SIMULATION AND CHARACTERISTICS STUDY OF SOLAR PHOTOVOLTAIC ARRAY USING MATLAB/SIMULINK +

Ahmed M. T. Ibraheem Alnaib *

Abstract :

The study of Photovoltaic (PV) systems in an efficient manner requires a precise knowledge of the I-V and P-V characteristic curves of solar PV array. Therefore, this paper presents modelling and simulation of solar PV module using Matlab/Simulink. This model is based on mathematical equations and is described through an equivalent circuit including a photo current source, diode, shunt resistor expressing leakage current and series resistor represents the internal losses due to the current flow. The developed model allows the prediction of PV array behaviour under different circuit model and environmental parameters (temperature, and solar radiation).A particular typical 175Watt solar panel was used for model evaluation, and results was compared with points taken directly from the manufacturer's published curves and show excellent correspondence to the model.

Keyword: **PV cell, PV array, I-V and P-V characteristic.**

نمذجة ودراسة خصائص مصفوفة الخلايا الشمسية باستخدام برنامج Matlab/Simulink

أحمد محمد توفيق ابراهيم النائب

المستخلص:

لدراسة الخلايا الشمسية بشكل كفوء يتطلب المعرفة الدقيقة لمنحنيات خصائص الخلايا الشمسية (منحني I-V و منحني P-V). لهذا السبب تم في هذا البحث تمثيل ونمذجة الخلايا الشمسية باستخدام برنامج Matlab/Simulink. تعتمد النمذجة على المعادلات الرياضية التي تصف الخلايا من خلال الدائرة المكافئة والتي تتضمن مصدر تيار ضوئي, ثنائي, مقاومة توازي تمثل تيار التسرب, ومقاومة توالي تمثل الخسائر الداخلية بسبب سريان التيار. تم دراسة خصائص مصفوفة الخلايا الشمسية التي تم تمثيلها تحت مختلف الظروف المحيطة بالخلية (درجة الحرارة و الاشعاع الشمسي) ومختلف العناصر الداخلية للخلية الواحدة (مثل مقاومة التوالي ومقاومة التوازي). لمصادقة التمثيل والنمذجة عمليا تم اختيارالبيانات اللازمة من وحدة خلية شمسية حقيقية ذات قدرة تساوي 175Watt. تمت مقارنة المنحنيات التي تم الحصول عليها من نموذج المحاكاة مع منحنيات خصائص الخلية الحقيقية التي تم اختيارها للنمذجة; وكانت النتائج متقاربة جدا.

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* Assistant Lecturer / Technical Institute / Hawija / Nothern Technical University

Introduction:

Among the renewable energy resources, the energy due to the PV effect can be considered the most essential and prerequisite sustainable resource because of the ubiquity, abundance, and sustainability of solar radiant energy [1]. Even though the PV system is posed to its high capital fabrication cost and low conversion efficiency, the skyrocketing oil prices make solar energy naturally viable energy supply with potentially long-term benefits [2].PV module represents the fundamental power conversion unit of a PV generator system. The output characteristics of a PV module depend on the solar radiation, cell temperature, and the output voltage of the PV module. Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of Maximum Power Point Tracking (MPPT) for PV system applications. In addition to the mathematical modelling and simulation of PV module enable researcher to have a better understanding of its working. The modelling of PV module generally involves the approximation of the non-linear I-V curve. Many researchers used circuit based approach to characterize the PV module of which the simplest model is the current source in parallel to a diode [1, 3, 4]

Mathematical Equations of Solar PV Cell:

There are many equivalent circuits of a solar cell, where the single-diode and two-diode models could be the most widely used. Since the single-diode model is simple and accurate enough in many cases [3]. It is applied in this paper. The equivalent circuit shown in Fig. 1; consists of a photo current source (I_{ph}) in parallel with a diode (D). The output of the current source is directly proportional to the light falling on the cell. During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. Shunt resistance (R_{sh}), in parallel with the diode, this corresponds to the leakage current to the ground and it is commonly neglected, finally series resistor (R_s) represents the internal losses due to the current flow [3, 5].

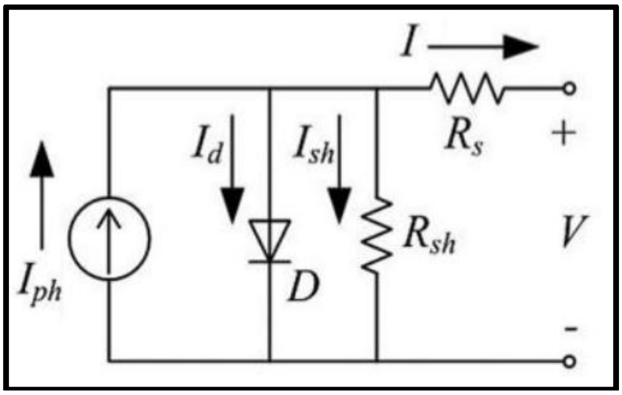


Figure (1): Equivalent circuit of a single solar cell

The voltage-current characteristic equation of a solar cell is given as:

$$I = I_{ph} - I_d - I_{sh} \quad (1)$$

$$I = I_{ph} - I_s\left[e^{q(V+IR_s)/AKT} - 1\right] - (V + IR_s)/R_{sh} \quad (2)$$

Where:
I: Output current of the solar cell,
I_d : Diode Current,
I_{sh}: Shunt-leakage current,
I_s : Reverse saturation current of the diode,
V : Output voltage,
q: Electron charge (1.602 × 10^{-19} C),
A : Ideal factor of the diode,
K : Boltzmann's constant (1.38 × 10^{-23} Joule/ºK), and
T : Cell's actual temperature in Kelvin (ºK).

The ideal factor (A) in equation (2) determines the cell deviation from the ideal p-n junction (diode) characteristics; it ranges between (1 and 5) 1 being the ideal value and is dependent on PV technology [6, 7] and is listed in Table (1).In our case, $A = 1.2$.

Table (1): Factor (A) Dependence on PV Technology [7]

Technology	A
Si-Mono	1.2
Si-Poly	1.3
a-Si:H	1.8
a-Si:H tandem	3.3
a-Si:H triple	5
CdTe	1.5
CTS	1.5
AsGa	1.3

The photocurrent mainly depends on the solar radiation (H) and cell's actual temperature (T), which is described as [5]:

$$\boldsymbol{I_{ph} = [I_{SC} + K_i(T - T_{ref})]\, H} \quad \text{.......} \quad (3)$$

Where:$I_{SC}$is thecell's short-circuit current at reference temperature (25°C) and reference solar radiation (1kW/m^2),$K_i$is the cell's short-circuit current temperature coefficient ($1.7 * 10^{-3}$A/ºK), $T_{ref}$is the cell's reference temperature, and $H$is the solar radiation in kW/m^2.
On the other hand, the cell's saturation current (I_s) varies with the cell temperature, which is described as [7]:

$$\boldsymbol{I_s = I_{rs}(T/T_{ref})^3 e^{[\frac{qE_G}{AK}(\frac{1}{T_{ref}} - \frac{1}{T})]}} \quad \text{.......} \quad (4)$$

Where:I_{rs} is the cell's reverse saturation current at a reference temperature and a solar radiation, E_G is the bang-gap energy of the semiconductor used in the cell(E_G= 1.12eV for silicon).

<u>Model of Solar PV Array</u>:

Since a typical PV cell produces less than 2W at 0.5V approximately, the cells must be connected in series-parallel configuration on a module to produce enough high power. A PV array is a group of several PV cells which are electrically connected in series and parallel circuits to generate the required current and voltage. The equivalent circuit for the solar module arranged in N_p parallel and N_s series is shown in Fig. 2 [5, 7].

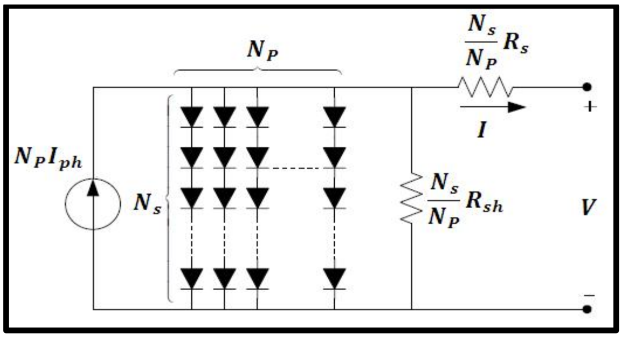


Figure (2): Equivalent circuit of solar PV array

The terminal equation for the current and voltage of the array becomes as follows:

$$I = N_P I_{ph} - N_P I_s\left[e^{(q(V/N_s + IR_s/N_P)\,/AKT)} - 1\right] - (\frac{N_P V}{N_s} + IR_s)/R_{sh} \quad \text{.....................} \quad (5)$$

The shunt resistance (R_{sh}) is inversely related with shunt leakage current to the ground. In general, the PV efficiency is insensitive to variation in R_{sh} and the shunt-leakage resistance can be assumed to approach infinity without leakage current to ground. On the other hand, a small variation in series resistor (R_s) will significantly affect the PV output power. The simplified model of PV solar cell with suitable complexity is shown in Fig. 3 and can be expressed as [5]:

$$I = N_P I_{ph} - N_P I_s\left[e^{(q(V/N_s + IR_s/N_P)\,/AKT)} - 1\right] \quad \text{...} \quad (6)$$

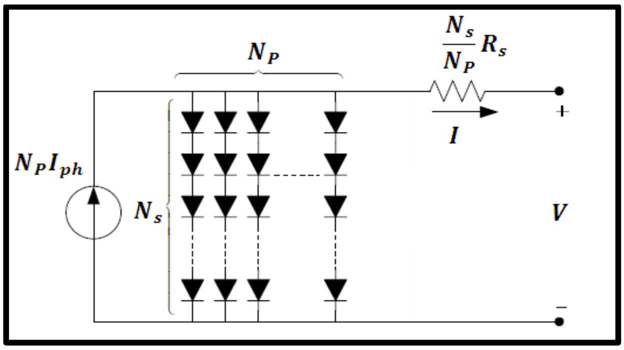


Figure (3): Simplified model of solar PV array

The most simplified model of generalized PV module is depicted in Fig. 4 [5, 7]. The equivalent circuit is described on the following equation:

$$I = N_P I_{ph} - N_P I_s\left[e^{(q\,V/N_s AKT)} - 1\right] \quad \text{...} \quad (7)$$

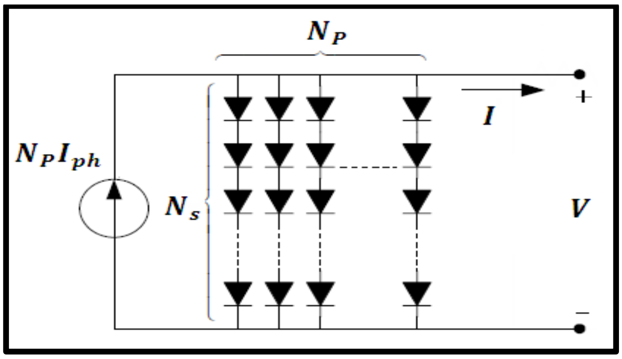


Figure (4): Appropriate model of solar PV array

The reverse saturation current at reference temperature can be approximately obtained as:

$$I_{rs} = I_{SC}/[e^{(qV_{OC}/N_s AKT)} - 1] \quad \text{........} \quad (8)$$

Where: $V_{OC}$is theopen-circuit voltage of a PV module.

<u>Simulink Modelling for Solar PV Array</u>:

The Solar PV model (CRM175S 125M-72) is chosen for modelling. The typical electrical characteristics of the model are given in Table (2) [8].

Table (2): Typical electrical characteristics of CRM175S 125M-72 Solar PVmodel [8]

Electrical characteristics	CRM175S 125M-72
Power	175W
Number of cells in series	36
Current at max. power point (I_{mp})	4.85A
Voltage at max. power point (V_{mp})	36.1V
Short-circuit current (I_{SC})	5.28A
Open circuit voltage (V_{OC})	44.5V
Max. voltage system	1000V

A block diagram of the step by step model based upon the equations (1 to 8) of PV array is represented in Simulink environment as given in the following steps; as shown in Figures (5 - 11).

Step 1:

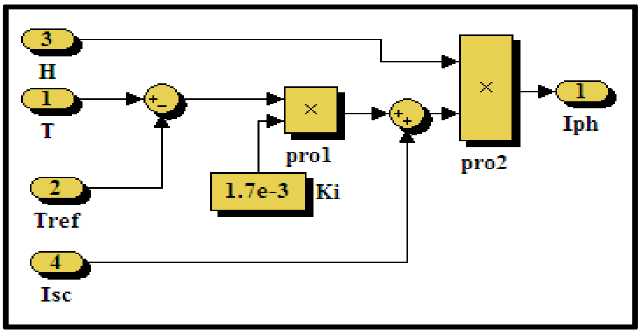


Figure (5): Subsystem for calculation of I_{ph}

Step 2:

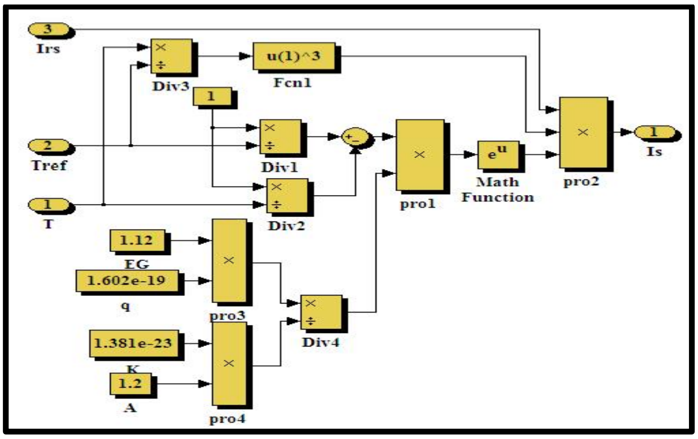


Figure (6): Subsystem for calculation of I_s

Step 3:

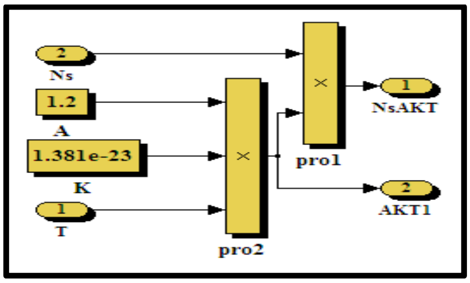


Figure (7): Subsystem for calculation of N_sAKT

Step 4:

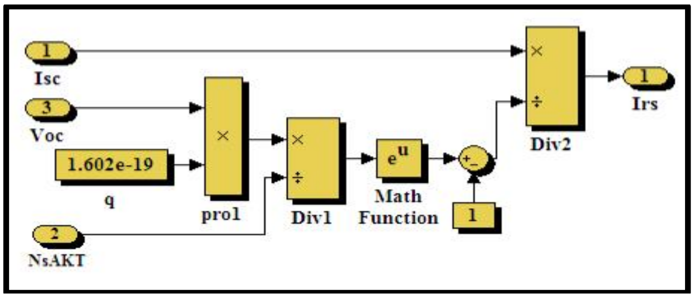


Figure (8): Subsystem for calculation of I_{rs}

Step 5:

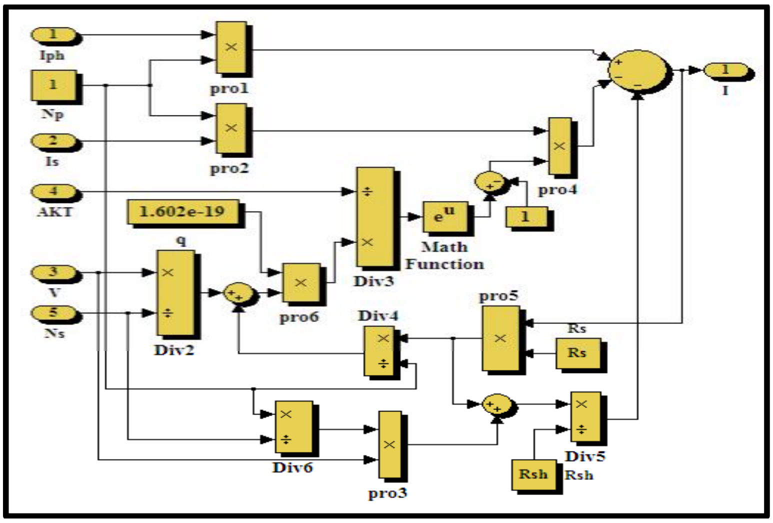


Figure (9): Subsystem for calculation of the output current

Step 6: All above five subsystems are interconnected as given in Fig.10.

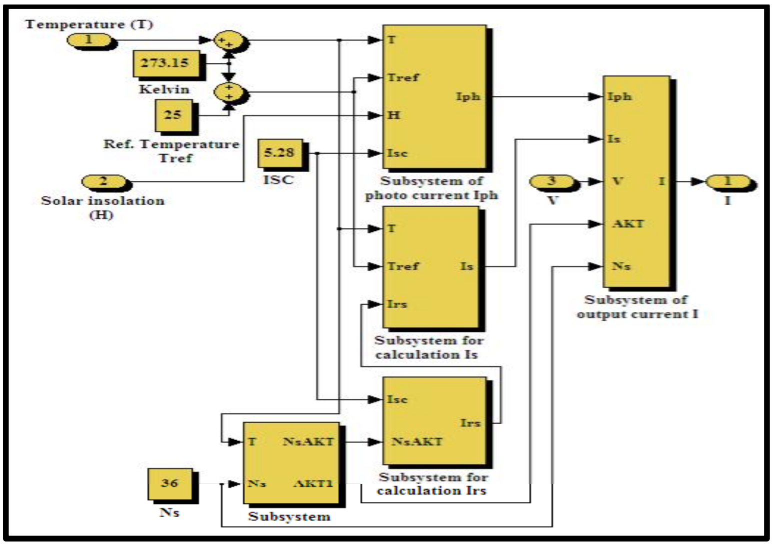


Figure (10): Interconnection of five subsystems

The final model is shown in Fig. 11.

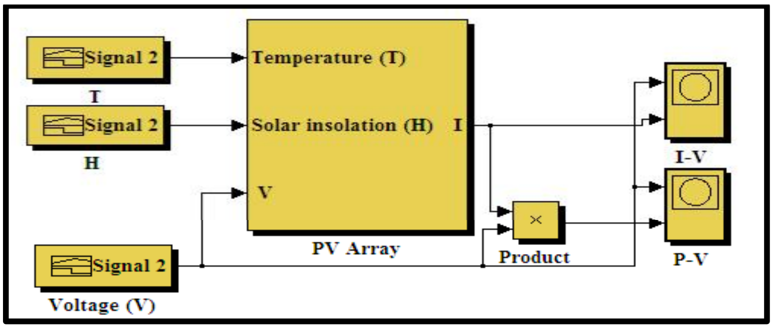


Figure (11): Simulink circuit of PV model

The final model takes radiation, operating temperature in (°C) and module voltage as input and gives the output current (I) and output voltage (V).

<u>Results and Discussion</u>:

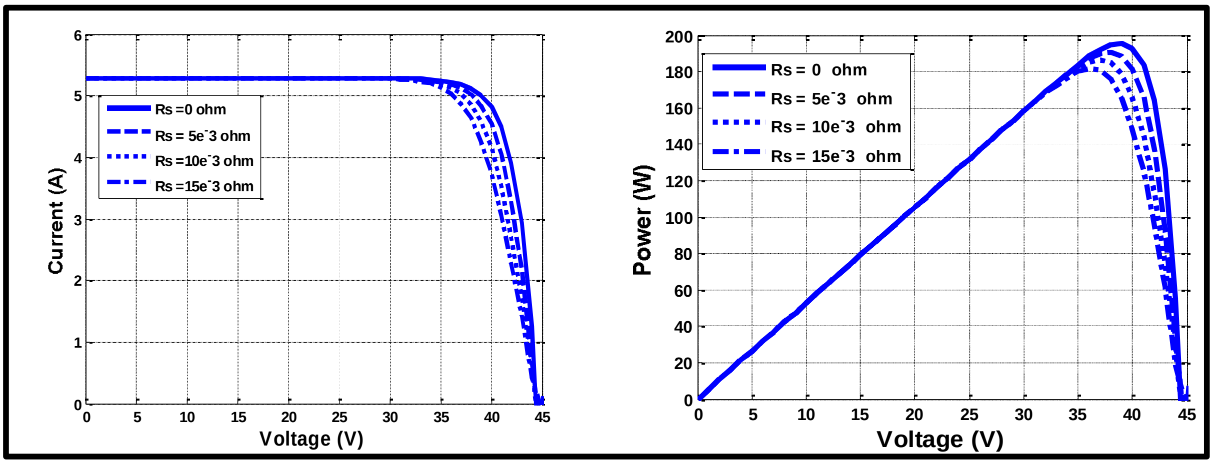
The Matlab/Simulink model in Fig. 11 readily offers an investigation in variation of model parameter (resistance R_s andR_{sh}) and variation of environmental parameter (solar radiation & working temperature).

A. Model Parameter Variation:

In this section, effect of variation of series and shunt resistance and their influence on I-V and P-V characteristics of PV model is studied.

1- Effects of Series Resistance (R_s)

The series resistance of the PV cell is low, and in some cases, it can be neglected. However, to render the model suitable for any given PV cell, it is possible to vary this resistance and predict the influence of its variation on the PV cell outputs. The effect of the R_s on the I-V and P-V characteristics is shown in Fig. 12. The simulation is produced for four different values ofR_s as 0Ω, 5mΩ, 10mΩ, and 15mΩ.



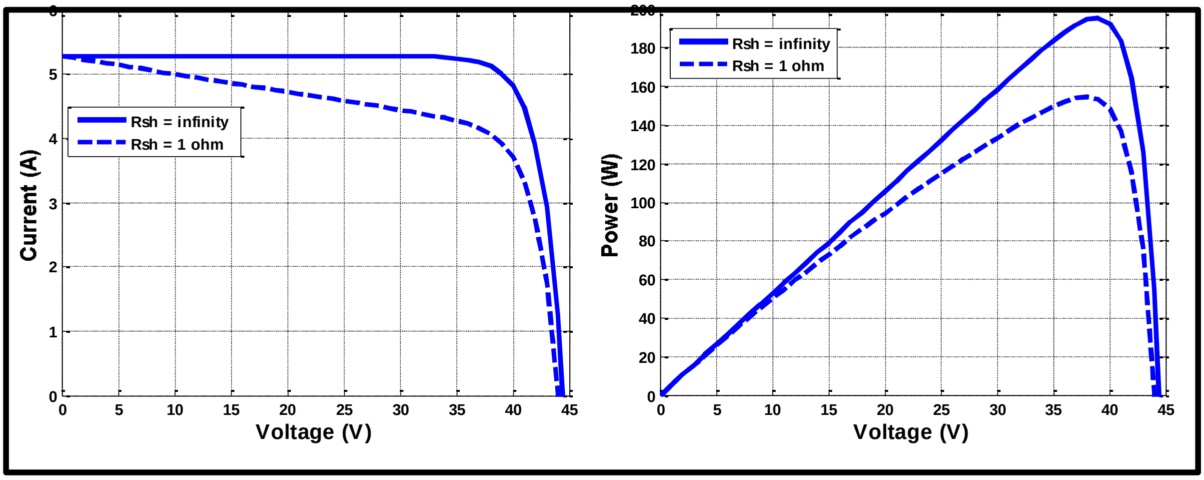
(a) **(b)**

Figure (12): Effect of R_s on the (a): I–V characteristics and (b): P–V characteristics at constant solar radiation (1kW/m^2) and constant temperature (25°C)

The variation of R_s affects the slope angle of the I-V curves resulting in a deviation of the maximum power point (i.e. reducing the series resistance lead to an increase in the power output and a deviation of the maximum power point as well).

2- Effects of Shunt Resistance (R_{sh})

The effect of varying R_{sh} is much less obvious in a PV model compared to the R_s, and it will only become noticeable when it (R_{sh}) decreased too much. Since for a low shunt resistor, the PV cell current collapses more steeply which means higher power loss.The simulation is produced for two different values of R_{sh}: infinity & 1Ω. The resultant I-V characteristics & power-curves plotted are shown in Fig. 13.



(a) **(b)**

Figure (13): Effect of R_{sh} on the (a): I–V characteristics and (b): P–V characteristics at constant solar radiation (1kW/m^2) and constant temperature (25°C)

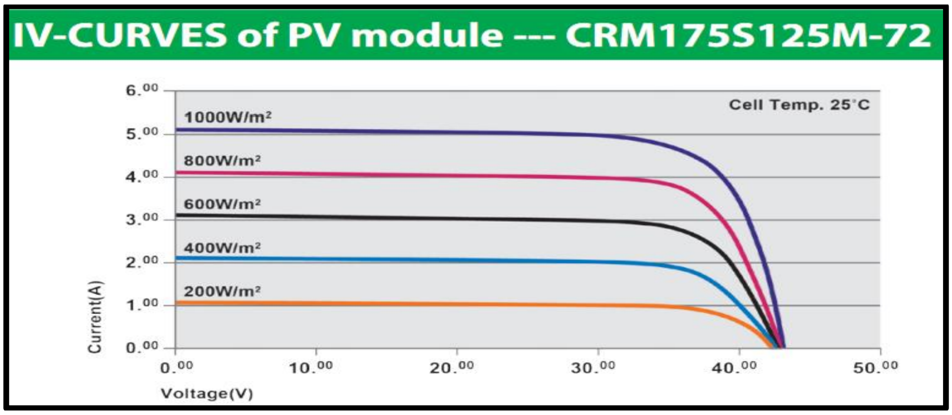
It is observed that the smallest value of R_{sh} causes PV cell current to fall more steeply indicating higher power loss. All practical PV cell therefore must have high value of R_{sh} and low value of Rs for giving more output power.

B. Environmental Parameter Variation:

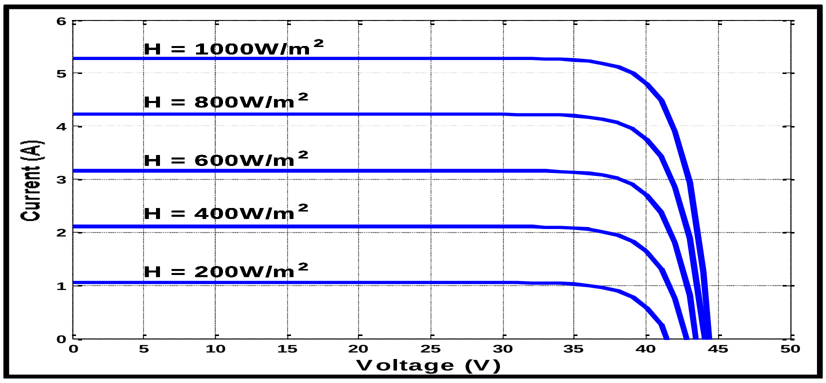
Simulink model is used to demonstrate behaviour of PV cell under varying two environmental conditions of solar insolation and temperature.

1- Effects of Solar Radiation(H)

The influence of the solar radiation on the solar cell voltage, current, and maximum power point at the constant temperature is shown in Figs. (14-15).



(a) [8]



(b)

Figure (14): I-V characteristic at constant temperature (25°C) with different solar radiation: (a) From data sheet, (b) From Matlab/Simulink

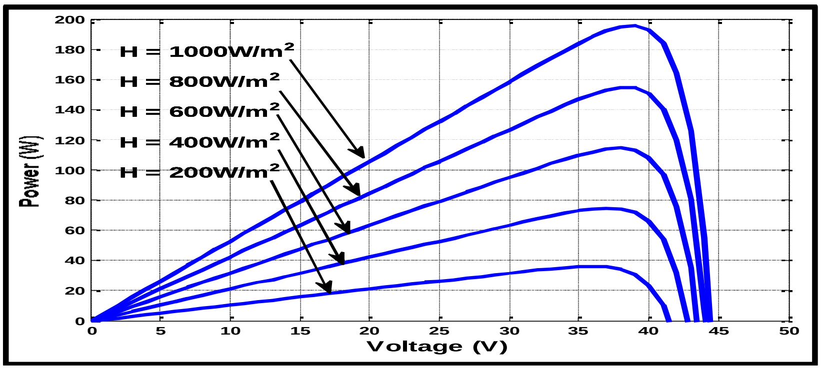
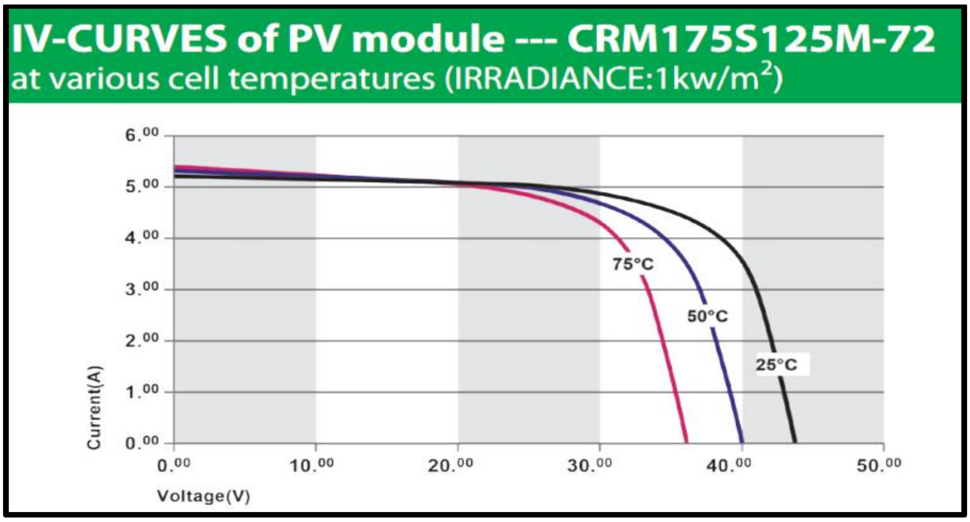


Figure (15): Effect of solar radiation on P–V characteristics at constant temperature (25°C)

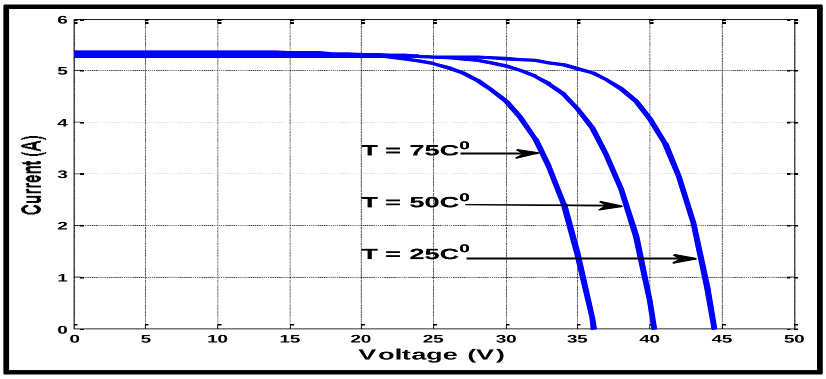
As it can be noted from these figures, more power is delivered from the solar cell as the irradiation level increases. This is due to increase in both the voltage and the current when solar cell is exposed to more irradiation. Solar radiation clearly has a major effect on the current, and the relationship of solar radiation with the current is indeed a linear one.

2- Effects of Temperature (T)

The temperature of a PV module greatly affects its performance. Although the temperature is not as important as the duration and intensity of sunlight, the PV module power output is reduced at high temperatures. The temperature of a PV module also affects its efficiency. In general, the efficiency of a PV module is reduced when the temperature is increased. The impacts of the ambient temperature on the solar cell voltage, current, and maximum power output are shown in Figs. (16-17).



(a) [8]



(b)

Figure (16): I-V characteristic at constant solar radiation (1kW/m^2) with different temperature: (a) From data sheet, (b) From Matlab/Simulink

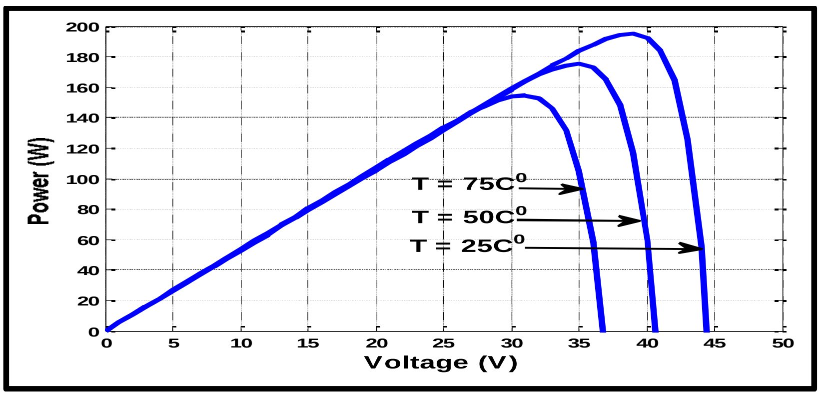


Figure (17): Effect of temperature on P–V characteristics at constant solar radiation (1kW/m^2)

With increase of working temperature, the short-circuit current of the PV cell increases, whereas the maximum power output decreases. Inasmuch as the increase in the output current is much less than the decrease in the voltage, the net power decreases at high temperatures.
I-V characteristic curves are obtained for the selected modules with the output power of 175W from simulation as shown in Fig. 14 (b) and Fig. 16 (b) and compared with the curves provided by the datasheet as in Fig. 14 (a) and Fig. 16 (a) respectively. The results obtained from the simulation model are well matched with the datasheet information.

Conclusions:

In this study, the developed model of PV array not only helps to predict the behaviour of any PV cell under different physical and environmental conditions, also it can be considered a smart tool to extract the internal parameters of any solar PV cell including the series and shunt resistance. Some of these parameters are not always provided by the manufactures. The Simulink for model PV array is developed based on the mathematical model of the PV module. The essential parameters required for modelling the solar PV array are taken from datasheets of typical 175W solar PV array. The results from the Matlab model show excellent correspondence to manufacturer's published curves.

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