Real Time Modeling of Triple Layers Amorphous Photovoltaic Panels

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***Abstract*-This paper presents a simple hybrid simulation model of PV cell/module using Matlab/Simulink/Simscape/ SimElectronics/Pspice library for triple layers Amorphous photovoltaic panels. The simulation model uses the basic circuit model of PV solar cell by manipulating Spice diode parameters and effect of changing series and parallel resistances in each cell of panel based on commercial datasheet catalog information. By using proposed model the effect of solar insolation and temperature variation captured by National Instrument (NI) data actuation card and *V-I* characteristic of PV modules can be obtained from real-time simulation. Also, partial shading conditions (PSC) effect, perfectly simulated in this method by changing solar insolation and temperature of each cell. This model applied for triple layers Amorphous PV panel (Uni-solar ES-62T) that is installed in MIS laboratory energy renewable platform.**

I. INTRODUCTION

THE fast evolution of the renewable energy sources during the two last decades had consequence the installation of many systems in the world. Solar energy is a sort of green energy, which is inexhaustible and environmentally friendly. Hence, worldwide installed photovoltaic power capacity shows a nearly exponential increase, despite the fact that they have still relatively high cost [1]. Enquiry for lower cost and higher efficiency devices motivates the researchers in the control of PV inverters to achieve higher efficiency and reliability.

For many reasons, Amorphous silicon technology is chosen for hot and air dust climates such as north of Africa. Amorphous silicon technology provides better energy yield at high temperatures, prevalence of annealing effect over light induced degradation, better matching of the solar spectrum due to air mass effects and smaller fraction of diffused light in comparison to direct one [2], [3]. Silicon heterojunction technology (Si-HJT) consists of thin Amorphous silicon layers on mono-crystalline silicon wafers and allows photovoltaic solar cells to have energy conversion efficiencies above 20 %.

Photovoltaic behavior identification in various solar irradiance, temperature and load conditions is very important for sizing the PV plant and converter, as well as for the design of the maximum power point tracking (MPPT) algorithm and control strategy [1]. In this paper a triple layers Amorphous cells/module model is proposed based on a combination of mathematical and electronic components-based modeling. Thus, the hybrid proposed model is implemented in MatlabSimulink/Simscape library. For that, the five-parameter model of photovoltaic solar cells, which is an equivalent electrical circuit [8], consist of diode, resistance and dependent current supply with solar irradiance and temperature dependent component, is used. To obtain model parameters from commercial datasheet in a simple way and without numerical iterative solving, an estimation of the PV modules loss resistance is done. Further, in this work diode fundamental parameters are manipulated according to the modules datasheet values [9].

In addition, the results shown the effect of solar insolation and temperature variation in each cell is appeared in output *V-I* characteristic in partial shading conditions [10], [11]. This method is implemented and tested on the a-Si:H triple layers Amorphe PV panel (Uni-solar Es-62), installed in MIS laboratory energy renewable platform (Fig.1).

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II. PV SOLAR CELLS/MODULES MODEL

A. *Amorphous Circuit based Model of PV Cells*

A mathematical description of current-voltage terminal characteristics of the PV panel is available in literature. The single exponential equation, models a PV cell is derived from the physics of the PN junction and is generally accepted as reflecting the characteristic behavior of the cell (Fig. 2), called five-parameter model [12-13].

Fig. 1. Energy renewable platform (University of Picardie Jules Verne).

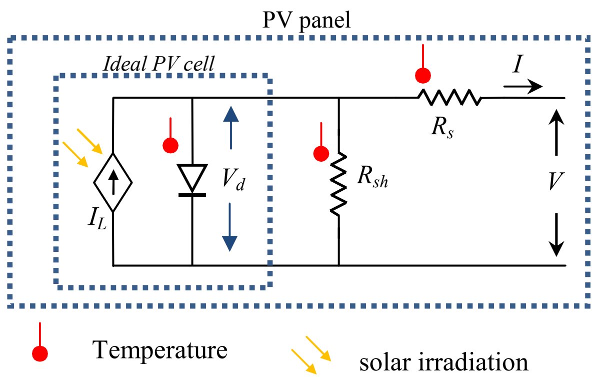

Fig. 2. Five-parameter model of the theoretical PV cell and equivalent circuit of a PV panel (single-diode model).

The five-parameter model for a PV panel with diode ideality constant of a, light generated currents of I_L, equivalent series resistance of R_s, equivalent parallel resistance of R_{sh}, output voltage V, number of cells connected in series of n_s and the number of multi-layer PV structure of n_l expresse as:

$$I = I_L - I_{sat}\left[exp\left(\frac{V+R_sI}{a.n_{sl}.V_{tn}}\right) - 1\right] - \frac{V+R_sI}{R_{sh}} \qquad (1)$$

with: $V_{tn} = k.T_n/q$

$n_{sl}=n_s.n_l$

where, V_{tn} is the thermal voltage of the array and I_{sat} is the saturation currents of the array.

Manufacturers of photovoltaic panels normally provide simply a few experimental data about electrical and thermal characteristics [14]. Typically flowing information could be find in a PV panel datasheet:

V_{ocn} Nominal open-circuit voltage;
I_{scn} Nominal short-circuit current;
V_{mp} Voltage at the maximum power point;
I_{mp} Current at the maximum power point;
K_V Open-circuit voltage/temperature coefficient;
K_i Short-circuit current/temperature coefficient;
$P_{max,e}$ Maximum experimental peak output power;

These information are always provided with reference to the nominal or Standard Test Conditions (STC) of temperature and solar irradiation according to IEC 61646 standard edition 2.0. Though, some manufacturers provide *V-I* curve for several irradiation and temperature conditions, which make the adjustment and the validation of the desired mathematical *V-I* equation easier. Basically, these are all the information one can get from datasheets of PV panel.

However, some of essential parameters for adjusting photovoltaic panels models such as: the light generated current, I_L, the diode reverse saturation current, I_{sat}, the diode ideality constant, a, the band-gap energy of the semiconductor, E_g, the series and shunt resistances, R_s and R_{sh} respectively, cannot be found in the manufacturers' data sheets [16], [7-8].

B. Photovoltaic Generation Currents Stage

The light generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation [7]:

$$I_L = \left(I_{Ln} + K_i.\Delta T\right).G/G_n \qquad (2)$$

where I_{Ln} is the light-generated current at the nominal condition (usually 25°C and 1000-W/m^2) and ΔT is the difference of nominal temperature and actual temperature, which could be calculated as:

$$\Delta T = T - T_n \qquad (3)$$

C. Band-Gap Energy and Diode Ideality Factor

In fact the nominal band-gap energy, E_g, for standard diode are depend on the structure and type of the semiconductors material. For instance, nominal value of the band-gap energy for different PV technology is shown in Table I.

TABLE I
THE BAND-GAP ENERGY FOR DIFFERENT PV TECHNOLOGY

Crystalline silicon	1.11-eV
4H-SiC silicon carbide	3.23-eV
6H-SiC silicon carbide	3.00-eV
Germanium	0.67-eV
Gallium arsenide	1.43-eV
Selenium	1.74-eV
Schottky barrier diodes	0.69-eV

An electron-volt is equal to the energy gained by an electron when it passes through a potential of 1 volt in a vacuum. The range of band-gap energies for the PV semiconductors is 1.0 to 1.6-eV. In this range, electrons can be freed without creating extra heat [17] while Amorphes panel energy band gap E_g is normally higher. This thin film silicon based solar cells, consisting of hydrogenated Amorphous silicon (a-Si:H) and/or hydrogenated micro-crystalline silicon (μc-Si:H), which are also referred to Nano-crystalline silicon (Nc-Si). Amorphous silicon has different material properties compared to c-Si:H. It has a band gap of about 1.8 to 2 eV, which is considerably higher than the band gap of c-Si (Eg = 1.1-eV).

To specify a custom value for the energy gap E_g in Matlab Simulink, from diode block parameters, the energy gap parameterization option in the temperature dependence tab should be selected.

Many authors discuss several ways to estimate the correct value of diode ideality factor, a. Usually, it is initialized as a constant value between 1 and 1.5, while this value depends on the other parameters of the *V-I* model. Some values for a could be found in [15] based on empirical analysis, some other use analytically solver to find [14] and other neglected calculation and initialized constant value [7], but in Amorphous photovoltaic panel the value of a would be between 2 to 4.5 which is depends on the cell material [20].

It is possible to obtain the value of band-gap energy for a PV panel regarding the information of its datasheet and substitute in the required diode parameter in the simulation [7]. For that, open-circuit voltage of the model is matched with the open-circuit voltage of the real panel regarding its temperature $T_n < T < T_{max}$ as well as short-circuit current (Noted that all PV product is tested according IEC 61646 standard). Considering $T = T_{max}$= 85ºC for number of large data manufacture, band-gap energy could be estimated according to the following equations:

$$I_{scTmax} = I_{scn} + K_i.\Delta T \tag{4}$$

$$V_{oc,Tmax} = V_{oc,n} + K_v.\Delta T \tag{5}$$

$$V_{Tn} = n_{sl}.k.T_n / q \tag{6}$$

$$V_{Tm} = n_{sl}.k.T_{max} / q \tag{7}$$

$$E_g = -Ln\left[\frac{\left(\frac{I_{scTmax}}{I_{satn}}\right)\left(\frac{T_n}{T_{max}}\right)^{\frac{3}{a}}}{exp\left(\frac{q.V_{ocTmax}}{a.n_{sl}.k.T_{max}}\right)-1}\right].\frac{a.k.T_n.T_{max}}{q.(T_n - T_{max})} \tag{8}$$

To find E_g from (8), iterative method could be used by initializing diode ideality factor a so the final value would converged to the actual amount (Fig.3). Actually the average of E_g for multi-layer Amorphous PV panel could be upper than silicon based technology regarding the type and number of PV panel layers, which could be found in the manufactures catalog [20]. For instance, it could be up to 1.7-eV for a single layer, 1.9-eV for a dual layer and it is reported for about 2.5-eV for a triple layer.

D. Diode saturation current

The diode saturation current I_{sat} is depends on the temperature. For a PV panel with n_s cells diode saturation current could be expressed by [7]:

$$I_{sat} = \frac{I_{scn} + K_i.\Delta T}{exp\left(\frac{V_{ocn} + K_v.\Delta T}{a.V_{Tn}}\right) - 1} \tag{9}$$

This value should be manipulated in the Matlab environment in the diode block parameter.

E. Loss resistance

The photovoltaic cell model shown in Fig.1 has a series and a shunt loss resistance, R_s and R_{sh} respectively. The series resistance, R_s, has influence directly on the light generated current, I_L, of the cell as in (1). Hence, photovoltaic generated current as well as power output would be decreased if the series resistance increases.

Considering photovoltaic generated current, I_L, as a function of output voltage and series resistance, *V-I* and *V-P* curves for three different values of series resistance, 1-Ω, 0.01-Ω, and 0.1-Ω are shown in Fig. 4a. Similarly, the shunt resistance, R_s, of the PV cell has a large impact on the slope of the *V-I* curve especially near the open-circuit voltage, V_{oc}. Influence of Varying shunts resistance on the generated current and consequently *V-I* and *V-P* curves are shown in Fig. 4b.

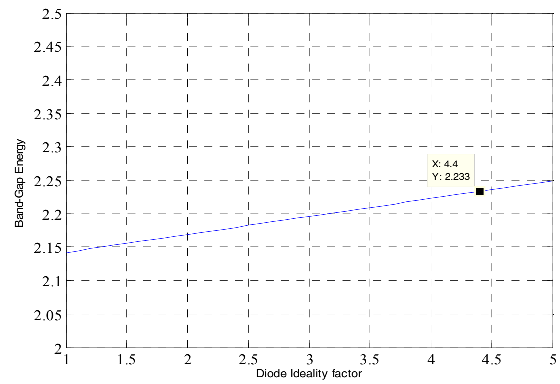

Fig .3 . *Eg-a* curve of Amorphous PV panel regarding iterative method.

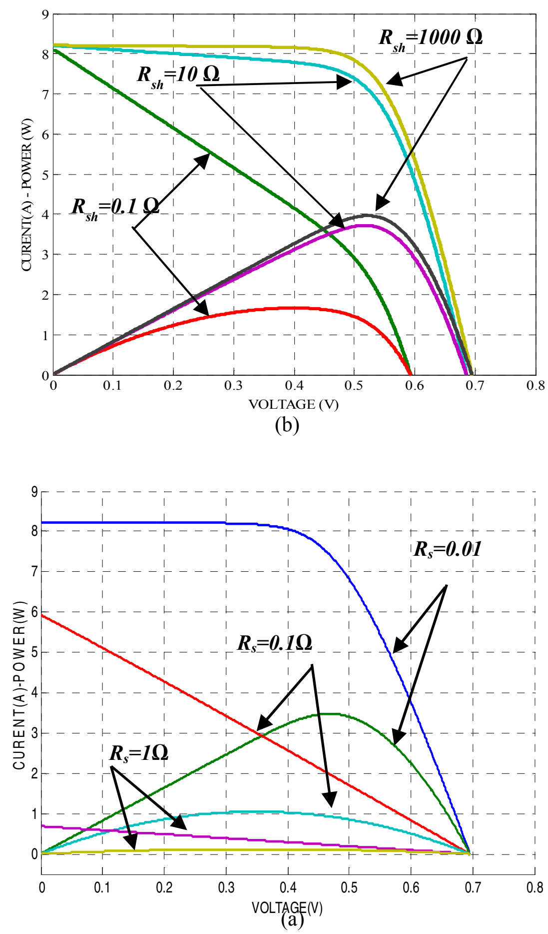

Fig. 4. PV cell characteristics with varying (a) Rs , (b) Rsh.

Obtaining accurate loss resistances is a matter of fact for which a large number of works have been done, describing or mentioning procedures to obtain loss resistances. Generally, simple methods lead to rough, unreliable results. Inversely, methods that offer good results are based on complex equations and interactive solutions [8] or are based on experimental data and its statistical treatment [14, 15]. In either cases solution is not that much easy to reach without the computer help and an iterative problem solving. Estimation of the series and shunt loss resistances, R_s and R_{sh}, could be derived using the defined parameters in the photovoltaic cell datasheet and their equations by rewriting and analyzing equation (1) for open-circuit, short-circuit and maximum power point conditions [4], [6], [9], [12].

In this work R_s and R_{sh} estimated with low error according C. Carrero method [9] .With the defined values of V_{mp}, I_{mp} and V_{oc}, the corresponding value of R_S could be obtained regarding following equation:

$$R_S \approx \left[V_{OC} - V_{mp} - a.n_{Sl}.V_t.Ln\left(\frac{V_{mp} + a.n_S.V_t - I_{mp}.R_S}{a.n_{Sl}.V_t} \right) \right] \Big/ I_{mp} \qquad (10)$$

Once R_S is calculated, R_{Sh} could be obtained from:

$$R_{sh} = \frac{\left(V_{mp} - a.n_{sl}.V_t\right).\left(V_{mp} - I_{mp}.R_s\right)}{\left(I_{sc} - I_{mp}\right).\left(V_{mp} - I_{mp}.R_s\right) - I_{mp}.a.n_{sl}.V_t} \qquad (11)$$

III. SIMULATION OF MULTI-LAYER AMORPHUS PHOTOVOLTAIC PANEL

Photovoltaic cells are connected in series and parallel to form a PV module. Based on single cell circuit module, the voltage and current relation of a PV module can be represented by (1).

Equation (1) is not able to accurately model the behavior of a solar module under partial shading conditions (PSC). In this paper to model the effect of PSC on the PV module, instead of using mathematical model, a components-based model in Matlab/Simscap (Fig. 5) is suggested and adopted according to the PV datasheet value and estimated V-I curve characteristics. The advantage of this method is that each solar cell is represented by a current source in real time condition under PSC, which could be simulated by adjusting values of current sources in each single solar cell that are connected in series and parallel to form a PV module. Also as shown in Fig.3 band-gap energy, E_g, as well as saturated current, I_{sat}, are calculated using datasheet value according to the equations (5) and (4) and substituting in the diode initial parameters in Matlab/Simscape. Also it is possible to change device simulation temperature according the average data acquainting from PV sensor in each capture start time.

It should be considered that using equation (9) and (10) it is possible to calculate series and shunt loss resistances, R_s and R_{sh}, for a PV panel (all cells), while the portion of each cell is depend on the cells connection configuration (Fig. 7).

For triple layer, three sub cells could be connected without bypass diode in series (Fig.6) and then combining the triple layers to form the PV panel (Fig.7). In this work, the PV model could be simulated in real-time without solving equation (1), as solving equation (1) need some iterative method and real-time workshop does not support models containing algebraic loops in real time Simulation. The result has good accuracy because the temperature effect on the diode for Amorphous triple layer could be passed up (Fig.8).

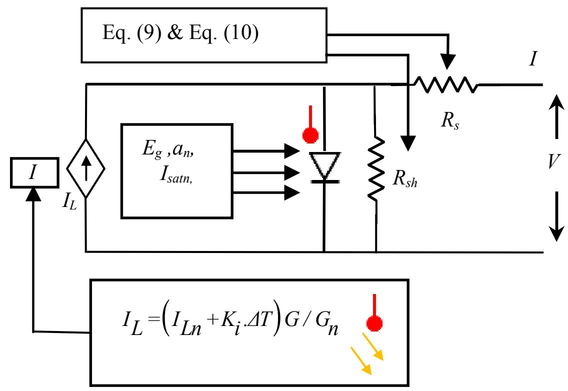

Fig. 5. PV cell model equivalent circuit with controlled current and adopted diode parameters.

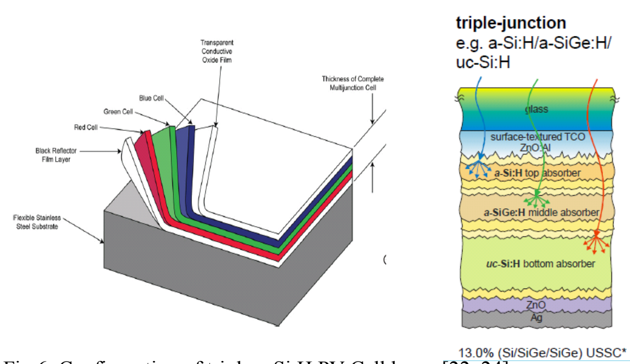

Fig.6. Configuration of triple a-Si:H PV Cell layers[22, 24].

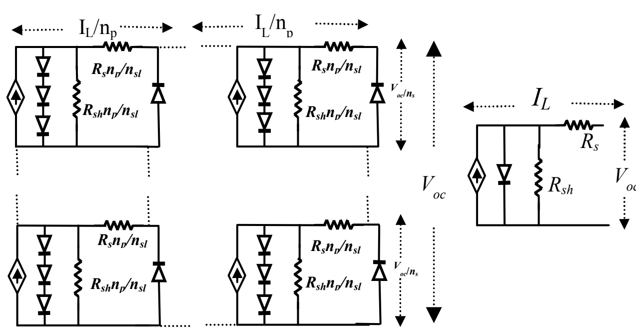

Fig. 7. PV cell model circuit with a controlled current and adopted diode.

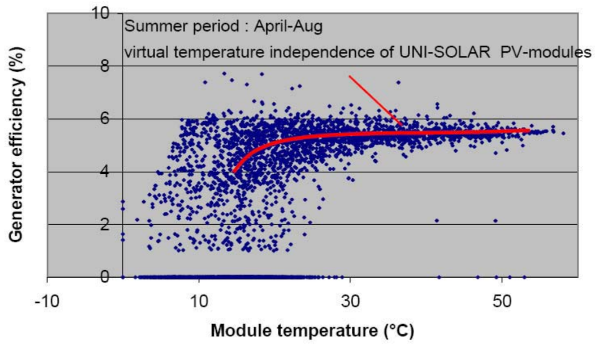

Fig. 8. UNI-SOLAR efficiency does not decline in temperature [23].

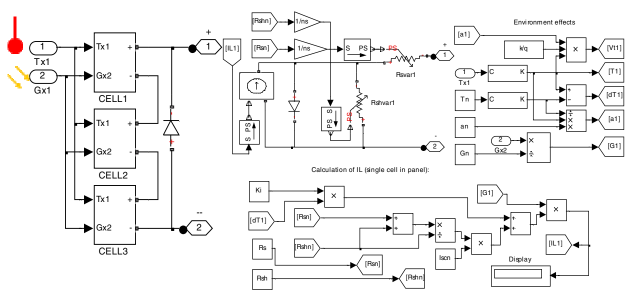

Fig. 9. GIU environment triple Amorphous Cell model.

The two parameters n and I_{sat} nearly have the same behavior at deferent temperature. Fig. 8 shows the efficiency- temperature curve that reported in Fraunhofer ISE, Freiburg, Germanyy under: 1200-kWh/m2 horizontal irradiance with Tilt: 30° for 1.5-kWp and used Fronius IG20 Inverters [22].

In this work, a Uni-Solar ES-62T panel, installed in the MIS laboratory, is simulated. The panels, shown in Figure 1, contains triple a-Si:H technology. Some common panel parameters, obtained from the manufacturer's data sheet, are illustrated in Table II.

As it is shown in Fig. 5 each of photovoltaic cells has two inputs, temperature and solar irradiation. In PV panel for the open-circuit condition, each cell voltage would be equal to the diode voltage, $V_{oc}/n_{sl} \approx Vd$, and the portion of each cell, series and shunt loss resistances, R_{scell} and R_{shcell}, from the whole panel loss resistances would be equal to:

$$R_{scell} = R_s . n_p / n_{sl} \qquad (12)$$

$$R_{shcell} = R_{sh} . n_p / n_{sl} \qquad (13)$$

TABLE II
CHARACTERISTICS OF UNI-SOLAR ES-62T SOLAR PANEL

V_{mp}	15 V	Ns	10
I_{mp}	4.10 A	No.of layer	3
V_{oc}	21 V	T_{max}	85°C
I_{sc}	5.10 A	T_n	25°C
K_v	-81 mV/K	K_i	5.1 mA/K

To calculate series and shunt loss resistances, R_{scell} and R_{shcell}, of the PV cells, equations (10) and (11) are employed. For series loss resistance calculation, an initial value of, R_{s0}, is considered as:

$$R_{s0} = \frac{1}{I_{mp}} . \left[V_{oc} - V_{mp} - a_n . n_s . V_t . Ln \frac{V_{mp}}{a_n . n_{sl} . V_t} \right] \qquad (14)$$

Then substituting R_{s0} in the following equation would give series loss resistance:

$$R_s \approx \frac{1}{I_{mp}} . \left[V_{oc} - V_{mp} - a . n_s . V_t . Ln \left(\frac{V_{mp} + a . n_s . V_t - I_{mp} . R_{s0}}{a . n_s . V_t} \right) \right] \qquad (15)$$

To improve the result the process can be repeated several times. Normally, with 2 or 3 times the result will be acceptable, here it is repeated 3 times and the accuracy obtained was 10^{-6}.

As indicated before, another advantage using this method is the simulation in the partial shading condition for the PV panel. Therefore, *V-I* and *V-P* curves for an Amorphous panel are obtained from Simulink under uniform shading conditions (Fig. 10).

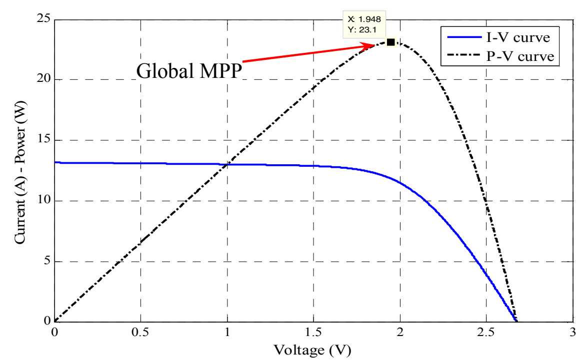

Fig. 10. *V-I* curves under uniform shading conditions (USC).

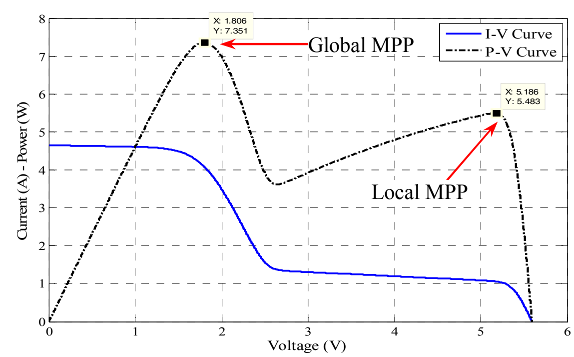

Fig. 11 . I-V curves for PV panel combined in one string in series form, under PSC condition.

The simulation has been done for the PV panel with ten cells (Uni-solar ES-62T) in series considering their ten bypass diode, containing the two cells shaded. The results of *V-I* and *V-P* curves under this partial shading condition (PSC) are shown in Fig. 11, from which the effect of the shading and hotspot is clearly sensible.

IV. CONCLUSION AND PERSPECTIVES

In this work a triple layers Amorphous photovoltaic solar cells/module model is proposed based on a combination of mathematical and electronic components which inherits the advantages of both types of modeling. The hybrid proposed model is implemented in MatlabSimulink/ Simscape/ SimElectronics / Pspice library. Thus, *V-I* equation of PV cells is solved using diode block of Simulink/ Simscape. In this regard some common method to calculate the series and shunt loss resistances of the PV panel is employed. Using proposed model, algebraic loop for finding *V-I* curve is not needed. Thereby we can generate code and use this simulation in real time, also partial shading and normal conditions are simulated. As a results partial shading effects on output current of a PV panel clearly observed. This model could be easily interfaced to the electronic devices and power converters for maximum power point tracking studies.

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