure 10. In all the graphs, currents are expressed in kA, with voltages in kV, active power in MW, reactive power in MVar, and rotational speeds in rad/s.
(a) Voltage (kV)

(b) Tracking PV Voltage (kV)

(c) Current (A)

Time, seconds

Voltage (kV)

Tracking PV Voltage (kV)

Current (A)

0 10 20 30 40 50 60 70 80 90 100

0 0.02 0.04 0.06 0.08 0.1

0.2 0.25 0.3 0.35 0.4 0.45 0.5

-0.02 0 0.02 0.04 0.06 0.08 0.1
Figure 10. Plots of (a) Input/ output voltages for PV converter (b) Tracking between the voltage of PV unit and Vmppt (c) Input/ output currents for PV converter (d) Solar irradiation.

Figure 10 shows that the output current of the boost converter is less than the input current, while the output voltage is large than the input voltage. The tracking between the PV voltage and maximum voltage extraction is also very effective. Figures 11 to 14 further illustrate that the active power, reactive power, frequency, inverter output voltage, inverter output currents, and the dc link voltage operate accurately.
Figure 11. Plots of droop control for (a) Active Power (b) Reactive Power (c) Droop frequency (d) DC link voltage.
**Figure 12.** Plots of output current inverter side for (a) AC output current (b) dq-Current (c) Tracking d-frame (d) Tracking q-frame.
Figures 11 to 14 also illustrate that when the solar irradiation reduces, the active power, output voltage inverter, output current inverter, and output current grid side also diminish and vice versa. DC link voltage and rotational speed are also reduced when the solar irradiation reduces, but these rapidly return to the setup reference voltage and droop frequency.
5. Conclusions

In this work, the design and simulation of two control strategies, a power control for a PV grid-tied system as commonly used; and a voltage control strategy for a PV grid-tied system were proposed. To link the PV unit with the main grid, the VSC with LCL filter is usually utilised in DG system. While the proposed grid-tied interfaced is capable of injecting the active power into the main grid more effectively under different levels of solar irradiation. PSCAD/EMTDC software was used for the modelling of the MG. In the first design of the PV converter with double-loop control strategy and VSC with third-loop control strategy, the external loop represented the droop control for Vdc and reactive power, while in the other, the voltage tracking loop was the outer loop (voltage loop) and the inner loop represented the current loop with a feed-forward function. The voltage control showed excellent performance in terms of active power control, reactive power control, DC link voltage control, output voltage and current inverter control.
References

[1] G. P. Willeke, “Progress in industrial crystalline silicon solar PV technology,” in IEEE 33rd Photovoltaic Specialists Conf., 2008, pp. 1–4.
[2] Lopes, J., C. Moreira and A. Madureira. “Defining control strategies for MicroGrids islanded operation.” IEEE Transactions on Power Systems 21 (2006): 916-924.
[3] Bin Wu, Yongqiang Lang, Navid Zargari, Samir Kouro “Power Conversion and Control of Wind Energy Systems,” pp 42, 2011
[4] Liu, F., Y. Kang, Y. Zhang and S. Duan. “Comparison of P&O and hill climbing MPPT methods for grid-connected PV converter.” 2008 3rd IEEE Conference on Industrial Electronics and Applications (2008): 804-807.
[5] C. A. Busada, S. Gómez Jorge, and J. A. Solsona, “Full-state feedback equivalent controller for active damping in LCL-filtered grid-connected inverters using a reduced number of sensors,” IEEE Trans. Ind. Electron., vol. 62, no. 10, pp. 5993–6002, Oct. 2015.
[6] Tang, Yi, P. Loh, P. Wang, F. H. Choo and F. Gao. “Exploring inherent damping characteristic of LCL-filters for three-phase grid-connected voltage source inverters.” 2010 IEEE Energy Conversion Congress and Exposition (2010): 312-319.
[7] Villanueva, Ignacio, Nimrod Vázquez, Joaquín Vaquero, Claudia Hernández, Hector Sanchez Lopez and René Osorio. “L vs. LCL Filter for Photovoltaic Grid-Connected Inverter: A Reliability Study.” International Journal of Photoenergy 2020 (2020): 1-10.
[8] Su YX, Sun Dong, Duan BY. Design of an enhanced nonlinear PID controller. Mechatronics 2005;15(8):1005–24.
[9] A. Ghosh and M. Dewadasa, “Operation Control and Energy Management of Distributed Generation,” iGrid, Brisbane, 2011.
[10] R. Teodorescu, F. Blaabjerg, U. Borup, M. Liserre,” A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation,” Applied Power Electronics Conference and Exposition, 2004. APEC’04. Nineteenth Annual IEEE 2004 (Vol. 1, pp. 580-586).
[11] S. Jiang, D. Cao, Li Y, FZ. Peng,” Grid-connected boost-half-bridge photovoltaic microinverter system using repetitive current control and maximum power point tracking,” IEEE Transactions on power Electronics. vol. 27, no. 11, pp.4711-22, 2017.
[12] Q. Lei, S. Yang, FZ. Peng,” Multi-loop control algorithms for seamless transition of grid-connected inverter,” Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE 2010 Feb 21 (pp. 844-848).
[13] Li YW.” Control and resonance damping of voltage-source and current-source converters with LCL filters,” IEEE Trans Ind Electron, 2009;56(5):151121.
[14] M. Dannehl, J. Liserre, FW. Fuchs.” Filter-based active damping of voltage source converters with LCL filter”. IEEE Trans Ind Electron 2011;58(8):362333.
[15] Bouhafs, Ali, Bendaa Mohamed Lokmane and Djarallah Mohamed. “Grid Connected Photovoltaic System, for a 800 W.” Energy Procedia 74 (2015): 414-422.
[16] M. E. Ropp and S. Gonzalez, “Development of a MATLAB/Simulink model of a single-phase grid-connected photovoltaic system,” IEEE Trans. Energy Conv., vol. 24, no. 1, pp. 195–202, Mar. 2009.
[17] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive approach to modeling and simulation of photovoltaic arrays,” IEEE Trans. Power Electron., vol. 24, no. 5, pp. 1 198-1208, May 2009.
[18] M. G. Villalva, T. G. D. Siqueira and E. Ruppert, “Voltage regulation of photovoltaic arrays: small-signal analysis and control design,” IET Power Electron., vol. 3, no. 6, pp. 869-880, 2010.
[19] Vechiu, I., O. Curea, A. Llaria and H. Camblong. “Control of power converters for microgrids.” Compel-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering 30 (2011): 300-309.
[20] Marwali M N, Keyhani A. Control of distributed generation systems part I: voltage and current control. IEEE Transaction on Power Electronics, 2004, 19(6):1541-1550.