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Modelling and Simulation of Grid-connected Photovoltaic Generation System

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Abstract— Nowadays, photovoltaic (PV) generation is developing increasingly fast as a renewable energy source. This paper presents modeling and simulation of the grid-connected PV generation system under MATLAB/Simulink. Firstly, the PV generator is connected to the boost DC-DC converter, the control systems based on the maximum power point tracking (MPPT) with P&O algorithm helps PV array to generate the maximum power to the grid with change weather conditions, and then integrated into the AC utility grid by DC/AC inverter control the power active and reactive for achieved the unit power factor in connection point. In this paper, different cases are simulated, and the results have verified the validity of models and control schemes.

Keywords—Photovoltaic array, modeling, grid-connected photovoltaic system, MPPT control, power inverter.

I. Introduction

The much concerned with the fossil fuel exhaustion and the environmental problems are caused by the conventional power generation. Nowadays, renewable energy sources, such as photovoltaic (PV) panels and wind-generators, are now widely used. PV systems are the most direct way to convert solar radiation into electricity and are based on the PV effect, which was first observed by Henri Becquerel in 1839.It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically, all PV devices incorporate a PN junction in a semiconductor across which the photovoltage is developed. These devices are also known as solar cells. Light absorption occurs in a semiconductor material. The semiconductor material has to be able to absorb a large part of the solar spectrum [1].

The PV generation is gaining increased importance as a renewable source. It is used today in many applications e.g. battery charging; water pumping, home power supply, swimming-pool heating systems, satellite power systems …etc. The PV systems have the advantage of being maintenance and pollution-free but their installation cost is high and, in most applications; they require a power conditioner (DC/DC or DC/AC converter) for load interface. Since PV modules still have relatively low conversion efficiency. The overall system cost can be reduced using high efficiency power conditioners which, in addition, are designed to extract the maximum possible power from the PV module.

The PV generators exhibit non-linear I-V characteristics. On the other hand, the optimum operating point changes with the solar irradiation, and cell temperature [2].Therefore, online tracking of the maximum power point of a PV array is an essential part of any successful PV system. A variety of maximum power point tracking (MPPT) methods is developed in literature. For example, in [3] a MPPT is implemented with a boost converter the Incremental Conductance algorithm, is based on the principle that the slope of the PV array power curve is zero at the maximum power point. Dual boost converter based MPPT using fuzzy logic has been reported [4].In order to extract the maximum amount of power from the PV generator, "Perturb and Observe" control method for the MPPT of a PV system under variable temperature and insulation conditions, is generally considered. This method compares the PV output power before and after and adjusts the duty cycle of the switch control waveform for MPPT as a function of the evolution of the power input at the DC/DC boost converter. In this control system, it is necessary to measure the PV array output power and to change the duty cycle of the DC/DC converter control signal.

This paper presents the analysis, modeling and control model of the electric part of a PV generation system connected to the utility grid by a boost converter and DC/AC inverter. The considered PV system is constituted of KC200GT (Kyocera, n.d.) solar array type. The model contains a detailed representation of the different components of the conversion system as the solar array, adapted and control systems. The simulation results show the control performance and dynamic behavior of grid connected PV system.

II. PV Array

PV cell is the most basic generation part in PV system. Single-diode mathematic model is applicable to simulate silicon PV cells. This model consists of a photocurrent source i_{Ph}, a nonlinear diode, series resistance R_S which represents the internal losses and shunt resistance, R_{Sh} in parallel with diode to take into account leakage current to the ground as shown in Fig. 1.

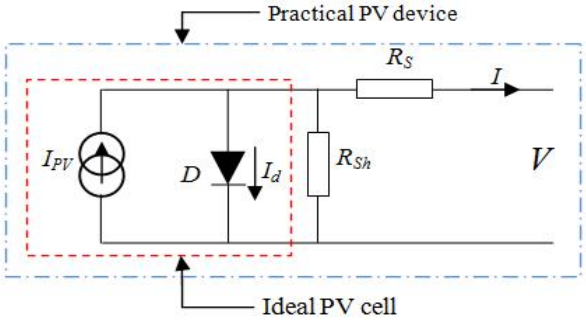


Fig. 1 Single-diode mathematic model of a PV cell

The mathematic relationship for the current and voltage in the single-diode equivalent circuit can be described as:

$$I = I_{ph} - I_s\left(e^{\frac{q(V+IR_s)}{AkT}} - 1\right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

Where, I_{ph} is photocurrent; I_s is diode saturation current; q is Coulomb constant ($1.602\times10^{-19} C$); k is Boltzmann's constant (1.381×10^{-23} J/K); T is cell temperature (K); A is PN junction ideality factor.

Photocurrent is the function of solar radiation and cell temperature described as:

$$I_{ph} = \left(\frac{S}{S_{ref}}\right)\left[I_{ph,ref} + C_T\left(T - T_{ref}\right)\right] \quad (2)$$

Where, S is the real solar radiation (W/m^2); S_{ref}, T_{ref}, $I_{ph,ref}$ are respectively the solar radiation, cell absolute temperature, photocurrent in standard test conditions; C_T is the temperature coefficient (A/K).

Diode saturation current I_S varies with the cell temperature as:

$$I_s = I_{s,ref}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3)$$

Where $I_{s,ref}$ the diode saturation is current in standard test conditions E_g is the band-gap energy of the cell semiconductor (eV) depending on the cell material.

PV cells, usually considered to have the same characteristics, are arranged together in series and parallel to form arrays. The equivalent circuit of PV array can be described as illustrated in Fig. 2.

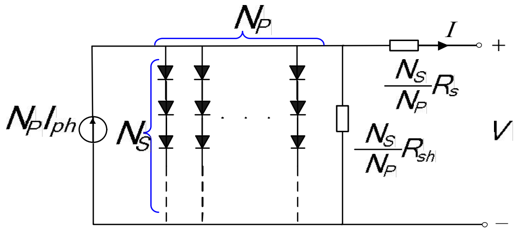


Fig. 2 Single-diode mathematic model of a PV cell

$$I = N_P I_{ph} - N_P I_S\left[\exp\left(\frac{q}{AkT}\left(\frac{V}{N_S} + \frac{IR_s}{N_P}\right)\right) - 1\right] - \frac{N_P}{R_{sh}}\left(\frac{V}{N_S} + \frac{IR_s}{N_P}\right) \quad (4)$$

Where, N_S and N_P are respectively cell numbers of the series and parallel cells.

The above model has been implemented using Matlab/Simulink as depicted in Fig. 3. All parameters of the model use the data in Table 1.

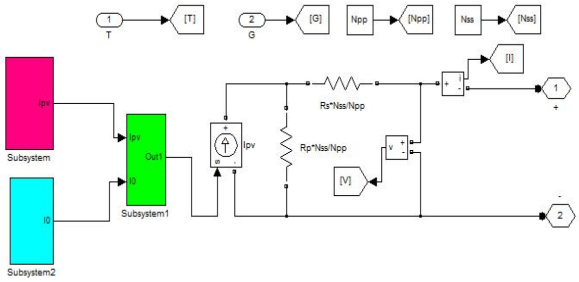


Fig. 3 PV array model implemented inMatlab/Simulink

TABLE I
PARAMETERS OF KC200GT SOLAR ARRAY AT 25 °C, A.M1.5, 1000 W/M^2 [5]

Parameters	Values
Referenced solar irradiance S_{ref}[W/m^2]	1000
Referenced cell temperature T_{ref}[K]	298
Cell numbers of a PV module	54
Nominal short-circuit voltage [A]	8.21
Nominal array open-circuit voltage [V]	32,9
Array current maximum power point [A]	7.61
Array voltage maximum power point [V]	26. 3
Current / temperature coefficient [A/K]	3.18 10^{-3}
Voltage/ temperature coefficient [V/K]	-0.123
Band-gap energy $E_g(eV)$	1.237
Cell internal resistance R_S [Ω]	0.2273
R_{Sh} [Ω]	540,55
P-N junction ideality factor A	0.065%

With different temperatures and solar radiations, output characteristics of PV array are simulated as Fig. 4 and Fig. 5.

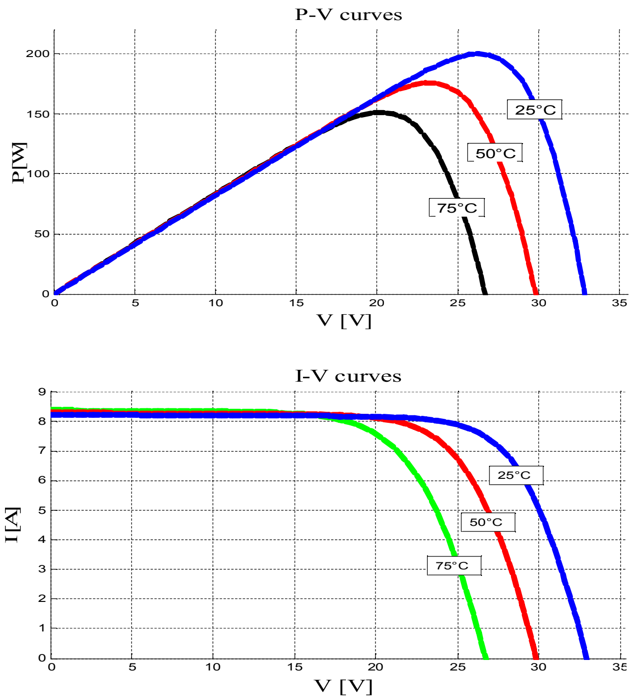


Fig. 4 Characteristic curves of the PV array with different cell temperatures and irradiation solar constant 1000 W/m^2

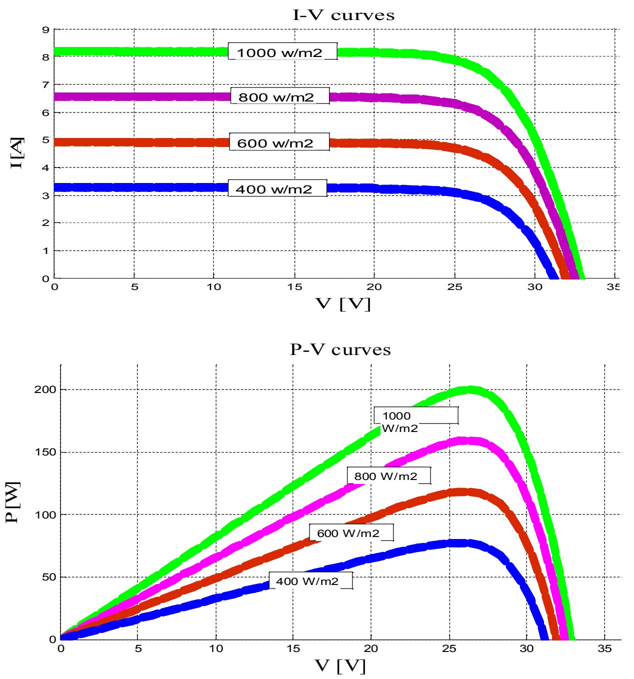


Fig. 5 Characteristic curves of the PV array with different solar Irradiations and constant temperature solar 25°C

As shown in Figures 4 and 5, a PV array has nonlinear voltage-current characteristics, and there is only one unique operating point for a PV generation system with a maximum output power under a particular environmental condition.

III. Grid-connected PV generation system

The penetration of renewable sources (particularly, solar power) in to the power system network has been increasing in the recent years. Grid connected PV generator systems always a connection to the electrical network via a suitable inverter because a PV module delivers only DC power. Figure 6 is the configuration of the grid-connected PV generation system. PV array is connected to the DC bus via a DC/DC boost converter, and then to the AC grid via a DC/AC inverter. The inverter has its independent control objective (boost inverter control PV generator to generate the maximum power and grid inverter control the active and reactive at AC bus to be constant).

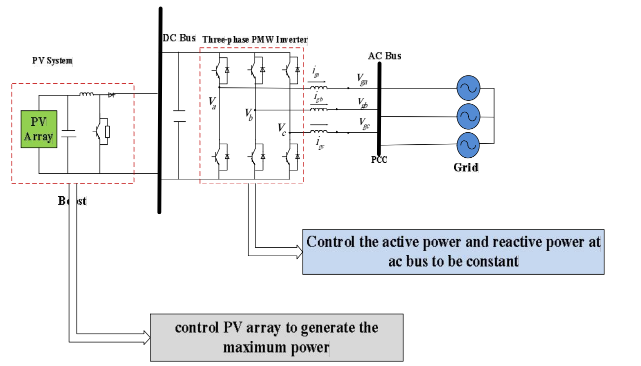


Fig. 6 Configuration of the grid-connected PV generation system

A. *Document PV generation system*

The PV generator using in the proposed systems is constructed with four KC200GT solar modules connected in series (a solar module is assembled of 54 solar cells).When is connected to the grid, it should be interconnected into the grid using power electronics to convert DC to AC power. In order to improve the efficiency of the PV generation system, PV array should be controlled to generate the maximum power by a MPPT algorithm, in order to extract the maximum possible power from the PV panels in all the irradiation conditions. For the two-stage PV system, the MPPT based in P&O algorithm is realized by controlling the DC/DC boost converter.

B. *Maximum Power Point Tracking*

The "Perturb and Observe" (P&O) algorithm is the most popular MPPT algorithm, since it is much simpler and needs fewer measured variables simplicity. Fig. 7 shows the flowchart of P&O method. It operates by constantly measuring the terminal voltage and current of the PV array, then constantly perturbing the voltage by adding a small disturbance, and then observing the changes of the output power to determine the next control signal. If the power increases, the perturbation will continue in the same direction in the following step, otherwise, the perturbation direction will be inversed.

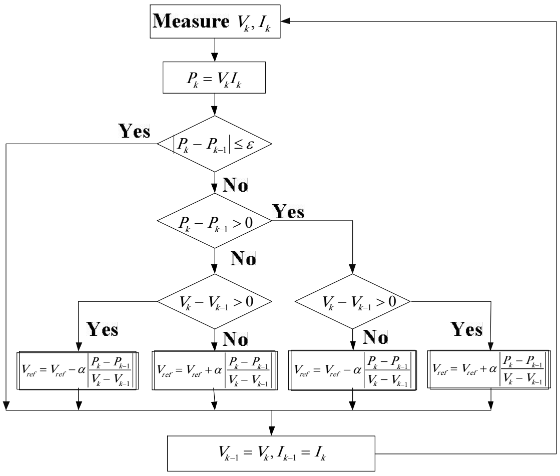


Fig. 7 P&O algorithmflowchart [6]

Where V_k, I_k are respectively the voltage and current of PV array at the moment k; V_{k-1}、I_{k-1} are respectively the voltage and current of PV array at the last sampling time.

The P&O method works well in slow changing environment but has some limitations under rapidly changing atmospheric conditions. From the characteristics curves of the PV array, power increment dP and voltage increment dV have the following relationship：

At the left of MPP: $dP/dV > 0$

At the right of MPP: $dP/dV < 0$

At the MPP: $dP/dV = 0$

Furthermore, as the operation point is nearer the MPP, the value of $|dP/dV|$ is smaller and smaller; consequently, the perturbation can be set as $\alpha|dP/dV|$. When the operation point is far from the MPP, the perturbation is large, and when the PV array is operating near the MPP, the perturbation is small.

C. Boost circuit and its control

For first-stage PV generation system, boost chopper circuit is always used as the boost DC/DC converter. The DC-DC converter rises the low solar voltage to a suitable level corresponding to the optimal PV power. A capacitor is generally connected between PV array and the boost circuit, which is used to reduce high frequency harmonics.

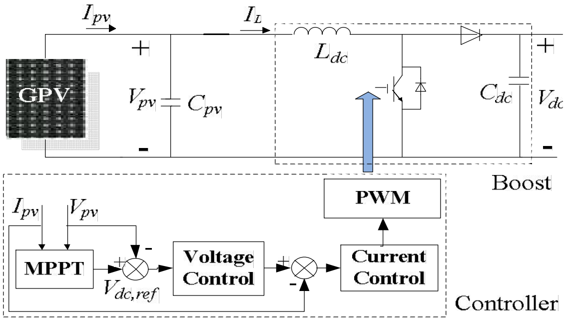


Fig. 8 Boost circuit and its control

The duty cycle α of the boost converter is determined by MPPT control system, then constantly perturbing between 0 and 1. T_S is the period of a switching cycle. When the IGBT is closed, the inductance voltage and capacitor voltage meet the following relationship:

$$\begin{cases} L_{pv}\dfrac{dI_{pv}}{dt} = V_{pv} = v_{L(on)} \\ C_{dc}\dfrac{dV_{dc}}{dt} = I_{dc} = i_{C(on)} \end{cases} \tag{5}$$

Similarly, when the IGBT is open, the equations of inductance voltage and capacitor voltage are described as:

$$\begin{cases} L_{pv}\dfrac{dI_{pv}}{dt} = V_{pv} - V_{dc} = v_{L(off)} \\ C_{dc}\dfrac{dV_{dc}}{dt} = I_{dc} - I_{pv} = i_{C(off)} \end{cases} \tag{6}$$

The maximum power point by regulating the duty cycle α is used to control the boost converter as shown in Figure 9. The P&O algorithm is used to find the maximum power point of the PV system [7].

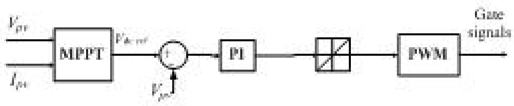


Fig. 9 Control structures of boost converter and MPPT algorithm

IV. GRID-CONNECTED INVERTER

PV array with boost DC-DC inverter are connected to the ac grid via a DC/AC inverter. The inverter is employed to step down and to modulate the output voltage according to the grid voltage. Finally, the filter is designed to reduce high-order harmonics introduced by the PWM modulation of the DC/AC converter.

The control strategy mainly consists of the DC/AC converter is designed to supply current into the utility line by regulating the bus voltage to 400V. The control of the power flow to the grid, according to the proposed power systems, is based on the control of active and reactive power. In the power DC-AC converters, active and reactive power from the grid-side inverter can be given by:

$$\begin{cases} P_g = v_{ga} i_{ga} + v_{gb} i_{gb} + v_{gc} i_{gc} \\ Q_g = \dfrac{1}{\sqrt{3}}\left(v_{gab} i_{gc} + v_{gbc} i_{ga} + v_{gca} i_{gb}\right) \end{cases} \quad (7)$$

Where, v_{ga}, v_{gb}, v_{gc} are three-phase voltages at the AC bus, i_{ga}, i_{gb}, i_{gc} are three-phase currents injected into the AC grid.

Applying Park transformation, Eq. (7) can be written as:

$$\begin{cases} P_g = 1.5\left(v_{gd} i_{gd} + v_{gq} i_{gq}\right) \\ Q_g = 1.5\left(v_{gq} i_{gd} - v_{gd} i_{gq}\right) \end{cases} \quad (8)$$

Where, v_{gq}, v_{gd} represent the *d,q* components of the voltage at connection point, i_{gq}, i_{gd} represent *d,q* components of the line current.

In the reference frame synchronized with the grid voltage, v_{gq}=0, v_{gd}=v_g, so

$$\begin{cases} P_g = 1.5 v_{gd} i_{gd} \\ Q_g = -1.5 v_{gd} i_{gq} \end{cases} \quad (9)$$

The inverter uses hysteresis switching and controls active power by manipulation of direct-axis current while holding reactive power at 0VAr.

$$\begin{cases} i_{gd,ref} = \left(K_{gd,p} + \dfrac{K_{gd,i}}{s}\right)\left(V_{dc,ref} - V_{dc}\right) \\ i_{gq,ref} = -\left(K_{gq,p} + \dfrac{K_{gq,i}}{s}\right)\left(Q_{g,ref} - Q_g\right) \end{cases} \quad (10)$$

The electrical model presented by three-phase voltages at the AC side of the inverter at Figure 1, is given by

$$\begin{cases} v_{ga} = v_a - \left(L_f \dfrac{di_a}{dt} + R_f i_a\right) \\ v_{gb} = v_b - \left(L_f \dfrac{di_b}{dt} + R_f i_b\right) \\ v_{gc} = v_c - \left(L_f \dfrac{di_c}{dt} + R_f i_c\right) \end{cases} \quad (11)$$

Where, v_a, v_b, v_c are three-phase voltages at the AC side of the inverter, L_f, R_f are the filter inductance and resistance.

Applying Park transformation, Eq. (11) represents the electrical model of the grid-side inverter in the d-q referential axis. It is given by:

$$\begin{cases} v_{gd} = v_d - \left(L_f \dfrac{di_d}{dt} + R_f i_d\right) + \omega L_f i_q \\ v_{gq} = v_q - \left(L_f \dfrac{di_q}{dt} + R_f i_q\right) - \omega L_f i_d \end{cases} \quad (12)$$

Where, ω is the grid frequency.

The current controller still uses PI regulator, described by

$$\begin{cases} v_{gd,ref} = v_d + \left(K'_{gd,p} + \dfrac{K'_{gd,i}}{s}\right)\left(i_{d,ref} - i_d\right) - \omega L i_q \\ v_{gq,ref} = v_q + \left(K'_{gq,p} + \dfrac{K'_{gq,i}}{s}\right)\left(i_{q,ref} - i_q\right) + \omega L i_d \end{cases} \quad (13)$$

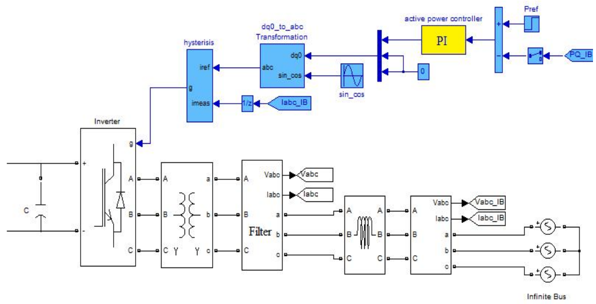


Fig. 10 Control scheme of the grid-side inverter in Simpower- systems

V. SIMULATION RESULTS AND DISCUSSION

A complete Matlab-Simulink simulation of the grid connected PV System with the MPPT algorithm and power active and reactive control of the grid-side inverter has been carried out with the following parameters:

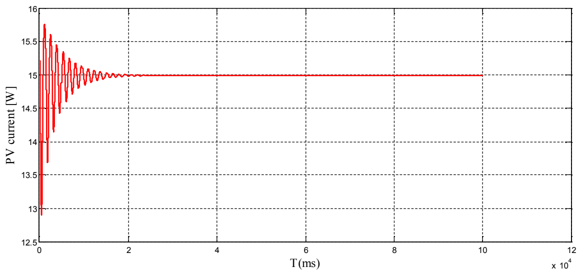
- The PV Generator is composed of 15 series and 2 parallel KC200GT modules.
- Each module is composed of 54 series cell, presents the following characteristics:
  - Nominal peak power: 200 W,
  - Nominal voltage: 26, 3 V,
  - Nominal current: 8.21 A,
  - Open-circuit voltage: 32.9 V
  - Short-circuit current: 7.61 A.
- The DC-bus capacitance: C = 200×10^{-3} F
- The grid filter: R = 5Ω, L = 0.02 H
- The grid voltage:400/50 Hz

Fig. 11 shows simulation results of electric characteristic of the PV generator in irradiation of 1000 W/m^2 and temperature of 25°C with MPPT control systems

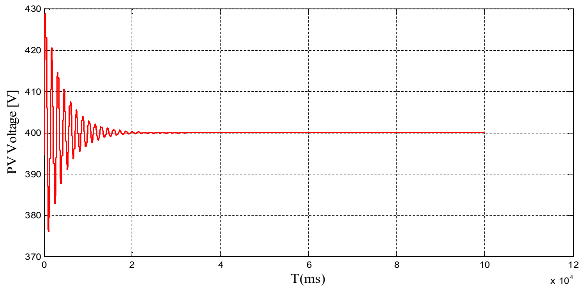
Simulation results of the system studies, the boost converter is controlled with MPPT system as shown the Fig. 8 and 9, in three phase PWM inverter control the active power and reactive powers at AC bus are considered to be constants. The input power P rapidly and accurately reaches the maximum power corresponding to V_{mpp} , I_{mpp} after 0.2 s. So, we can demonstrate the importance of the MPPT algorithm performance in resolution of the problem of the degradation of the climatic factors.

Fig. 12 shows simulation results of active and reactive powers at the AC bus for compare with the reference values by inverter DC-AC. The inverter control is based on a decoupled control of the active and reactive powers.

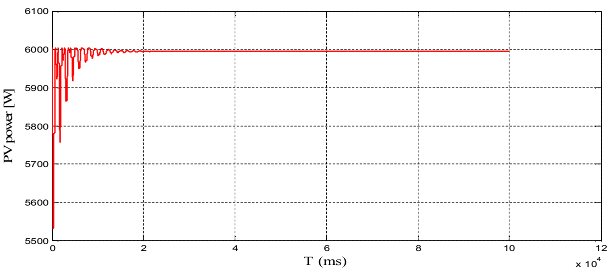
The maximum output power of PV system is 6000W. Set the power demands to be 1800W at the t €[0,4.2sec] after 4.2 sec it is equal to 6000W.This variation of the active power demands are controlled by the PI regulator with reactive power reference equal to zero. The simulation results present the performance of the control systems.



a- PV current

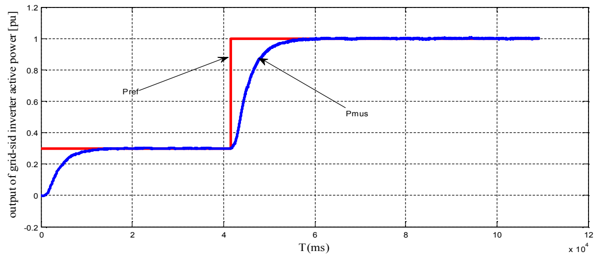


b- PV voltage

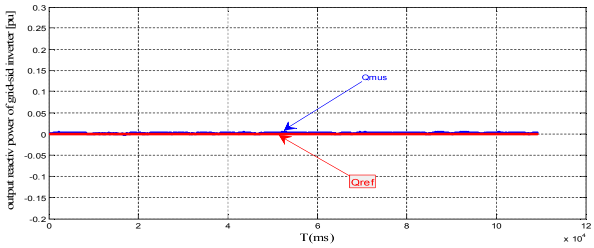


c- PV power

Fig. 11 Electric characteristics of the photovoltaic generator in irradiation 1000 W/m^2 and temperature 25°C



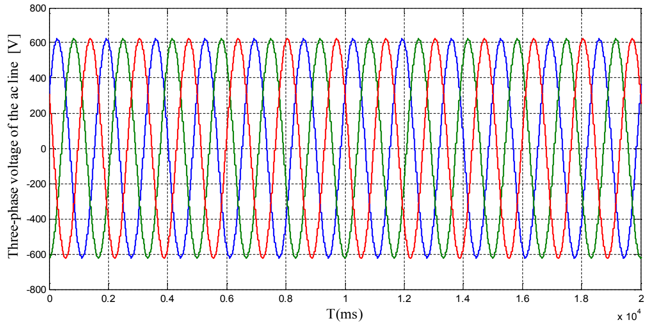
a. Active power at the AC bus



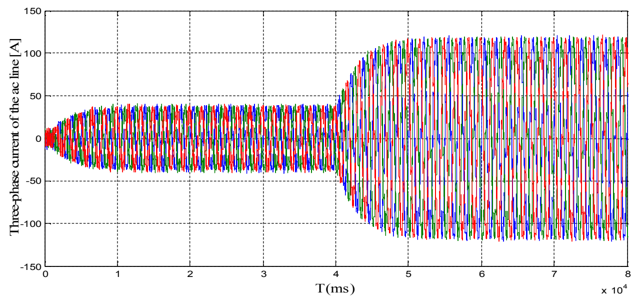
b. Reactive power at the AC bus

Fig. 12 Active power and reactive power at the AC bus

Fig. 13 shows the current injected into the main utility and the grid side voltage. As it can be noted, the voltage and current are in phase which means that the MP extracted from the PV array can pass into the DC-AC grid-side inverter as the whole system operates at unity power factor ($Q = 0$) with no reactive power exchange.



a. Three-phase voltages at the AC bus



b. Three-phase currents injected into the grid at the AC bus

Fig. 13 grid side voltage (a)and Injected current (b).

By applying the inverse Park transformation to d-q current vector components, the phase current references are obtained. These are passed to a PI controller, which outputs the pulses to drive the inverter switches. The output line voltage of the inverter is shown in Fig. 14.

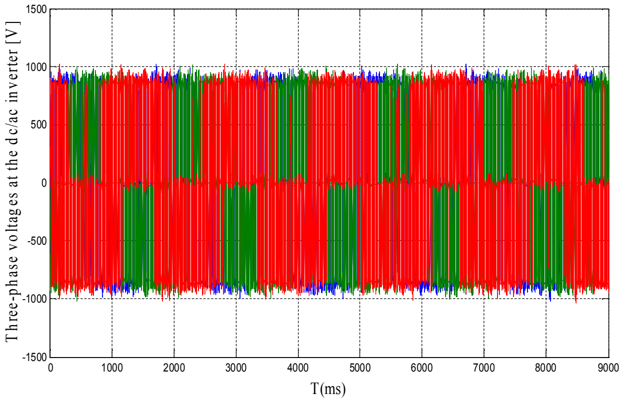


Fig. 14 Inverter line three-phase voltage.

VI. CONCLUSION

This paper presents a technique to design and control of grid-connected PV generation system, identify its components, and describe how it works. In order to convert the solar energy efficiently, the MPPT algorithm for photovoltaic systems based on P&O algorithm has been presented. It should be tracked to ensure the PV array to generate most power to utility grid, and describe the following control algorithms used for the inverter DC-AC for regulate active and reactive power sat connection bus. All simulation results, obtained under Matlab/Simulink environment, show the control performance and dynamic behavior of grid connected photovoltaic system provides good results and show that the control system is robust and efficiency.

REFERENCES

[1] Jordana, Bratt, “grid connected PV inverters: modeling and simulation”, Master Thesis of Science in Electrical Engineering Presented to the Faculty of San Diego State University 2011.

[2] Benkhlil Ehlal, Gherbi Ahmed “Modélisationet Simulation d’un Générateur Photovoltaïque Avec un étage d’adaptation DC/DC”, *The first International Conference on Energy and Sustainable Development* 29-30 November 2011, University of Adrar, Algeria.

[3] Trishan Esram. Patrick L. “Comparison of Photovoltaic Array Maximum PowerPoint Tracking Techniques,” *IEEE transactions on energy conversion*, vol. 22, no. 2, june 2007.

[4] Mohamed Salhi and Rachid El-Bachtri. “Maximum Power Point Tracker using Fuzzy Control for Photovoltaic System”, *International Journal of Research and Reviews in Electrical and Computer Engineering* (IJRRECE) Vol. 1, No. 2, June 2011S. M. Metev and V.

[5] Marcelo Gradella Villalva, Jonas Rafael Gazoli, Ernesto Ruppert Filho, “Modeling and circuit-based Simulation of photovoltaic arrays,” *10th Brazilian Power Electronics International Conference* (COBEP), 2009

[6] Br. Khiari, A. Sellami, R.Andoulsi,“ MPPT control of Photovoltaic pumping system based on discrete Sliding mode,”*International Renewable Energy Congress* November 5-7, 2010 – Sousse, Tunisia

[7] M. Salhi, R. El-Bachtiri, “Maximum Power Point Tracking Controller for PV Systems using a PI Regulator with Boost DC/DC Converter”, *ICGST-ACSE Journal,* Volume 8, Issue III, January 2009.