Novel Photovoltaic Module Modeling using Matlab/Simulink

Amevi Acakpovi
Accra Polytechnic -Ghana
P.O Box: GP561

Essel Ben Hagan
Accra Institute of Technology - Ghana
P.O.Box AN-19782, Accra-North

ABSTRACT

Extensive works exist in literature about modeling solar power generation by photovoltaic cell. However, some fundamental aspects of the design making it flexible and exploitable for other research works remain difficult and unclear under Matlab Simulink. This work proposes an understandable model of PV cell, suitable for upgradability and further use for other designs. After dealing with a sound analytical model on the PV cell, the paper presents a clear modeling under Simulink. The model is designed to take excitation from three inputs including temperature, irradiance and voltage. Simulations were run and results in terms of peak power and current were analyzed. In total the similarities were quite satisfactory as compared to previous works. However, some little differences in the responses of the model to various inputs were observed. These results, further confirm the novelty of the proposed model.

General Terms

Modeling, Simulation, Solar Energy Conversion

Keywords

Photovoltaic Effect, Solar Cell Modeling and Simulation, Irradiance, Temperature.

1. INTRODUCTION

Solar energy has the advantage of being environmentally friendly, pollution free and has unlimited availability [1]. All these factors make solar energy to be attractive. Solar energy can be extracted through many ways including the photovoltaic effect that consists of a direct transformation of sunlight into electricity by means of solar panels. Modeling an accurate photovoltaic effect has been a great challenge for science for several years. However common and simple models of solar panel have been developed and integrated to many engineering software including Matlab. These models are not necessarily adequate for application involving hybrid energy system as they need a flexible tuning of some parameters that are not made available with the existing models. Therefore, this paper investigates an accurate, reliable and easy-to-tune model of photovoltaic cell.

2. PREVIOUS WORKS

Recent works done by Ciobotaru (2007), Pandiarajan (2012) and Jamri (2010), respectively [2], [3] and [4], revealed some basic aspects of photovoltaic cell modelling. They have adopted similar model of solar cell and carried out some simulation works on their output characteristics including power vs voltage and current vs voltage using MATLAB/Simulink. The output characteristics are similar showing a power that increases proportionally to the voltage from an initial stage up to a certain threshold after which it decreases rapidly down to zero.

Marcelo Gradela's (2009), [5], also did intensive works on solar, especially through his paper: "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays". A PV array model normally follows a nonlinear I-V equation which parameters can be found by considering three basic points: open circuit, maximum power, short circuit. Given these three parameters as usually provided by manufacturers, the approach of modeling try to find the best I-V equation for a single diode photovoltaic model including the effect of series and parallel resistance and warranties that the maximum power of the model matches with the maximum power of the real array. Results show emphasis on the value of the series resistance which can actually act dramatically on the output characteristics. Other modeling methods include the state space averaging technique by Ramos-Paja (2010), [6]. This technique consists of developing two controllers to optimize the non-linear output characteristic of a PV array. These controllers are calculated to mitigate input and load disturbances. In addition, the proposed model of Ramos-Paja (2010) and its underlying control strategy are used with a Maximum Peak Power Tracking (MPPT) algorithm to show the feasibility in advanced control strategies for PV systems. In summary, the PV model involving a diode with series and parallel resistances have been commonly depicted by Tsai & al. (2008), [7], as well as Castener and Sylvester (2002), [8]. However the results are very similar with some slight variations depending on the direction given to the analysis carried out in the paper.

3. METHOD

3.1 Overview of the Proposed Model

The generalized model of PV cell, [9] as presented in Figure 1 consists of a diode in parallel with a current source to which are added a series and a parallel resistance.
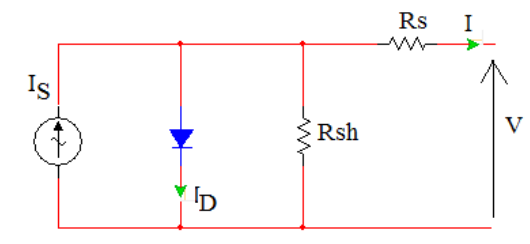

Fig 1: General Model of PV solar cell

3.2 Analytical Model of Solar Panel

A certain number of solar cells, Ns are put in series and a certain number of them, Np are put in parallel in order to achieve some levels of voltage and current that are convenient for applications. The combination of Ns and Np solar cells put respectively in series and in parallel, constitutes a solar panel. Commonly encountered solar panels have a voltage output ranging from 12V to 20V with a current also ranging from 1.5 to 3.5A. They can be directly used to power home appliances.

Based on the general model of solar cell illustrated in figure 1, a solar panel which is a combination of Ns and Np solar cells put in series and parallel respectively, can be modeled as shown in Figure 2.
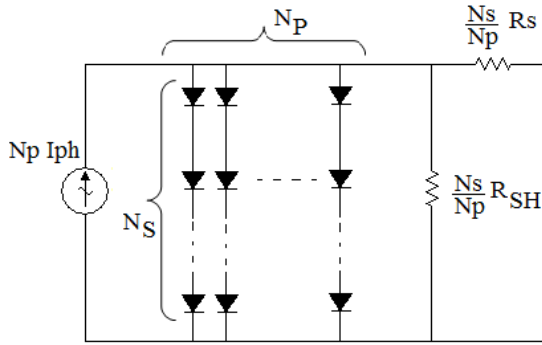
Fig 2: Model of solar panel with Ns series cell and Np parallel cells

Consequently, the following equations (1-4), as described by [7], hold:

$$I = N_P I_{PH} - N_P I_S \left[exp\left(\frac{q}{kT_C A} \cdot \left(\frac{V}{N_S} + \frac{IR_S}{N_P} \right) \right) - 1 \right] - \frac{1}{R_{SH}}$$
$$\cdot \left(\frac{N_P V}{N_S} + IR_S \right) \qquad (1)$$

with:

$$I_{PH} = \left[I_{SC} + K_I (T_C - T_{Ref}) \right] \cdot \lambda \qquad (2)$$

$$I_S = I_{RS} \left(\frac{T_C}{T_{Ref}} \right)^3 \cdot exp\left[\frac{qE_G}{kA} \left(\frac{1}{T_{Ref}} - \frac{1}{T_C} \right) \right] \qquad (3)$$

And

$$I_{RS} = \frac{I_{SC}}{exp\left(\frac{qV_{OC}}{N_S kAT_C} \right) - 1} \qquad (4)$$

Where

- I_{PH}: photocurrent
- I_S: Cell saturation current
- q: Electron charge. $q = 1.6 \times 10^{-19} C$
- k: Boltzmann's constant. $k = 1.38 \times 10^{-23} J/K$
- T_C: Cell operating temperature
- A: Ideal factor dependent of the PV characteristic, A=1.3 for poly-crystalline solar cell
- R_{SH}: Shunt resistance=100Ω
- R_S: Series resistance =0.01Ω
- I_{SC}: Cell short-circuit current at 25°C, 1kW/m²

- V_{OC}: Open-circuit voltage
- K_I: Short-circuit current temperature coefficient
- T_{Ref}: Cell reference temperature
- λ: Solar insolation (irradiance) in kW/m²
- I_{RS}: Cell reverse saturation current
- E_G: Band gap energy of semiconductor used in a cell = 1.11eV
- N_P: Number of cells in parallel=12
- N_S: Number of cells in series=20

In addition, Table 1 gives some intrinsic characteristics of PV cell, extracted from manufacturer data [10] that would be used for the Simulink modelling:

Table 1. PV Cell characteristics from manufacturer

Characteristics	Specifications
Typical peak power (P_P)	235W
Voltage at peak power (V_{PP})	29.3 V
Current at peak power (I_{PP})	8.03A
Short-circuit current (I_{SC})	6.9A
Open-circuit voltage (V_{OC})	34 V
Temperature coefficient of open-circuit voltage	-73mV/°C
Temperature coefficient of short-circuit current (KI)	0.047mA/°C
Approximate effect of temperature on power	-0.43W/°C
Nominal operating cell temperature (NOCT)	45°C

3.3 Simulink Modelling

Using the Simulink simulation tool, the model of photovoltaic cell illustrated in Figure 3 was first obtained. The model consists of a direct implementation of the analytical expressions described above. The concept of source/sink was used throughout the simulation so that variable can carry on their respective names and make the model readable. In the first instance, all constants were defined, labelled appropriately and later combined using mathematical tools (sum, product, division and function box) of Simulink to build the analytical model presented above.

However, this was not able to be run directly under Simulink because of the presence of two algebraic loops. Algebraic loop error appears when an output is directly dependent on the combination of other inputs and itself [11]. This transpires through equations having the same output parameter on both side of the equal sign. For instance, if we reconsider equation (1) as follow:

$$I = I_1 + I_2 - \frac{1}{R_{SH}} \cdot \left(\frac{N_P V}{N_S} + IR_S \right) \qquad (5)$$

With $I_1 = N_P I_{PH}$

And $I_2 = N_P I_S \left[exp\left(\frac{q}{kT_C A} \cdot \left(\frac{V}{N_S} + \frac{IR_S}{N_P} \right) \right) - 1 \right] \qquad (6)$

The variable I appears on both side of the equation (5) creating an algebraic loop in Simulink. Also the second part of equation (6) also shows an exponential function having the same parameter I as its input. This is a second algebraic loop appearing in our model (see Figure 3).

To solve the first algebraic loop, the equation has been rewritten as follow:

$$I\left(1 + \frac{R_S}{R_{SH}}\right) = I_1 + I_2 - \frac{1}{R_{SH}} \cdot \frac{N_P V}{N_S}$$

And the value of I is inferred:

$$I = \frac{1}{\left(1 + \frac{R_S}{R_{SH}}\right)} \cdot \left(I_1 + I_2 - \frac{1}{R_{SH}} \cdot \frac{N_P V}{N_S}\right) \qquad (8)$$

This practice help to eliminate the first algebraic loop but the second one contained in the expression of I_2 still exists and shows up with the error message below at the running of the simulation:

Warning: Block diagram 'solar1' contains 1 algebraic loop(s). To see more details about the loops use the command line Simulink debugger by typing "sldebug solar1" in the MATLAB command window. To eliminate this message, set the Algebraic loop option in the Diagnostics page of Simulation Parameters Dialog to "None" (7)

Found algebraic loop containing:

'solar1/Sum4'

'solar1/Divide6'

'solar1/exp1'

'solar1/Sum5'

'solar1/Product9'

'solar1/Sum7'

'solar1/Divide7'

'solar1/Product7' (algebraic variable)

The second algebraic loop was finally solved by inserting a delay block in the feedback loop coming from the output I before entering the exponential block so that the current value can be calculated based on the previous one. With all these changes, the model of Figure 3 has been improved to become Figure 4 which simulates without error and produce convenient results.

Also, a multiplexer was used in Figure 4 to collect the results produced by simulation into a variable "Vout" that is later used to plot the different curves under Matlab command

mode. The short code below, helps to plot the results for various simulations:

V=Vout(:,1);

I=Vout(:,2);

P=Vout(:,3);

figure(1)

%clf

plot(V,I), xlabel('Voltage'), ylabel('Current'),title ('Current characteristic'), grid on, hold on, axis([0 20 0 17]);

figure(2)

%clf

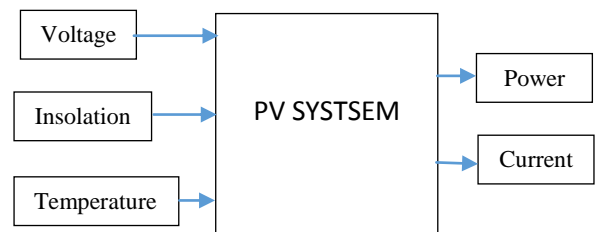plot(V,P), xlabel('Voltage'), ylabel('Power'),title ('Power characteristic'),grid on,hold on, axis([0 20 0 280]);

3.4 Simulation Scenarios

The investigated outputs of the PV system include the instantaneous power and current characteristics. These parameters vary according to the following input parameters: solar insolation, temperature and voltage as shown by the Figure 5.


Fig 5: Inputs / Outputs of the model to be simulated

Two scenarios were simulated.

- First the temperature was kept constant and the insolation was varied within a reasonable range.

- In second instance, the insolation was kept constant whilst the temperature was varied to show the effect of solar radiation on PV cells.
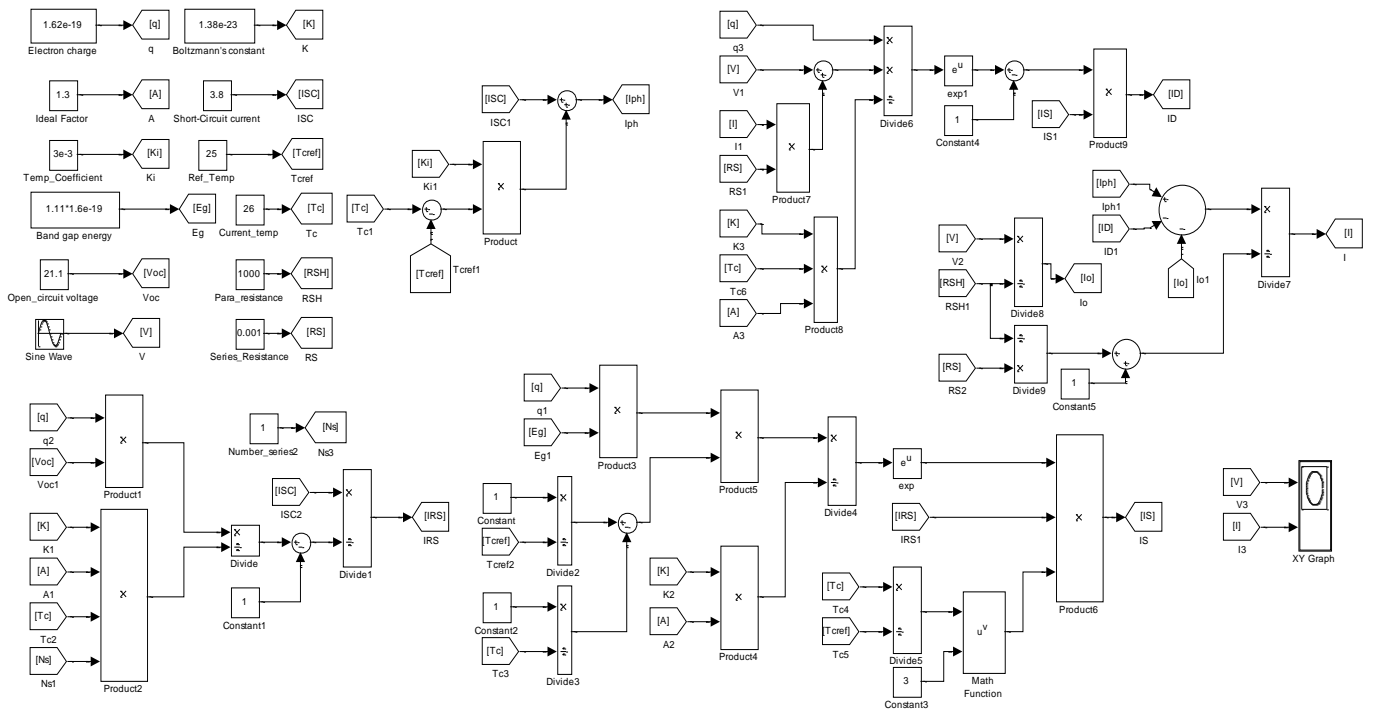
Fig 3: Initial Model of Solar Panel under Matlab/Simulink
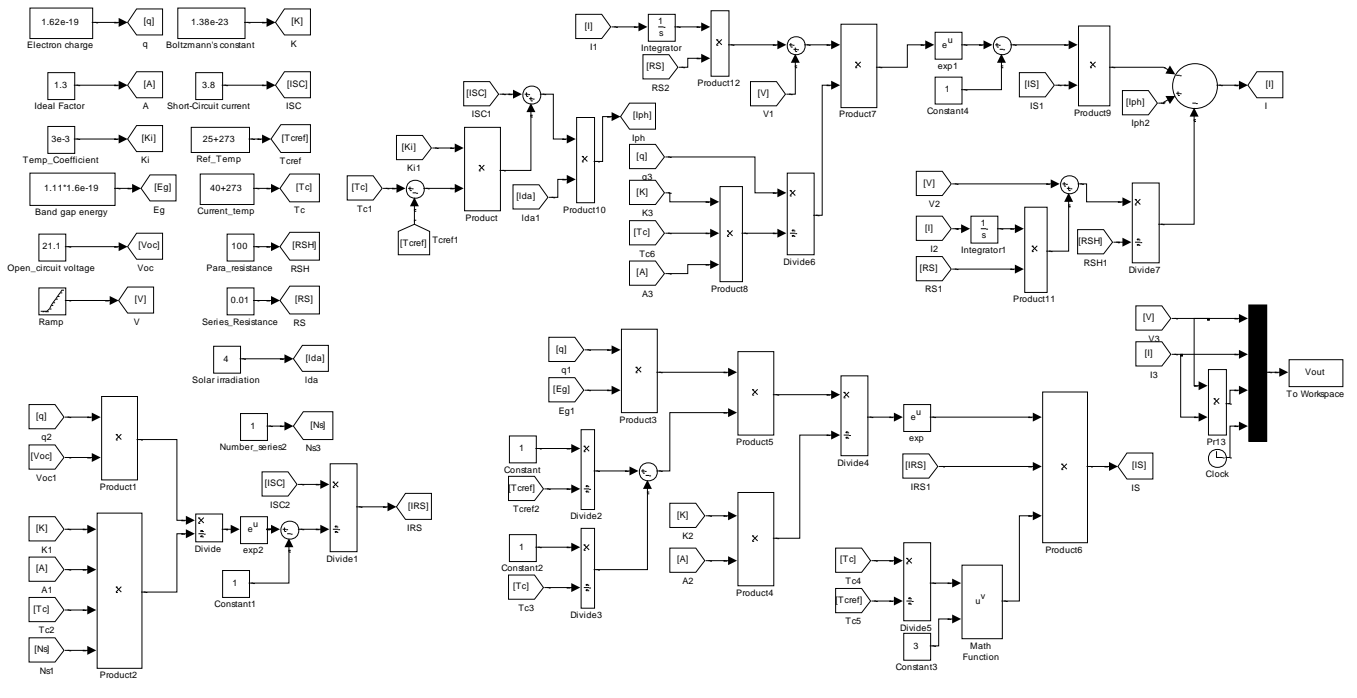
**Fig 4: Improved Model of solar panel under Matlab/Simulink**

4. RESULTS AND ANALYSIS

The simulation results are shown below. Figure 6 and Figure 7 represent respectively, the current and power characteristics of the designed model for a fix temperature of 26°C and for varying values of irradiation between the ranges of 4 to 6kW/m^2.
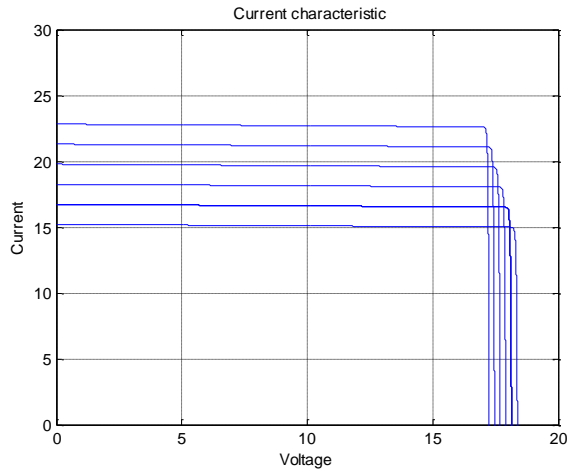
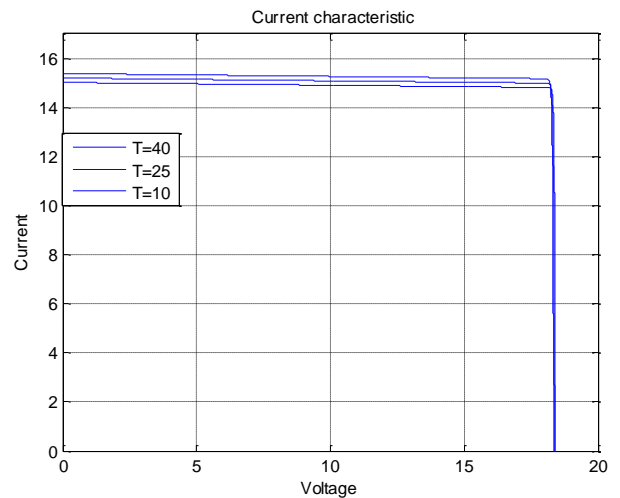**Fig 6: Current characteristics of PV panel for varying solar irradiation**

The current characteristic shows a constant variation of the current followed by a sudden decrease after exceeding a threshold voltage. As the irradiation increases, the constant value of the current also increases but the threshold voltage reduces slightly. This result is good and can be confirmed by previous studies including [12-15].
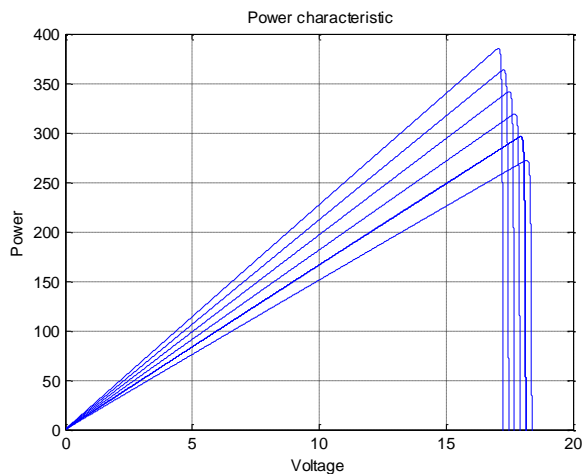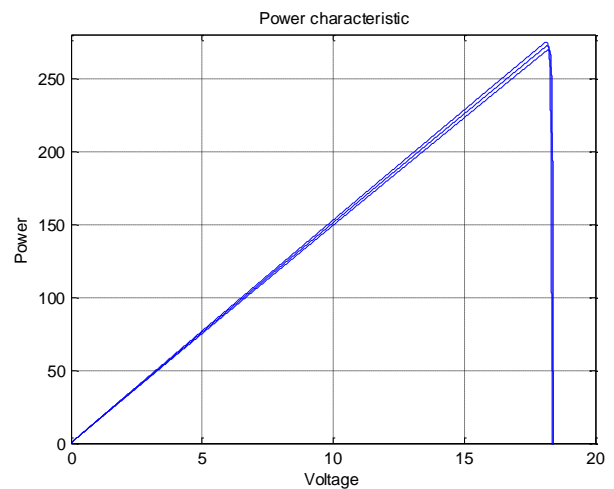

Fig 7: Power characteristics of PV panel for varying solar irradiation

Moreover, the power characteristic also shows two fundamental aspects including a proportional increase in the first instance followed by an exponential decrease after attainment of the threshold voltage. Again increasing solar irradiation impact positively on the power characteristic producing higher power for a constant voltage. These results are also in conformity with previous studies done on solar such as [12-15].

Furthermore, the irradiance was kept constant and the temperature was varied apart from the standard temperature in order to determine the effect on the results. Figure 8 and Figure 9 show the impact of temperature variation on the model. It appears that the model develops some small sensitivity to big variation of temperature. However, this effect is negative i.e. as the temperature increases the current and the power characteristics decrease.

Fig 8: Current characteristics of PV panel for varying temperature

Fig 9: Power characteristics of PV panel for varying temperature

5. CONCLUSION

In summary, this paper dealt with the modelling of solar energy conversion through photovoltaic effect. An analytical model presented in first instance was later constructed under Matlab/Simulink and simulated for two effects: varying irradiance and varying temperature. The developed model was firstly not simulating successfully because of the presence of two algebraic loops. However, the model has been later improved with a comprehensive solution to the two algebraic loops. One was solve by insertion of delay block while the other was solve by a re-working of necessary formula. Finally, simulation results show that more irradiance greatly increase the generation of energy while big variation of temperature reduces the current and power produced. This results obtained in form of two fundamental graphs namely power characteristic (power over voltage) and current characteristic (current over voltage) are very similar to empirical results known for solar system and this, further confirms the effectiveness of the proposed model.

6. REFERENCES

[1] Alsayid, B., and Jallad, J. 2011. Modeling and Simulation of Photovoltaic Cells Module Arrays. *International Journal of Research and Reviews in Computer Science (IJRRCS).* Vol. 2, No. 6, pp. 1327-1331.

[2] Gow, J. A. and Manning, C. D. 1999. Development of a Photovoltaic Array Model for Use in Power-Electronics Simulation Studies. *IEEE Proceedings of Electric Power Applications.* Vol. 146, No. 2, pp. 193–200.

[3] Pandiarajan, N., Ramaprabha, R., and Muthu. R. 2012. Application of Circuit Model for Photovoltaic Energy Conversion System. *Hindawi Publishing Corporation: International Journal of Photo Energy*, ID410401, 14 p.

[4] Jamri, M., S., and Wei, T., C. 2010. Modeling and Control of a Photovoltaic Energy System Using the State Space Averaging Technique. *American journal of Applied Sciences.* ISSN 1546-9239. pp. 682-691.

[5] Villalva, M., G., Gazoli, J., R., and Filho. E., R. 2009. Comprehensive Approach of Modeling and Simulation of a Photovoltaic Arrays. *IEEE Transaction on Power Electronics*, Vol.24, No.5. pp. 1198-1208.

[6] Ramos-Paja, C., A., Perez, E., Montoya, D., G., Carrejo, C., E., Simon-Muela, A., and Alonso, C. 2010. Modelling of Full Photovoltaic Systems applied to Advanced Control Strategies. *Columbia: Universidad Nacional de Columbia*

[7] Tsai, H., L., Tu, C., S., and Su, Y., J. 2008. Development of Generalized Phottovoltaic Model Using MATLAB/SIMULINK. *Proceedings on the world congress on Engineering and Computer Science. WCECS,* ISBN: 978-988-98671-0-2, 6p.

[8] Castaner, L., and Sylvestre, S. 2002. Modelling photovolaic system using Pspice. *Spain: Universidad Polytecnica de Cataluna Barcelona*. Wiley edition.

[9] Padmanabhan, B. 2008. Modelling of Solar Cell. *US: Arizona State University*

[10] Trinasolar. 2012. TSM-PC05, The Universal Solution. http://ww.trinasolar.com/HtmlData/downloads/us/products/multi/PA05_EN_datasheet_June_2012_US.pdf

[11] The MathWorks, Inc 1999. Simulink: Dynamic System Simulation for Matlab.http://mathworks.com

[12] Gupta, S. C., Kumar, Y., and Gayatri, A. 2007. Optimal sizing of solar-wind hybrid system. *Information and Communication Technology in Electrical Sciences (ICTES 2007). ICTES.* IET-UK International Conference.

[13] DenHerder, T. 2006. Design and Simulation of a Photovoltaic Super System Using Simulink. San Louis Obispo: Electrical Engineering Department, California Polytechnic State University.

[14] Wei, Z. 2008. Simulation and optimum design of hybrid solar-wind and solar-wind-diesel power generation systems. Hong Kong Polytechnic University.