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Photovoltaic Generator Characteristics Modeling Using MATLAB/SIMULINK

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***Abstract* — This paper describes a simple photovoltaic model (single diode) and its characteristics at different temperatures and irradiance conditions. Photovoltaic cells data sheet, which are supplied by manufactures, includes only PV data at reference conditions. To predict PV performance at actual operation conditions it is necessary to evaluate PV characteristics at non-reference conditions. For this purpose, an electrical circuit model of PV is selected and governed equation of model for a sample PV is solved using MATLAB solvers. After finding the model unknowns, related equations of model inputs are implemented in SIMULINK blocks to generate the model outputs. So the model will be simulated by SIMULINK to generate photovoltaic characteristics curves. These curves allow estimating behavior of sample PV with respect to temperature and irradiance changes.**

***Keyword* — Photovoltaic, Single diode model, MATLAB, SIMULINK.**

Introduction

Solar cell power system's design and their performance assessment are to be based on the electrical characteristics, that is the voltage-current (V-I) relationship of the PV cells under various cell temperatures and radiation levels. PV module has nonlinear characteristics and so needs to model and simulated. PV modeling is being continuously updated to enable researchers to have a better understanding of its performance. Several electrical models have been proposed. The most commonly used models are single diode, two-diode and simplified [2]. The single diode model emulates the PV characteristics fairly and accurately. Equivalent circuit of above mentioned models are presented in figure 1. In current paper single diode model (Fig. 1-a) has been selected and will be studied. I-V characteristic of PV is a non-linear equation with multiple parameters. Some of those are constant and others must be computed. In simplified model some un-known parameters cannot be calculated and thus they are assumed constant. Sometimes, searchers develop simplified methods where, some unknown parameters cannot be calculated. They are thus assumed constant. For example, in Walker and Geoff (2001) the series resistance $R_s$was included, but not the parallel resistance for a model of moderate complexity. The same assumption is adopted in Benmessaoud et al. (2010),S Atlas and Sharaf (1992), Beckman et al. (xxxx), Bryan (1999), Bouzid et al. (2005), by considering the parallel resistance very large. Other authors neglect both parallel and series resistances; the former due to being very large, the latter being very small. There are in the literature other papers, in which, these two internal characteristics of the PV module are very important and have to be determined more accurately as in Townsend (1989), Alsayid and Jallad (2011), KashifIshaque and Syafaruddin (2011), Gazoli et al. (2009), De Soto (2006) and Chouder et al. (2012)[4].As mentioned above single diode model is studied in current paper and both series and parallel resistance and also three other parameters will be calculated. The main contribution of the paper is the solving non-linear equations of model by MATLAB and then implementation of PV model in the form of masked blocks to generate model behavior in different condition of temperature and irradiance levels.

PV mathematical model

By selecting single diode model and considering related equivalent circuit (Fig.1-a) the output current can be determined by applying Kirchhoff law:[1]

$$I = I_l - I_D - I_{sh} = I_l - I_o\left[\exp\left(\frac{V+IR_s}{a}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

Where: "I" is PV output current.
"V" is PV output voltage.
"I_l" is the light current.
"I_o" is the diode reverse saturation current.
"R_s" is the series resistance.
"R_{sh}" is the shunt resistance.

The parameter "a" which is called the modified ideality factor and is defined as:[1]

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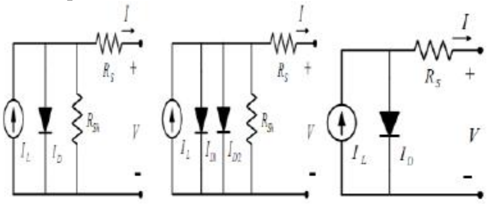
$$a \equiv \frac{nkTNs}{q}$$

(2)

To obtain V-I characteristic from equation (1), five unknowns I_l, I_o, a, R_s and R_{sh} are to be determined. These parameters will determine by rewriting equation (1) in five independent conditions to generate system of non-linear equations.



(a) (b) (c)

Fig. 1- PV models: (a) single diode model – (b) two-diode model (c) simplified model

Characteristics equation solving

PV manufactures supply V-I characteristics at standard reference conditions. It means PV electrical characteristics traditionally are made at a standard reference condition. Standard reference conditions are defined as: incident radiation of 1000 w/m^{2,} a cell temperature of 25 °C and an air mass of 1.5. Measurements of I-V pairs at standard reference conditions are usually available from the manufactures at open circuit condition, short circuit condition and maximum power condition. In addition the temperature coefficient of short circuit current ($\mu_{I,sc}$) and the temperature coefficient of open circuit voltage ($\mu_{V,oc}$) are supplied by manufactures. Since five parameters of equation (1) are unknown, to obtaining unknown parameters, with considering supplied manufacture information five independent equations are to be written. The results are presented as the followings;

Short circuit condition:

At reference short circuit condition output voltage is zero and the current ($I_{sc,ref}$) will be:

$$I_{sc,ref} = I_{l,ref} - I_{o,ref}\left[\exp\left(\frac{I_{sc,ref}R_{s,ref}}{a_{ref}}\right) - 1\right] - \frac{I_{sc,ref}R_{s,ref}}{R_{sh,ref}} \qquad (3)$$

Open circuit condition:

At open circuit condition the output current is zero, hence the voltage ($V_{oc,ref}$) will be:

$$I_{l,ref} - I_{o,ref}\left[\exp\left(\frac{V_{oc,ref}}{a_{ref}}\right) - 1\right] - \frac{V_{oc,ref}}{R_{sh,ref}} = 0 \qquad (4)$$

Maximum power condition:

With substitution of I-V values related to maximum power point (V_{mp}, I_{mp}) into equation (1):

$$I_{mp,ref} = I_{l,ref} - I_{o,ref}\left[\exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}\right) - 1\right] - \frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{R_{sh,ref}}$$

(5)

Derivative of power:

Derivative of power respect to voltage at maximum power point will be equal to zero, so:

$$\frac{I_{mp,ref}}{V_{mp,ref}} = \frac{\frac{I_{o,ref}}{a_{ref}}\exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}\right)+\frac{1}{R_{sh,ref}}}{1+\frac{I_{o,ref}R_{s,ref}}{a_{ref}}\exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}\right)+\frac{R_{s,ref}}{R_{sh,ref}}}$$

(6)

Variations of parameters due to temperature changes:

Light current at operation condition is related to light current at reference condition by:[1]

$$I_l = \frac{S}{S_{ref}}\left[I_{l,ref} + \mu_{I,sc}(T_c + T_{c,ref})\right]$$

(7)

S/S_{ref} is the effective absorbed solar ratio.

The ratio of diode reverse saturation current at the operation temperature to that at the reference temperature could be stated as below:[1]

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 exp\left\langle \frac{E_g}{kT}\middle|T_{c,ref} - \frac{E_g}{kT}\middle|T_c\right\rangle \qquad (8a)$$

$$\frac{E_g}{E_{g,ref}} = 1 - C(T_c - T_{c,ref})$$

(8b)

Where Eg is the material band gap energy ($E_{g,ref}$=1.794e-19 j for silicon) and C is a constant equal to 0.0002677 (for silicon). K is Boltzmann's constant (k=1.381e-23 J/K).

Also with considering temperature coefficient of open circuit voltage and modified ideality factor as [1]:

$$\frac{\partial V_{oc}}{\partial T} = \mu_{V,oc} \approx \frac{V_{oc}(T_c)-V_{oc}(T_{c,ref})}{T_c-T_{c,ref}} = \frac{V_{oc}-V_{oc,ref}}{T_c-T_{c,ref}}$$

(9)

$$\frac{a}{a_{ref}} = \frac{T_c}{T_{c,ref}}$$

(10)

Now by substituting equations 7, 8, 9 and 10 into equation 1 and re writing that for open circuit condition we will reach to 5th equation of system of equations:

$$I_{l,ref} + \mu_{I,sc}(T_c - T_{c,ref}) - \left[I_{o,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3\exp\left(\frac{E_{g,ref}}{kT_{c,ref}} - \right.\right.$$

$[1-C(Tc-Tc,ref)]Eg,refkTc\exp(\mu V,ocTc-Tc,ref+Voc,refTcTc,refaref)-1-\mu V,ocTc-Tc,ref+Voc,ref Rsh,ref=0$ (11)

System of equations solving

By setting five equations of sections 3-1~5 in a system of equation and solving that the five I_l, I_o, a, R_s and R_{sh} unknowns will be determined at reference conditions. These equations are nonlinear and will be solved by using MATLAB solvers.

Nonlinear system of equation solving using MATLAB

Nonlinear system of equations can be solved by MATLAB using "fsolve" command. For this purpose, the

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system of equations should be defined at m file as a function. Then by calling "fsolve" command in MATLAB environment and giving an initial guess for unknowns the equations will be solved and after convergence, the results (parameters at reference condition) are produced.

Simulation of model by SIMULINK

After obtaining unknown parameters at reference conditions, model is implemented into SIMULINK to determine parameter's variation due to temperature and solar radiation changes. Described method will be done for a sample solar cell module as below.

A sample PV module simulation

The sample PV has 36 cells in series with an area of 0.633 m^2 at 67◦C. Characteristics of PV at reference conditions are:

- Short circuit current Isc=4.5 A
- Open circuit voltage Voc=21.4 V
- Maximum power current Imp=3.95 A
- Maximum power voltage Vmp=16.5 V
- Temperature coefficient of short circuit current $\mu_{I,sc}$=0.00026 A/k
- Temperature coefficient of open circuit voltage $\mu_{V,oc}$=-0.085 V/k

Characteristic equation formulation:

Firstly five unknowns of characteristic equation (i.e. equa.1) at reference conditions are to be determined. This unknown's vector is defined in MATLAB as below:

M=[$R_{sh,ref}$; a_{ref}; Il, ref; $I_{o,ref}$; $R_{s,ref}$] (12)

By considering equations 3, 4, 5, 6 and 11 with module data (sec.5-1) and putting unknowns by vector M arrays, the system of equations will be:

4.5-M(3)+M(4)*(exp(4.5*M(5)/M(2))-1)+4.5*M(5)/M(1)=0 (13)

M(3)-M(4)*(exp(21.4/M(2))-1)-21.4/M(1)=0 (14)

3.95-M(3)+M(4)*(exp((16.5+3.95*M(5))/M(2))-1)+(16.5+3.95*M(5))/M(1)=0 (15)

3.95*(1+M(4)*M(5)/M(2)*exp((16.5+3.95*M(5))/M(2))+M(5)/M(1))-16.5*(M(4)/M(2)*exp((16.5+3.95*M(5))/M(2))+1/M(1))=0 (16)

M(3)+0.00026*(339.2-298)-(M(4)*((339.2/298)^3)*exp(1.79e-19/1.38e-23*(1/298-(1-0.00026*(339.2-298))/339.2))*(exp((-0.085*(339.2-298)+21.4)/(339.2*M(2)/298))-1))-(-0.085*(339.2-298)+21.4)/M(1)]=0 (17)

Where M(i) is vector M array.

Equation solving using MATLAB

To solve nonlinear system of equations (equations 13, 14, 15, 17 and 17) and determination of vector M, MATLAB "fsolve" command is used. For this a m-file (PVcharec1.m) which contains a function is defined as below;

PVcharec1.m:

function out=PVcharec1(M)

Out=[equa.13; equa.14; equa.15; equa.16; equa.17]

And considering initial guesses for vector M as;

$M_{initial}$=[100;1.387;4.5;8.6e-7;0.503]

By calling "fsolve" command and after some iterations system of equations will be solved and vector M will be;

M = [5.2446e+001;9.3563e-001;4.5487e+000; 4.8275e-010;5.6723e-001] (18)

So the characteristic equation for this sample PV at reference conditions will be:

$$I_{ref} = (4.5487e+000) - (4.8275e-010)\left[\exp\left(\frac{V_{ref}+I_{ref}(5.6723e-001)}{(9.3563e-001)}\right) - 1\right] - \frac{V_{ref}+I_{ref}(5.6723e-001)}{(5.2446e+001)}$$ (19)

SIMULINK modeling

To indicating temperature and solar radiation variations effect on sample PV module, the model is simulated by SIMULINK.

I_L implementation:

This block is implemented by using equation 7 as shown in Fig. 2.

I_o implementation:

This block is implemented by using equation 8 as shown in Fig. 3.

I implementation:

By using equations 1 and 10 and considering below equations for series and shant resistance variations as below [1], I block is produced as shown in Fig.4.

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{S_{ref}}{S}$$ (20)

$$R_s = R_{s,ref}$$ (21)

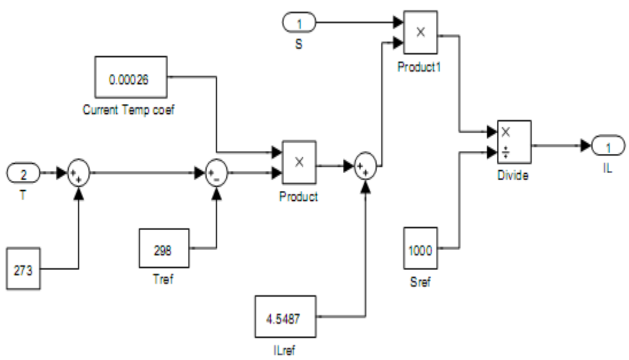

Fig.2- I_L implementation

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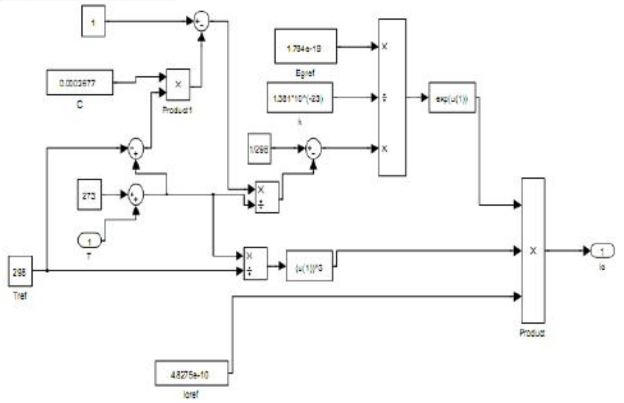

Fig.3- I_o implementation

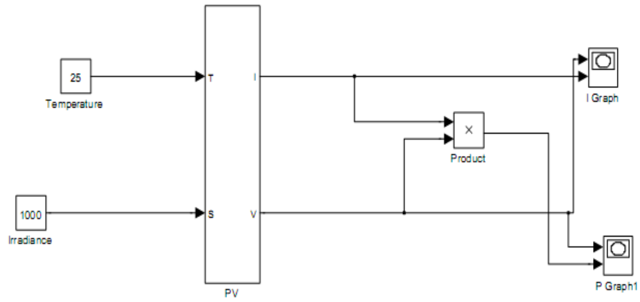

Fig.6- Final block diagram

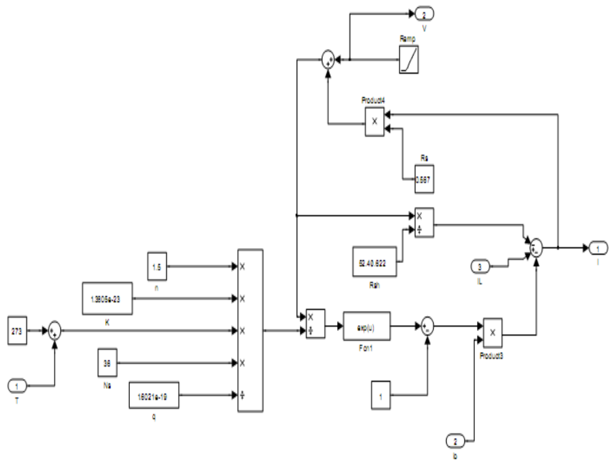

Fig.4- I implementation

Final block:

By grouping above blocks, (Fig.5) final block diagram is produced as Fig.6.

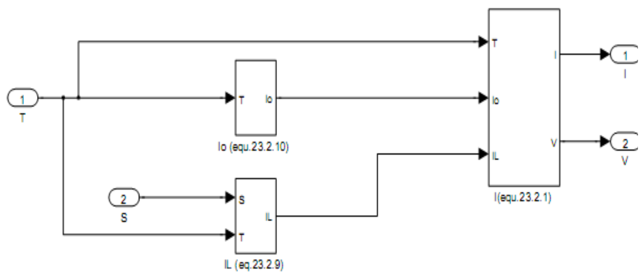

Fig. 5- subsystem creation

Model simulation

Final model is simulated by ramp signal input (with rate 1) for specified time duration. This signal acts as voltage input for PV. Simulation is done in two modes. One for constant irradiance level (1000 w/m^2) and different temperatures including 10, 25, 40 and 55 deg. And other mode is simulated in constant temperature (25°C) and different irradiance levels including 250, 500, 750 and 1000 w/m^2. The results have been presented in Figs (7) and (8).

Fig.7 indicates power output of model is decreased by increasing temperature and for irradiance changes the effect is reverse. It means irradiance rising will increase power output. The same is for current behavior as is shown in Fig.8.

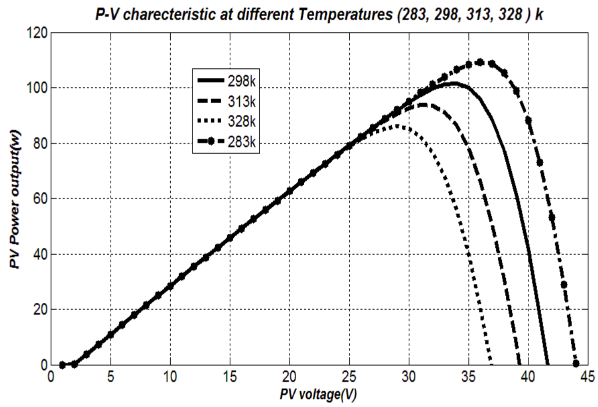

Fig.7a

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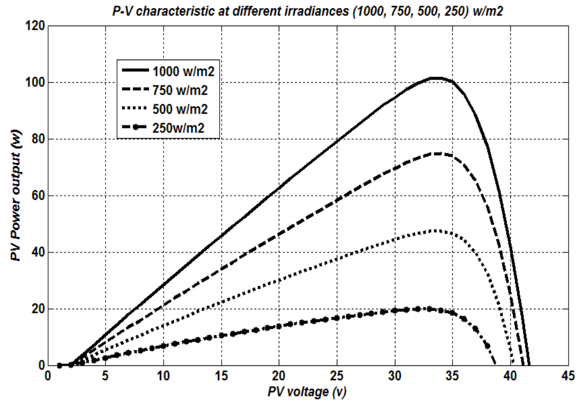

Fig.7b

Fig.7- sample PV model power- voltage characteristic curves: a) at different temperatures b) at different irradiances

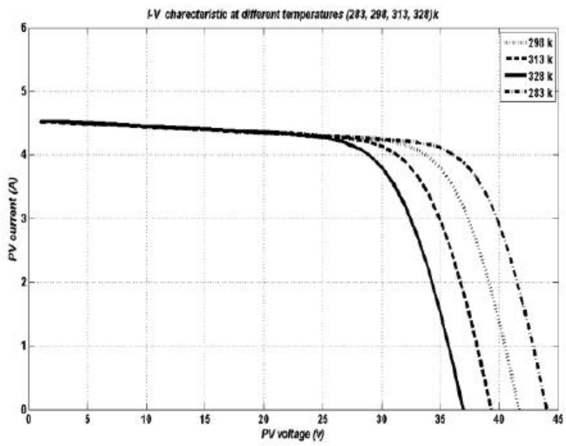

Fig.8a

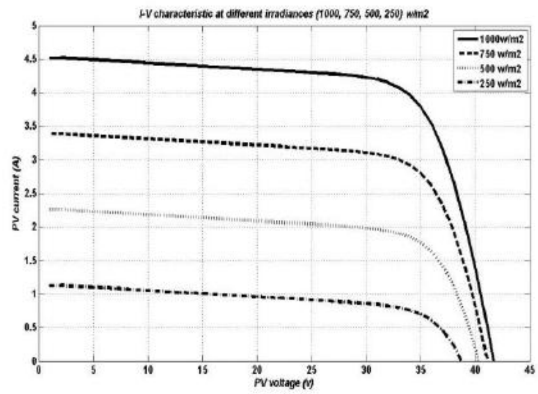

Fig.8b

Fig. 8- sample PV model current- voltage characteristic curves: a) at different temperatures b) at different irradiances

Conclusion

Since PV module performance characteristics are given at reference condition by manufactures which are actually different from operation conditions so it is necessary to predict the PV performance at non reference condition. A sample PV case has been selected to indicate step-by-step modeling and simulation of that PV to achieve the PV performance behavior in some non-reference conditions. To do this, characteristic equation of sample PV in base of single diode model has been solved by MATLAB to find characteristic equation un-known parameters after specifying V-I and V-P equations, those are implemented as Simulink mask blocks to produce characteristics curves at different temperature and irradiance conditions. As the model outputs curves indicatecurrent and power output of model will be decreased by temperature raising. In addition, PV model will have lower current and power output if irradiance level decreased in such conditions. The described model can be used to optimal placement of PV modules and will be useful to predict PV performance behavior at different climate conditions.

Nomenclature

I: PV output current.
V: PV output voltage.
Il : the light current.
Io: the diode reverse saturation current.
Rs: the series resistance.
Rsh: the shunt resistance.
a is modified ideality factor
$V_{oc,ref}$: voltage at reference open circuit condition
$I_{sc,ref}$: current at reference short circuit condition
V_{mp}, : voltage at maximum power point
I_{mp} : current at maximum power point
$\mu_{I,sc}$: the temperature coefficient of short circuit current
$\mu_{V,oc}$: the temperature coefficient of open circuit voltage
T_c : operation temperature
$T_{c,ref}$: reference temperature
Eg : the material band gap energy
K : Boltzmann's constant

References

[1] John A.Duffie, William A. Beckman-"Solar Engineering of Thermal Processes." – John Wiley&sons, Inc. – 2013

[2] Krismadinata, NasrudinAbd. Rahim Hew Wooi Ping, JeyrajSelvaraj "Photovoltaic module modeling using Simulink/matlab" The 3rd International conference on Sustainable Future for Human Security SUSTAIN 2012

[3] Chen Qi, Zhu Ming "Photovoltaic Module Simulink Model for a Stand-alone PV System"- 2012 International Conference on Applied Physics and Industrial Engineering

International Journal of Current Trends in Engineering & Technology
ISSN : 2395-3152. Volume : I, Issue : IV (May- June 2015)

[4] Habbati Bellia, Ramadani Yousef, Moulay Fatima, "A detailed modeling of photovoltaic module using MATLAB", NRIAG journal of Astronomy and Geophysics, (2014)3, 53-61

[5] N.Pandiarajan, Ranganath Muthu, "Mathematical modeling of Photovoltaic Module with Simulink", International conference on electrical Energy systems ICEES 2011

[6] kashifIshaque, Syafaruddin, Zinal Salam, "A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two diode model.", Sol. Energy 85, 2217-2227, 2011

[7] Awodugba, A. O., Sanusi, Y. K., and Ajayi, J. O., "Photovoltaic solar cell simulation of shockley diode parameters in matlab", International Journal of Physical Sciences, Vol. 8(22), pp. 1193-1200, 16 June, 2013

[8] J.A. Ramos-Hernanz, J.J. Campayo, J. Larranaga, E. Zulueta, O. Barambones, J. Motrico, U. Fernandez Gamiz, I. Zamora, "TWO PHOTOVOLTAIC CELL SIMULATION MODELS IN MATLAB/SIMULINK", International Journal on Technical and Physical Problems of Engineering (IJTPE), March 2012 Issue 10 Volume 4 Number 1 Pages 45-51

[9] I.H. Atlas and A.M sharaf, " A photovoltaic array simulation model for MATLAB- SIMULINK GUI environmental," IEEE, clean electrical power international conference on clean electrical power (ICCEP 07), June 14-16,2007, Ischia, Italy.

[10] M.G Villalva, J.R. Gazoli, and E.R Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays", IEEE Transa ctions on , vol. 24, pp 1198-1208, 2009.