

# SIMULATION AND EXPERIMENTAL STUDY OF SHADING EFFECT ON SERIES AND PARALLEL CONNECTED PHOTOVOLTAIC PV MODULES

Mohammed Abdulazeez<sup>1</sup>, Ires Iskender<sup>2</sup>

Electrical and Electronics Engineering Department, Engineering Faculty, Gazi University, Ankara, Turkey

[1mehmetzeki@gazi.edu.tr](mailto:mehmetzeki@gazi.edu.tr), [2iresis@gazi.edu.tr](mailto:iresis@gazi.edu.tr)

## Abstract

Partial shading of photovoltaic modules is a widespread phenomenon in all kinds of Photovoltaic (PV) systems. In many cases the PV arrays get shadowed, completely or partially, by the passing clouds, neighboring buildings and towers, trees or the shadow of one solar array on the other, etc. This further leads to nonlinearities in characteristics. In this study, the simulation and experimental results of uniform and partial shading of PV modules are presented. Different shading pattern have been investigated on series and parallel connected photovoltaic module to find a configuration that is comparatively less susceptible to electrical mismatches due shadow problems. Simscape simulation model is employed to model the solar cell taking into account its series and parallel resistance.

**Key words:** Partial Shading, Photovoltaic Module, Simulation

## 1. Introduction

From the first space applications to the GW planned systems, more than 40 years have passed. The last decade has seen PV technology emerging as a potentially major technology for power generation in the World. The robust and continuous growth experienced in the last ten years is expected to continue in the coming years. By the end of 2008, the World cumulative PV power installed was approaching 16 GW and today, almost 23 GW are installed globally which produce about 25 TWh of electricity on a yearly basis [11].

As a result of this growth, PV installations are being increasingly employed in several applications, such as water pumping, refrigeration, air conditioning, communications, lighting, electric vehicles, PV power plants, and hybrid systems, as well as, military and space applications. However, a major challenge in using a PV source is to tackle its nonlinear output characteristics, which vary with temperature and solar insolation. The characteristics get more complicated if the entire array does not receive uniform insolation, as in partially cloudy (shaded) conditions, resulting in lower energy production yields [5, 8].

Cells under shade absorb a large amount of electric power generated by cells receiving high insolation and convert it into heat. This heat may damage the low illuminated cells under certain conditions. To relieve the stress on shaded cells, bypass diodes are added across the modules. In such a case multiple peaks in power-voltage characteristics are observed under non uniform insolation [7].

The aim of this study is to examine the effects of partial shading of series and parallel connected PV modules and compare their maximum power for varying shading patterns. The model was simulated using Simscape simulation model and the study was validated with experimental results of 75w commercial module.

## 2. The photovoltaic module models

Many models of varying complexity describing the behavior of a PV cell are available. The simplest model is insufficient in most application, therefore we need a more complex model if we are going to be able to deal with realities such as the shading problem. Fig. 1 shows the single-diode equivalent circuit model of PV cell which is commonly used in many studies and provides sufficient accuracy for most applications.

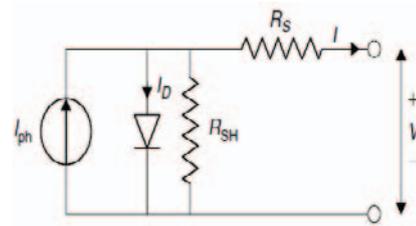


Fig. 1. Single diode model

The basic equation from the theory of semiconductors that mathematically describes the  $I-V$  characteristic of the ideal PV cell is

$$I = I_{ph} - I_o \left[ \exp \left( \frac{V + I \times R_s}{V_t} \right) - 1 \right] - \frac{V + I \times R_s}{R_{sh}} \quad (1)$$

The single diode equivalent circuit of a solar cell consists of a diode, a current source, a series and a parallel resistance. The current source generates photo-current ( $I_{ph}$ ) which is a function of incident solar irradiation and cell temperature. The diode represents p-n junction of the solar cell. At real solar cells, the voltage loss on the way to the external contacts is observed. This voltage loss is expressed by a series resistance  $R_s$ . Furthermore, leakage currents are described by a parallel resistance  $R_p$  [6].

Manufacturers of photovoltaic modules, instead of the parameters that forms I-V equation, provide only a few experimental data about electrical and thermal characteristics at STC conditions. All photovoltaic array datasheets bring basically the following information: the open-circuit voltage  $V_{oc}$ , short-circuit current  $I_{sc}$ , voltage at the maximum power

point  $V_{mp}$ , current at the maximum power point  $I_{mp}$ , the open-circuit voltage/temperature coefficient  $K_V$ , the short-circuit current/temperature coefficient  $K_I$ , and the maximum peak output power  $P_{max}$ . This information is always provided with reference to the standard test conditions (STC) of temperature and solar irradiation[10].

To estimate the electrical characteristics of a PV module under real operation conditions. The parameters that form solar cell model must be compute. In this study the single diode model parameters that forms the I-V equation is determined from the data-sheet values, given by the manufacturer at STC [8,10]. Then Simscape eight-parameter simulation model is employed to simulate solar cell and modules under real operation conditions. To be able to predict the performance of solar PV arrays and optimize its output power in case of non-uniform solar irradiation distribution the effects of total and partial shadow on energy output of different interconnected configurations in photovoltaic (PV) arrays is investigated.

Fig. 2 shows the Simscape model, the general appearance of simulation environment of the photovoltaic modules.

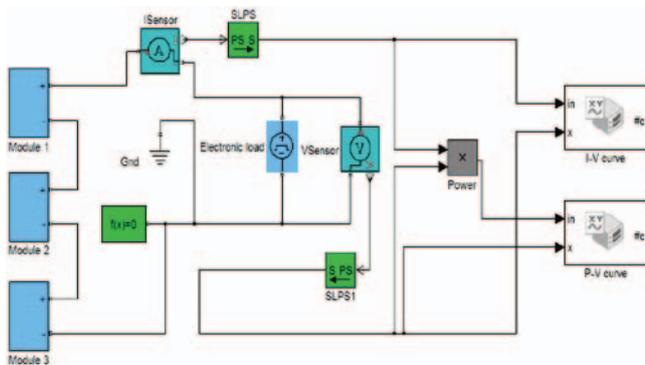


Fig. 2. General appearance of series connected modules

### 3. partial shading of PV module

Non-uniform illumination is the general problem when using solar energy. The reasons that create non-uniform illumination might be anything in the nature such as clouds, leaves, electric poles, the shadow of buildings, even guano and so on[3]. When the part of a PV module is shaded, shaded cells cannot produce as much current as unshaded cells. Since all cells are connected in series in a module, the same amount of current must flow through every cell. Unshaded cells will force shaded cells to pass more current than their new short circuit current. The only way that shaded cells can operate at a current higher than their short circuit current is to operate in the region of negative voltage. This causes a net voltage loss in the system. Shaded cells absorb power and begin to act as a load. In other words, shaded cells dissipate power as heat and cause hot spots. Consequently the current available in a series string is limited by the current of the solar cell with the lowest level of illumination.[6]

### 4. Bypass diode implementation

To overcome the effects of partial shading in a series string, a bypass diode is added in parallel with solar cell. Under normal conditions, with no shading, each diode is reverse-biased and all cells generate power. When a cell is shaded, it ceases to generate, acts as a high resistance and tends to be reverse-biased by the other cells, causing the diode across the cell to conduct, bypassing the shaded cell. The diode's internal resistance is greater than that of a PV cell when exposed to sunlight. The current follows the path of least resistance and flows through each consecutive cell in the string. When a cell in the series string is shaded, cell resistance increases significantly, making the bypass diode the path of least resistance. The current naturally follows the path of least resistance, shunting the power through the bypass diode. Thus, bypass diode reduces the amount of local heating drastically at the shaded area. On the other hand, the bypass diode holds the corresponding group of cells to a small negative voltage of approximately -0.6 V, therefore limiting the reduction in array output power.

Besides the power degradation, the shaded cells drastically change the overall I-V curve of PV module because of the bypass diodes. For modules in parallel, an additional problem, thermal runaway, can occur when bypass diodes are exercised. When one string of bypass diodes becomes hotter than the rest, they take up a larger share of the current, hence becoming even hotter. Diodes should be rated to handle the parallel module current.[5,6]

### 4. Testing and Experimental Validation of The Simulation

To investigate the accuracy of the study, a measurement system has been established. For this study LORENTZ 75W PV module that consists of 32 cells in series is used. This kind of module use a by-pass diode across 8 cells. The specifications of the solar cell and module used in this simulation study are given in Table. 1

Table 1. Electrical Specifications

Peak power ( $P_{max}$ )	75 [Wp]
Max. power current ( $I_{mp}$ )	4.6 [A]
Max. power voltage ( $V_{mp}$ )	16.5[V]
Short circuit current ( $I_{sc}$ )	5.4 [A]
Open circuit voltage ( $V_{oc}$ )	21 [V]
Number of cells per module	32

Several profile of shading have been performed on the test module using two different systems configuration, series and parallel. The shading effect was artificially generated by covering parts of the module with partially transparent gelatin paper which reduces the incoming solar radiation by approximately 90%. Irradiance, module temperature, current and voltage values are measured and recorded simultaneously via data logger. Shading patterns which are examined are given in table 2 and 3.



Fig. 3. Experimental setup for validation of the model

Table 2. series connected modules

Case	Shading conditions
1	Series connected three PV module ( $G=960\text{W/m}^2$ , $T=48^\circ\text{C}$ )
2	Module1 $G_{SH}=115\text{W/m}^2$ ; Module2 $G=970\text{W/m}^2$ ; Module3 $G=970\text{W/m}^2$
3	Module1 $G_{SH}=115\text{W/m}^2$ ; Module $G=980\text{W/m}^2$ ; Module3 $G_{SH}=70\text{W/m}^2$
4	Module1 $G=1020\text{W/m}^2$ ; Module2 $G=1020\text{W/m}^2$ ; Module3 50% shadow $G_{SH}=115\text{W/m}^2$
5	Module1 50% shadow $G_{SH}=110\text{W/m}^2$ ; Module2 $G=975\text{W/m}^2$ ; Module3 50% shadow $G_{SH}=110\text{W/m}^2$
6	Module1 $G_{SH}=400\text{W/m}^2$ ; Module2 $G=930\text{W/m}^2$ ; Module3 $G_{SH}=700\text{W/m}^2$

Fig. 4 to Fig. 15 shows the simulated and experimental results for different shading patterns. It is observed that the simulated results closely match the measured values.

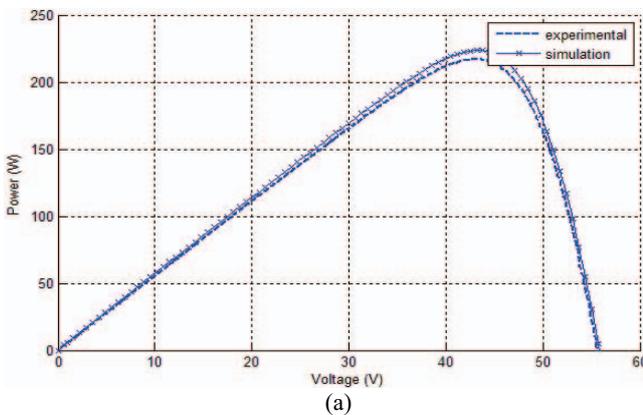


Fig. 4. Case1 series connected modules P-V curve

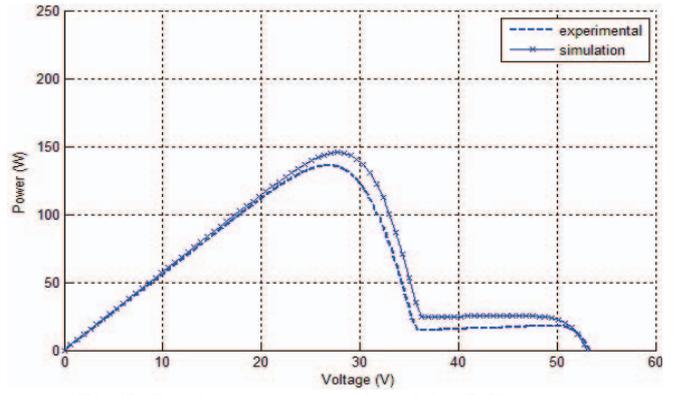


Fig. 5. Case2 series connected modules P-V curve

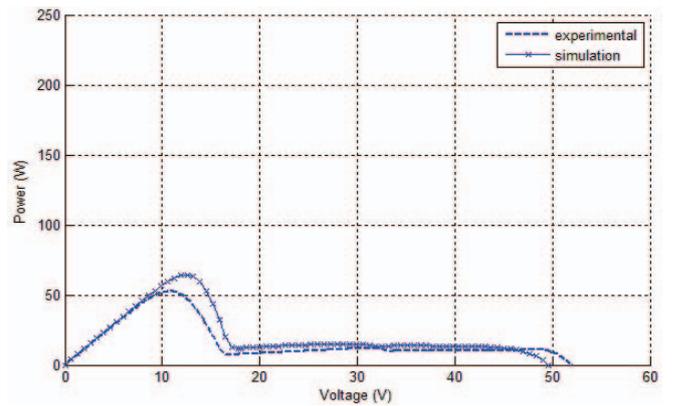


Fig. 6. Case3 series connected modules P-V curve

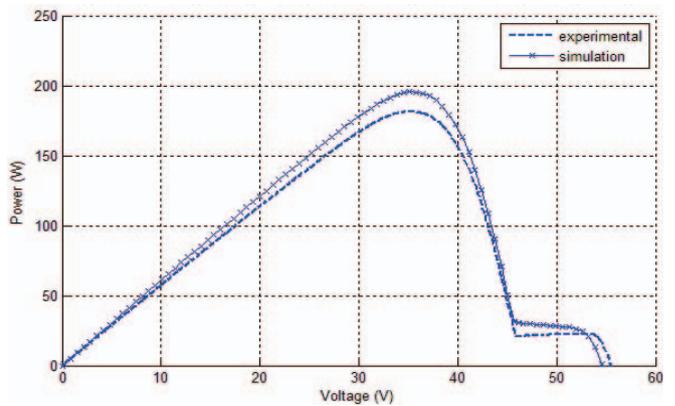


Fig. 7. Case4 series connected modules P-V curve

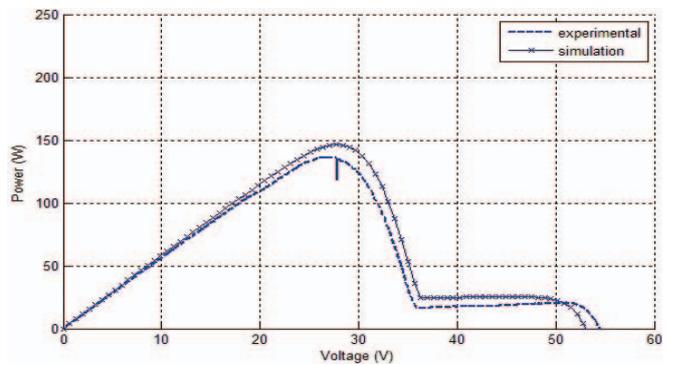


Fig. 8. Case5 series connected modules P-V curve

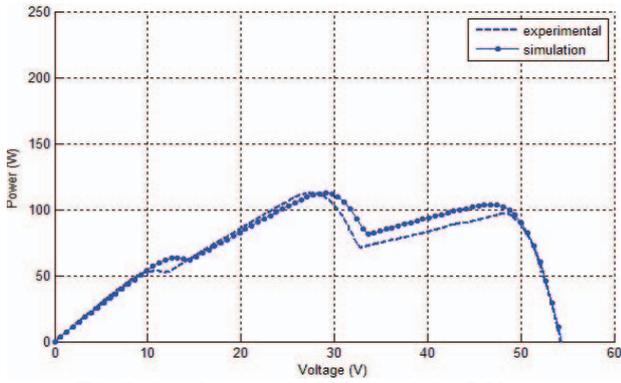


Fig. 9. Case6 series connected modules P-V curve

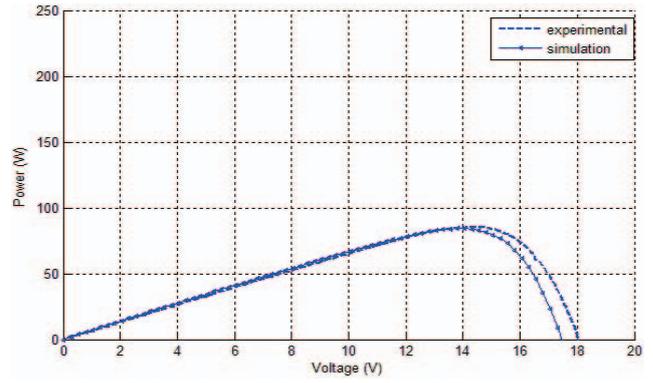


Fig. 12. Case3 Parallel connected modules P-V curve

Table 3. parallel connected modules

Case	Shading conditions
1	parallel connected three modules ( $G=1000\text{W}/\text{m}^2$ , $T=48^\circ\text{C}$ )
2	Module1 $G_{SH}=120\text{W}/\text{m}^2$ ; Module2 $G=983\text{W}/\text{m}^2$ ; Module3 $G=983\text{W}/\text{m}^2$
3	Module1 $G_{SH}=120\text{W}/\text{m}^2$ ; Module2 $G=985\text{W}/\text{m}^2$ ; Module3 $G_{SH}=75\text{W}/\text{m}^2$
4	Module1 $G=985\text{W}/\text{m}^2$ ; Module2 $G=985\text{W}/\text{m}^2$ ; Module3 50% shadow $G_{SH}=115\text{W}/\text{m}^2$
5	Module1 50% shadow $G_{SH}=110\text{W}/\text{m}^2$ ; Module2 $G=975\text{W}/\text{m}^2$ ; Module3 50% shadow $G_{SH}=110\text{W}/\text{m}^2$
6	Module1 $G_{SH}=400\text{W}/\text{m}^2$ ; Module2 $G=930\text{W}/\text{m}^2$ ; Module3 $G_{SH}=700\text{W}/\text{m}^2$

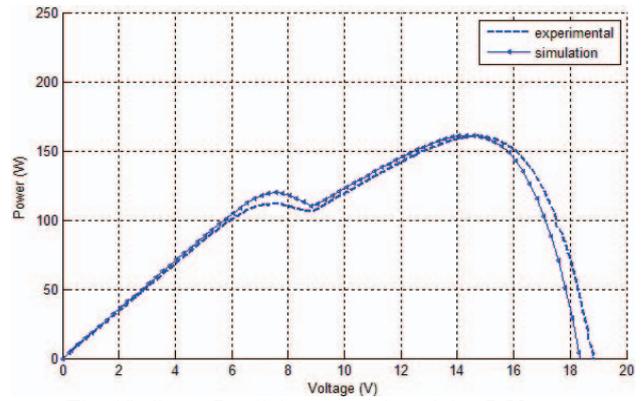


Fig. 13. Case4 Parallel connected modules P-V curve

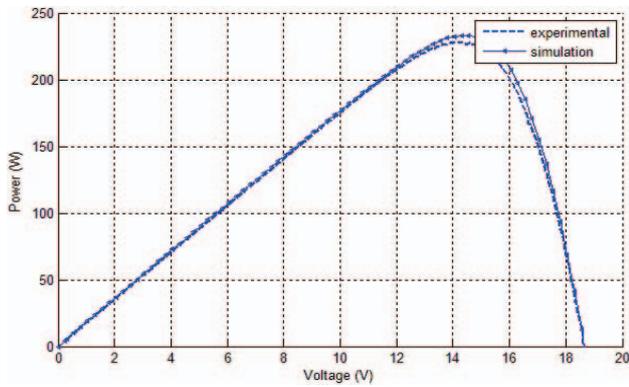


Fig. 10. Case1 Parallel connected modules P-V curve

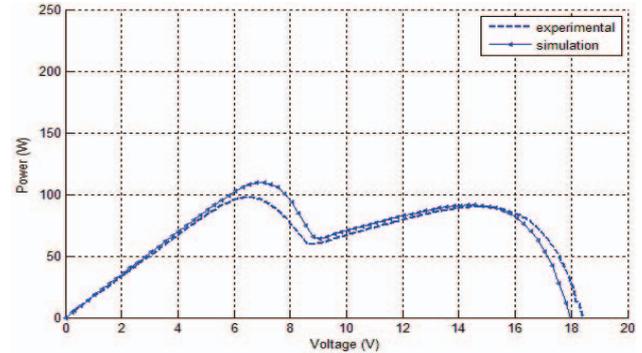


Fig. 14. Case5 Parallel connected modules P-V curve

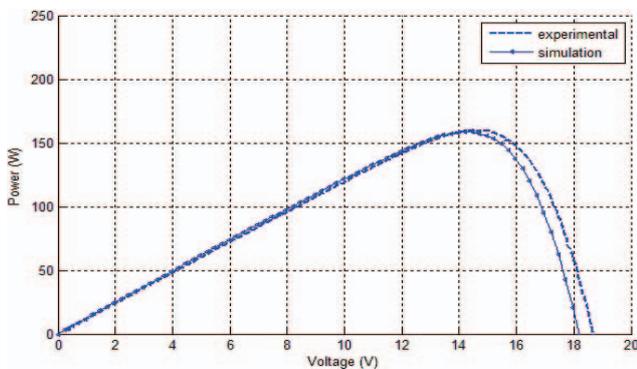


Fig. 11. Case2 Parallel connected modules P-V curve

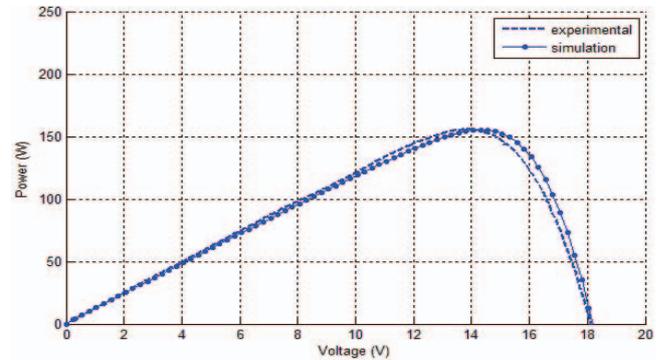


Fig. 15. Case6 Parallel connected modules P-V curve

The difference in the curves at some points may be due to the change in irradiation over a time span during which the measurements were carried out, manufacturer's tolerances and the temperature differences between shaded and unshaded cells which are taken as a constant value.

**Table 4.** maximum power and fill factor (series connected)

Case	$P_{max}$	$I_{max}$	$V_{max}$	Fill factor(FF)
1	217	5.037	43.08	0.69
2	136.1	5.09	26.74	0.44
3	52.61	4.91	10.7	0.17
4	181.5	5.158	35.19	0.55
5	136.4	5.12	26.65	0.43
6	112.3	4.06	27.61	0.35

**Table 5.** maximum power and fill factor (parallel connected)

Case	$P_{max}$	$I_{max}$	$V_{max}$	Fill factor(FF)
1	288.1	15.96	14.29	0.68
2	160	10.99	14.56	0.7
3	85.35	5.95	14.35	0.7
4	160.7	7.85	14.08	0.35
5	97.4	14.98	6.5	0.30
6	155.5	11.14	13.97	0.68

## 5. Conclusions

The electrical performance of series and parallel connected modules have been investigated to find a configuration which is comparatively less susceptible to electrical mismatches due to shadow problems. Simscape simulation model is employed to model solar cell by taking series and parallel resistance of the cells into account. For this study various shading patterns have been simulated using the Simscape simulation model. These models have been successfully contrasted by comparing of simulation results with real measured data. An advantage of the presented simulation procedure is the possibility of simulation the whole PV array introducing different input, parameters for each one of the solar cells presents in the PV generator, making possible the study of different shadow patterns as well as temperature variations in particular solar cells. Also the simulation model is handy to design the most optimum configuration of the PV array to extract the maximum power. Simulation and measurement results establish the superiority of parallel type over the series one in most shading profiles.

## 6. References

- [1] M.C. Alonso-Garcia, J.M. Ruiz, and F. Chenlo, "Experimental study of mismatch and shading effects in the I-V characteristic of a photovoltaic module", *Solar Energy Materials & Solar Cells*, vol. 90, no. 3, pp. 329-340, February, 2006.
- [2] N. D. Kaushika and N. K. Gautam, "Energy Yield Simulations of Interconnected Solar PV Arrays", *IEEE Transactions on Energy Conversion*, vol. 18, no. 1, pp. 127-134, March, 2003.
- [3] Y. Liu, Z. Pang, and Z. Cheng, "Research on an Adaptive Solar Photovoltaic Array Using Shading Degree Model-Based Reconfiguration Algorithm", Control and Decision Conference, Xuzhou., 2010, pp. 2356-2360.
- [4] J E. Díaz-Dorado, A. Suárez-García, C. Carrillo, and J. Cidrás" Influence of the shadows in photovoltaic systems with different configurations of bypass diodes", *International Symposium on Power Electronics*, Pisa, 2010, pp. 134-139.
- [5] A.S. Masoum, F. Padovan, and M.A.S. Masoum, " Impact of Partial Shading on Voltage and Current Based Maximum Power Point Tracking of Solar Modules", *IEEE Power and Energy Society General Meeting*, Minneapolis., 2010, pp. 1-5.
- [6] E. Karatepe, M. Boztepe, and M. Çolak "Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells ", *Solar Energy*, vol. 81, no. 8, pp. 977-992, August, 2007.
- [7] R. Ramabadran, and B. Mathur " MATLAB Based Modelling and Performance Study of Series Connected SPVA under Partial Shaded Conditions", *Second International Conference on Emerging Trends in Engineering & Technology*, Maharashtra, 2009, pp. 85-94
- [8] H. Patel, and V. Agarwal, " MATLAB-Based Modeling To Study The Effects of Partial Shading on PV Array Characteristics ", *IEEE Transactions On Energy Conversion*, vol. 23, no. 1, pp. 302-310, March, 2008.
- [9] S. Silvestre, A. Boronat, And A. Chouder, " Study of bypass diodes configuration on PV modules ", *Applied Energy*, vol. 86, no. 9, pp. 1632-1640, September, 2009
- [10] M. G. Villalva, J. R. Gazoli, and E. Ruppert F., " Modeling and circuit-based Simulation of photovoltaic arrays", *Power Electronics Conference*, Bonito-Mato Grosso do Sul, 2009, pp. 1244-1254
- [11] ] The EPIA Global Market Outlook for Photovoltaics (PV) until 2014.[Online] 2010. <http://www.epia.org>