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DESIGN, FABRICATION, TESTING AND SIMULATION OF A MODERN GLASS TO GLASS PHOTOVOLTAIC MODULE IN IRAQ

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Abstract

The aim of the present paper is to design, fabricate, test and simulate a PV module. Conventional PV module glass to tedlar suffers from several problems that threat PV technology. These problems are lack in output power due to yellowing EVA layer during the years, moisture permeation in the module through EVA and tedlar layers and drop in thermal performance during winter season due to lower operating cell temperature. In order to overcome these problems, glass to glass PV module is the appropriate solution to minimize the amount of wet into the module and increase heat gain. This PV module was fabricated and tested in Al-Mansour State Company / Ministry of Industry and Minerals, Iraq at Standard Test Conditions. The test result showed that the maximum power is 94.2 W and the module efficiency is 11.1%. The PV module was simulated using MATLAB/Simulink software in order to estimate the output characteristics under different conditions such as solar irradiance and cell temperature. Simulation results were validated with data sheet parameters. The percentage error between the simulated results and the data sheet parameters for the open circuit voltage, short circuit current and the maximum power are 0.041%, 0%, 0%, respectively. Results showed a good closeness between parameters of data sheet and the simulated results.

Keywords: cell temperature, Design PV module, Simulink, Solar irradiance

1. Introduction

Energy is a significant issue that plays a fundamental role in economic growth and industrialization all over the world. The crisis of fossil fuels and oil prices due to increasing the energy demand faces the world to exploit solar energy. Solar energy inexhaustible, effective, unpolluted and cost-free source [1]. Photovoltaic module is one of substitutes for conventional energy source that gaining more concern because it has a large potential to supply energy demand such as electricity, heating and cooling in all aspects. Mainly, PV module is a collection of silicon cells (semiconductor) that convert directly solar radiation in to DC electricity. Silicon cell can be recognized into three types according to the kind of crystal. These types are mono crystalline, poly- crystalline and thin amorphous [2]. Iraq receives an enormous amount of solar radiation due to location near the Sun Belt. It receives solar radiation with an average of (6.5-7) kilowatt-hour per square meter. During the year, the period of sunshine ranges from 2800 to 3300 hours. This previlage gives Iraq the possibility to exploit solar energy widely and used it to provide the load demands in national grid, which represent a challenge [3].

Pern [4] studied the effect of encapsulation materials, processing and testing of PV panel. It was concluded that the various type of encapsulation materials provides various performance. Further, lamination quality and reliability of PV panel dependence on encapsulation manner and processing factors. Mahajan and Bhole [5] presented a Simulink model by using MATLAB software to describe current - voltage and power – voltage characteristics of PV panel. It was observed that the output power from the panel increased by increasing the solar radiation while reduced when cell temperature increased. Jiang et al. [6] developed a mathematical and a simulation model to predict the output behaviour of the PV panel under different weather conditions. They found that the simulation model was simple, accurate and used to design and simulate PV module with any converter and controller.

Jadallah et al. [7] presented a simulation model for PV cells by using a computer program in MATLAB software to study the effect of different parameters such as solar irradiance, diode ideality factor and dark saturation current. The results showed that the output power increased by increasing the solar irradiance and ideality factor, but Decreased when dark saturation current and operating cell temperature increased. Bellini et al. [8] improved a mathematical model based on data sheet manufacture parameters only. They reported that the output electrical (open circuit voltage and short circuit current) parameters varies from the parameters provided by data sheet due to the change in electrical output of PV module during the years. Islam et al. [9] studied the influence of environmental conditions, shunt resistance and series resistance on the performance of PV panel by using MATLAB/Simulink environment. It was observed that adopted model could be used for any rated size of PV module.

Salmi et al. [10] developed MATLAB/ Simulink model for PV panel and array. The simulation model taken into consideration the effect of climatic and physical parameters. Abd El-Basit et al. [11] presented a simulation model by using MATLAB/ Simulink to verify (I-V) and (P-V) characteristic of PV module under different operating conditions. It was found that the electrical efficiency reduced by increasing cell temperature and the increase in solar radiation leads to increase in current and series resistance. Khezzar et al. [12] improved four parameters model to simulate PV module to study (I-V) characteristic under various conditions.

Park et al. [13] proposed a novel modelling algorithm for simulating any kind of PV cell material (Cr-Si, Thin film, tandem) to predict (I-V) characteristic of PV cell. It was observed that this modelling gave accurate results with minimal error, do not required long time to estimate the five parameters and suitable for any kind of solar cell.

This paper focuses on fabrication process of glass-to-glass PV module with various packing factor to generate electrical power and enhance thermal gain. Further, simulink module to predict the output characteristic of the module. The main phases of PV module are soldering of the electrical connection between cells and encapsulation through the lamination process. The PV module will be undergone several tests such as pull test and visual inspection before the measuring process.

2. Design, Fabrication and Testing Photovoltaic Module

The following sections reveal the whole process of designing, fabrication and testing the PV module considered in this work.

2.1. Design of PV module

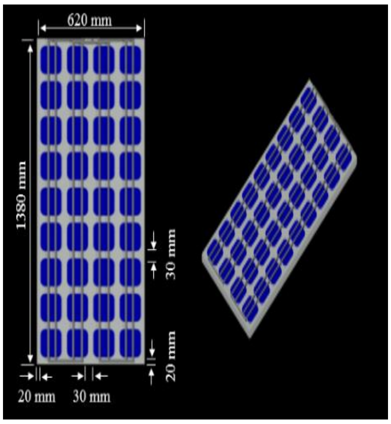
Figure 1(a) shows the adopted design of the PV module. The basic step upon, which the proposed design is the setting of the range of electrical efficiency of mono crystalline PV module, is started from 10% to 15%. The significant parameters which affected the proposed design are cell efficiency, number of cells, area of cell, area of module and packing factor. In this study, the packing factor is 0.63. All the data used for evaluating packing factor are illustrated in Table 1. The layers of PV module are solar cells, Ethylene vinyl acetate (EVA), and glass cover as shown in Fig. 1(b). In the future scope, this PV module will be employed in hybrid photovoltaic thermal system to enhance electrical and thermal performance at the same time.

2.2. Fabrication of PV module

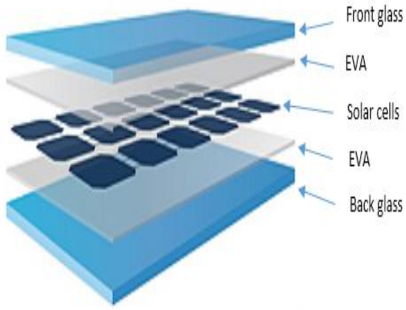
Photovoltaic module is a group of solar cells electrically connected in series to increase the voltage or in parallel to increase the current. Fabrication process of PV module is started by putting a wood template of width 30 mm between each of two cells as shown in Fig. 2(a). After that the ribbon are manually weld on the solar cells. The manner of welding is from top face (negative) to back face (positive) that which form the strips of PV module as shown in Fig. (b).

Table 1. Component characteristics of PV module.

Component	Number	Dimension	Function
Mono crystalline solar cell	36	125×125± 0.5 mm	Convert sun light into electricity
Tempered glass	2	Length 1380 mm Width 620 mm Thickness 3.2 mm	Suitable for outdoor conditions and cannot be broken into sharp large pieces when exposed to damage
EVA layer	2	Length 1380 mm Width 620 mm Thickness 0.45 mm	Adhesive material and protect electrical connection



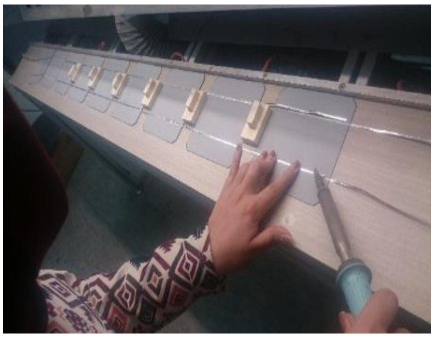
(a) Layout of the designed PV module.



(b) Layers of PV module.

Fig. 1. Design photovoltaic module.

(a)Wooden structure between cells.



(b) The first strip.

Fig. 2. Soldering process.

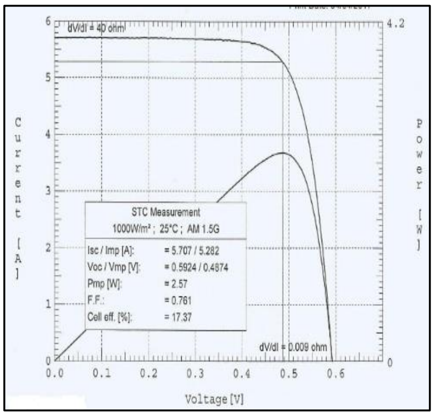
2.3. Testing process

Testing process of PV module occur on five steps. The first step is before soldering process and the others after the soldering process. Firstly, solar cell must be tested to know output power and cell efficiency at STC. The cell can be tested by cell tester, which is shown in Fig. 3(a). The results of the test of one solar cells that which form PV module was found 17.37 % as presented in Fig. 3(b). The second step is to check soldering durability of ribbon by using Pull tester, as shown in Fig. 3(c). The cell is subjected to an applied force of 125 g, the results of pull test is accepted. The results of pull test for proposed design is 150 g. The third step is visual inspection. Array of cells is placed on lightening table as shown in Fig. 3(d), which is easily to seek the defects or misalignment of the strips and the results of this inspections was found reasonable.

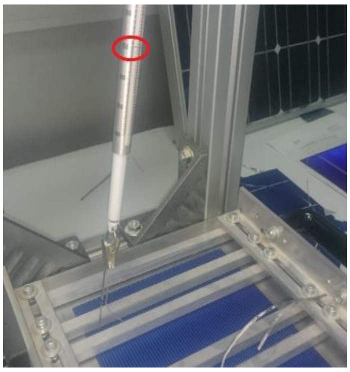
Hence, the end of strips was connected electrically to form the final electrical circuit. The output voltage is measured by digital multi meter as shown in Fig. 3(e).

Finally, after covering cells array with second EVA and glass layers PV module enter laminator machine to get final product, electrical characteristic of PV module is tested at STC, the tested results were obtained as shown in Fig. 3(f). PV module in final look is shown in Fig. 4.

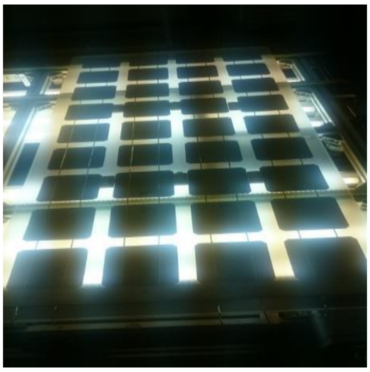
(a) Cell tester.



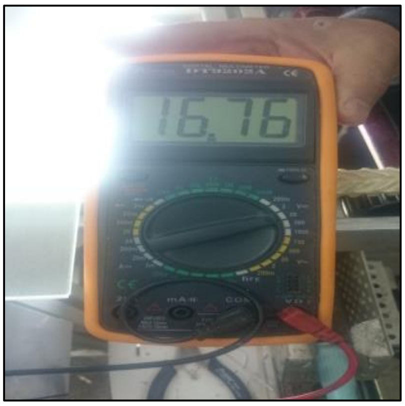
(b)Tested result of selected cell.



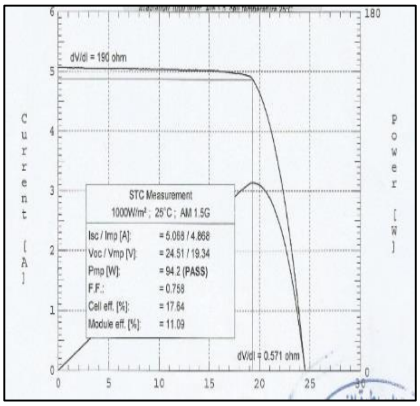
(c) Pull tester.



(d) Visual inspection.



(e) Circuit test.



(f) Tested result of PV module.

Fig. 3. Testing Process.

(a) Front face of PV module. **(b) Back face of PV module.**

Fig. 4. PV module.

3. Methodology

3.1. Packing factor and module efficiency

The most important parameter that effect on the proposed design is the packing factor (*PF*), which represent the ratio of the solar cells occupied by the module area. Mainly, it depends on the area of cell, number of solar cells and module area. The relationship of (*PF*) can be represented as below [14]:

$$PF = \frac{A_c \ N_c}{A_m} \tag{1}$$

Cell efficiency (η_c) represents maximum power of solar cell to the solar irradiance receiving by solar cell.

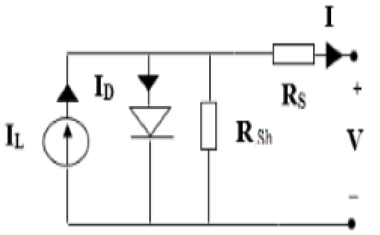
$$\eta_c = \frac{P_{m,c}}{G \ A_c} \tag{2}$$

Module efficiency is the product of cell efficiency by packing factor, thus module efficiency will be less than cell efficiency.

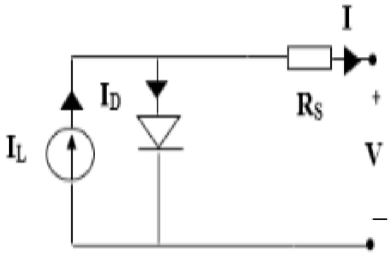
$$\eta_m = \eta_c \ PF \tag{3}$$

3.2. Equivalent circuit of photovoltaic cell

Equivalent circuit of PV cell is based on single diode model. This model includes current source (current generated by the sun light), a diode, series resistance and shunt resistance as shown in Figs. 5 [15]. In general, five parameters (I_L, I_D, R_S, R_{sh}, a) must be evaluated to describe current-voltage characteristics of PV module as shown in Fig. 5(a). These parameters are function of two environmental conditions (solar radiation and temperature).



(a) Equivalent circuit with R_{Sh} and R_S



(b) Simplified equivalent circuit with R_S
Fig. 5. Single diode model [15].

In reality, the value of series resistance is very small, which represent the resistance of silicon cell while shunt resistance value is large which referred to the leakage current through parallel resistor. Shunt resistance can be neglected to simplify equivalent circuit. The four parameters model (I_L , I_D , R_S, a) is more practical model used to predict photovoltaic panel behaviour.

An equation of output current of PV module can be obtained by applying Kirchhoff's current law at the equivalent circuit provided in Fig. 5(b) [16].

$$I = I_L - I_D \quad (4)$$

Mainly, diode current is proportional to the saturation current as in Eq. (2).

$$I_D = I_o\ [exp\left(\frac{V + I\,R_S}{B}\right) - 1\ ] \quad (5)$$

$$B = V_T\ \mathrm{a} \quad (6)$$

where B is the product of thermal voltage to ideality factor.

3.3. Influence of cell temperature and solar irradiance on PV module

Cell temperature and solar irradiance effect on the following parameters:

Thermal voltage of diode is exclusive depend on cell temperature, (V_T) is given by the equation:

$$V_T = \frac{T_C\,k}{q} \quad (7)$$

Saturation current of diode various with cell temperature, which is defined as below [17].

$$I_o = I_{o,ref}\ (\frac{T_C}{T_{C,ref}})^{\ 3}\ exp\ [(\frac{q\,E_g}{ak})\ (\frac{1}{T_{C,ref}} - \frac{1}{T_C}\ )] \quad (8)$$

where saturation current of diode can be approximately obtained as:

$$I_{o,ref} = \frac{I_{sc}}{exp\left(\frac{V_{oc}}{B}\right)-1} \tag{9}$$

Current generated by the sun light is depend on both solar radiation and Cell temperature.

$$I_L = (I_{sc,ref} + \lambda\,(T_C - T_{C,ref}))\,\frac{G}{G_{,ref}} \tag{10}$$

while, open circuit voltage may be given as [18]:

$$V_{oc} = (V_{oc,ref} + \mu\,(T_C - T_{C,ref})) \tag{11}$$

where λ is the voltage coefficient of open circuit voltage provided from manufacture data sheet of PV panel at STC (V/K), μ is the temperature coefficient of short circuit current taken from manufacture data sheet of PV panel at STC (A/K).

3.4. Series and parallel connection of solar cells

Solar cells are electrically connected in series or in parallel to rise the voltage and current. When the cells connected in series, the voltages of each cell are added up while the current is the same as the cells one. As cells are connected in parallel the current of each cell are added up while the voltage is the same as the cells one.

Saturation current and output current formula of PV module containing a number of cells are presented as [17]:

$$I_{o,ref} = \frac{I_{sc}}{exp\left(\frac{V_{oc}}{BN_S}\right)-1} \tag{12}$$

$$I = I_L\,N_p - I_o\,N_p\,[exp(\frac{V + I\,R_S\left(\frac{N_S}{N_p}\right)}{B\,N_S})\,] \tag{13}$$

4. Simulation

Based on the mathematical equation of PV module, a model is simulated by using MATLAB /Simulink environment. This model taken in to account the effect of solar radiation and cell temperature on the output characteristic. Electrical parameters of PV module (Tabark Ha, 94.2 W) at STC used in Simulation model as illustrated in Table 2.

Table 2. Key specification of the adopted PV module.

Name	Tabark Ha
Maximum power (P_m)	94.2 W
Open circuit voltage (V_{OC})	24.51 V
Short circuit current (I_{SC})	5.07 A
Voltage at maximum power (V_m)	19.34 V
Current at maximum power (I_m)	4.87 A
No. of cells connected in series (N_S)	36
No. of cells connected in Parallel (N_P)	1

Simulink block for current generated by the sun light (I_L) as given in equation (10) is illustrated in Fig. 6. Open circuit voltage (V_{OC}), which is given in equation (11). It was simulated via the block diagram shown in Fig. 7.

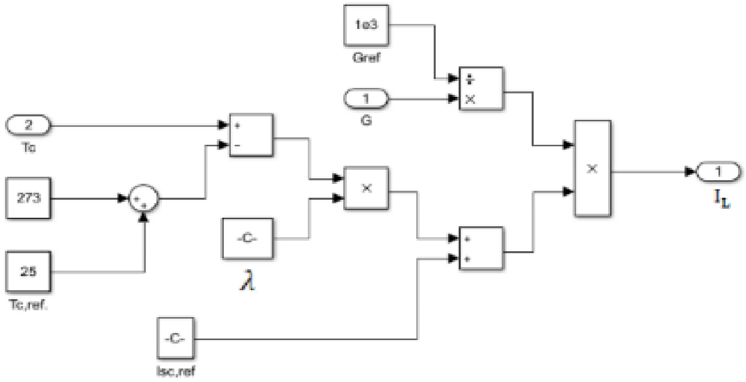


Fig. 6. Model of current generated by sun light.

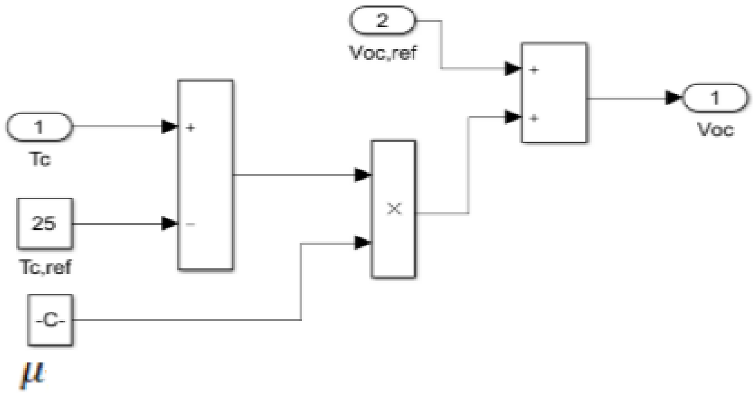


Fig. 7. Model of open circuit voltage.

Saturation current of diode described by equation (8). Is simulated in the block diagram shown in Fig. 8. Final Simulink block for output current of PV module (I) as written in equation (13) is shown in Fig. 9. Simulink model of PV module was represented by block diagram as shown in Fig. 10.

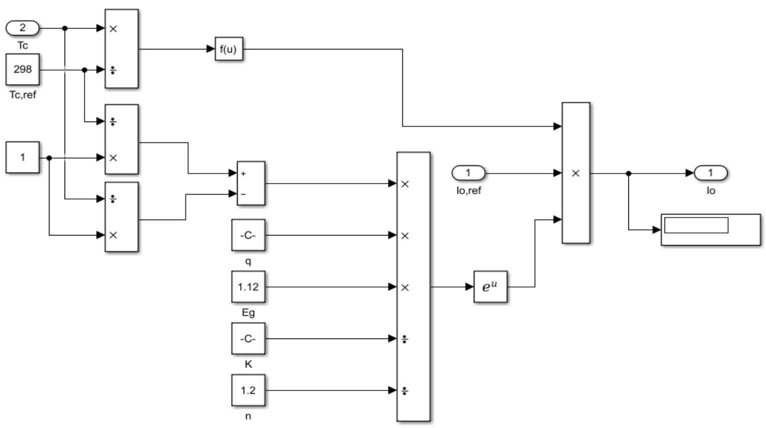


Fig. 8. Model of saturation current of diode.

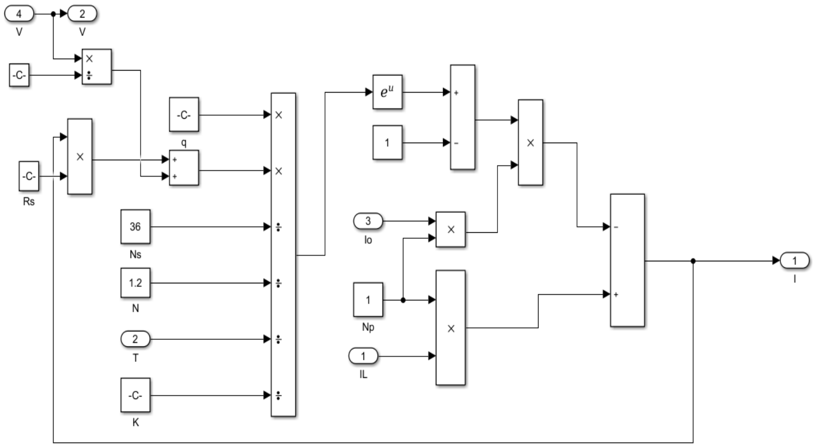


Fig. 9. Output current of PV module.

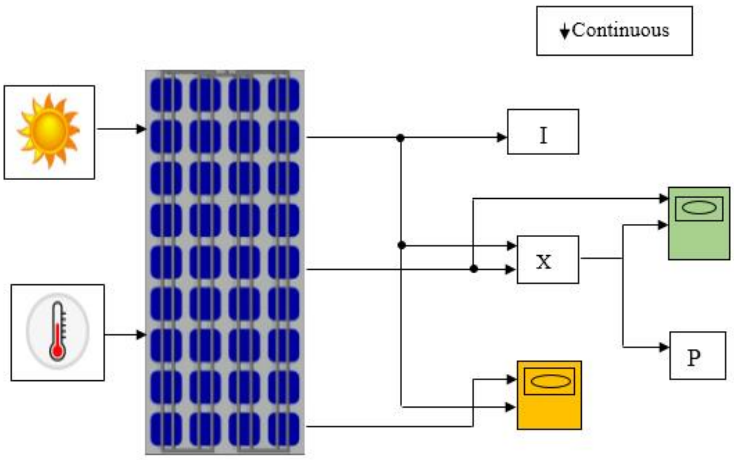


Fig. 10. Block diagram of simulink model.

5. Results and Discussion

The effect of packing factor on the design are shown in Fig. 11. Packing factor value various from 0.33 to 0.83 based on the present design. It was observed that at packing factor equal 0.63. Module efficiency is kept on an acceptable efficiency 11.1%. As the value of packing factor is lowered, module do not remain in range of mono crystalline PV module efficiency. The reduction in module efficiency resulting from uncovered total module area with cells will be compensated as a heat gain for PVT system.

Power –voltage and current – voltage characteristics of the proposed PV module at STC are simulated using MATLAB/Simulink Software are shown in Figs. 12 and 13. It is found that simulation results of open circuit voltage and short circuit current and maximum power are 24.52 V, 5.07 A, 94.2 W, respectively. Simulation curves and data sheet of PV module are in a good closeness. The percentage error between simulated results and data sheet parameters for open circuit voltage, short circuit current and maximum power are 0.041%, 0%, 0%, respectively. Figures 14 and 15 reveal the effect of various solar radiation at constant cell temperature 25 ℃ on I-V and P-V characteristics of PV module. It was noticed that the current increased linearly with the increase of solar radiation but the voltage increased nonlinearly which lead to an increase in output power. The influence of different cell temperature at constant solar radiation 1000 W/m^2 on P-V and I-V characteristics are presented in Figs. 16 and 17, respectively. It was observed that increasing cell temperature lead to a linearly decrease in voltage while the current increased slightly which lead to reduce the power generated of PV module.

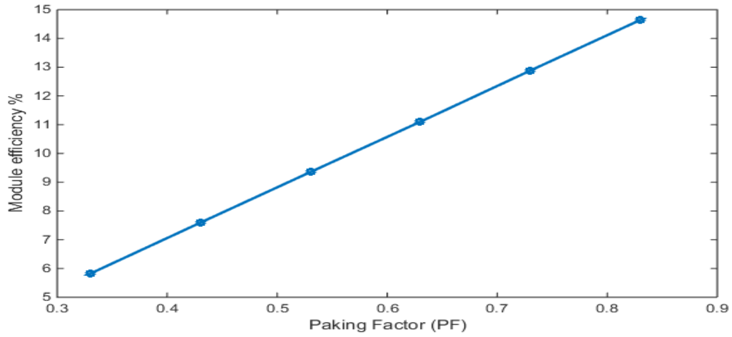


Fig. 11. Effect packing factor on module efficiency.

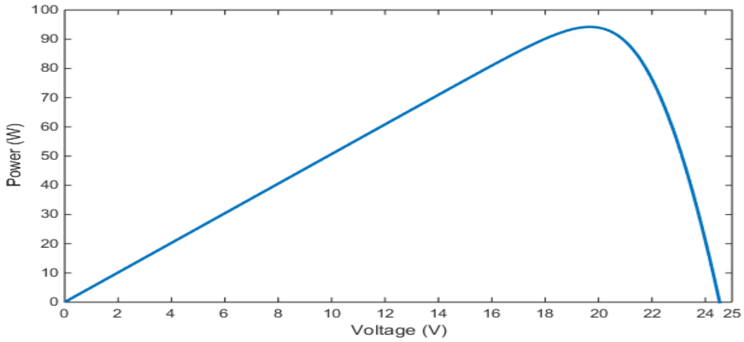


Fig. 12. P-V characteristic of the proposed PV module at STC.

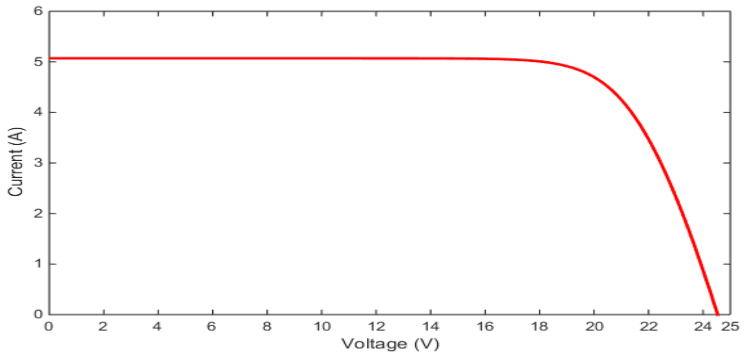


Fig. 13. I-V characteristic of the proposed PV module at STC.

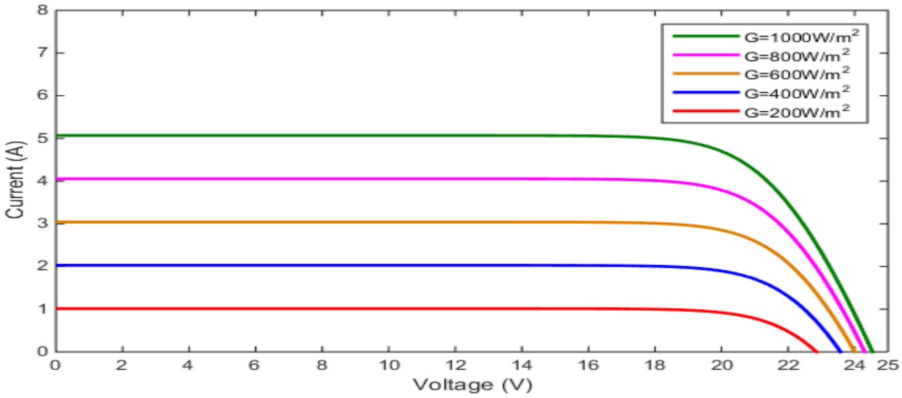


Fig. 14. I-V characteristic of the PV module at various solar radiation and constant cell temperature.

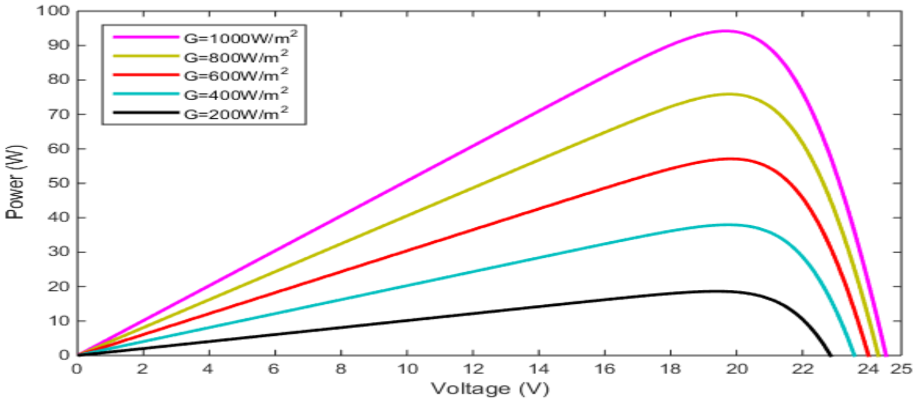


Fig. 15. P-V characteristic of the PV module at various solar radiation and constant cell temperature.

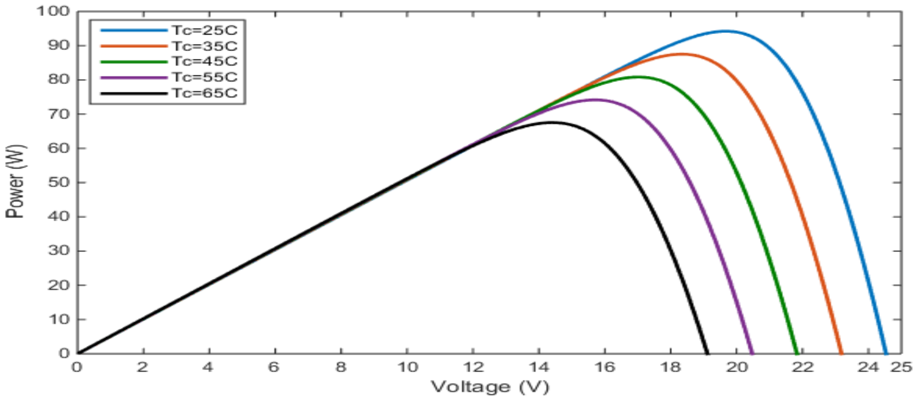


Fig. 16. P-V characteristic of the PV module at various cell temperature and constant solar radiation.

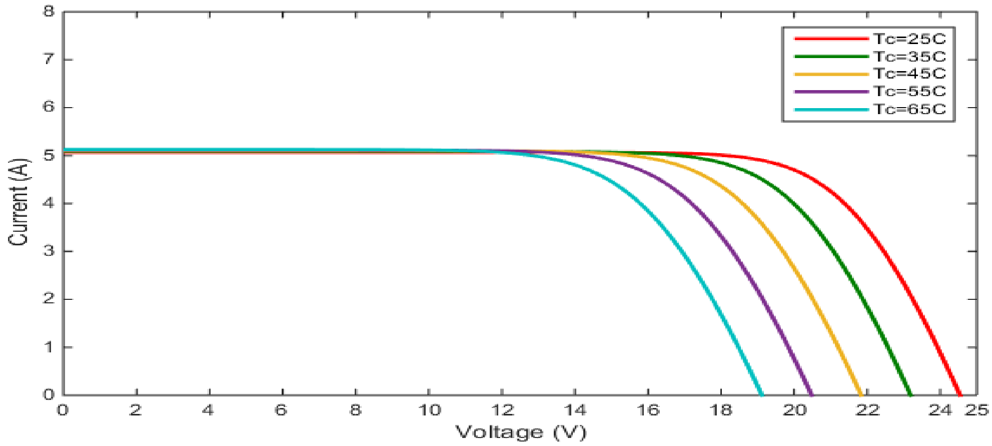


Fig. 17. I-V characteristic of the PV module at various cell temperature and constant solar radiation.

6. Conclusions

PV cells and thermal solar collectors are hybridized in PV/T systems to improve the electrical and thermal efficiencies as well. Although the air-based PV/T system has an efficiency lower than that of the water-based PV/T system, it may be considered as a promising design concept because of its simplicity in manufacturing. Design and fabrication of PV module (glass to glass) with packing factor 0.63 was achieved to be compatible with the climate of Iraq. Alternating the packing factor from standard value only module conducts a compensation between electricity productivity and heat production in summer and winter seasons. The increase in solar radiation has a favorable effect on the output current, while the increasing in operating cell temperature reducing output voltage of PV panel. The simulation results show a good closeness with manufactures data sheet.

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Nomenclatures

a	Ideality factor of diode which is depend on PV cell technology for mono crystalline Cell (1.2)
A_c	Cell area, cm^2
A_m	Module area, m^2
E_g	Energy band gap for silicon 1.12 eV
G	Solar irradiance, W/m^2
$G_{,ref}$	Solar irradiance at STC, W/m^2
I	Output current of PV module, A
I_D	Diode current, A

I_m	Maximum current of PV module, A
I_L	Current generated by the sun light, A
I_o	Saturation current of diode, A
$I_{o,ref}$	Saturation current of diode at STC, A
I_{sc}	Short circuit current, A
$I_{sc,ref}$	Short circuit current at STC, A
k	Boltzmann constant (1.381×10^{-23}), J/K
N_c	Number of cells
N_p	Number of cells connected in parallel
N_s	Number of cells connected in series
PF	Packing factor
P_m	Maximum power of PV module, W
$P_{m,c}$	Maximum power of solar cell, W
q	Electron charge (1.602×10^{-19}), Coulombs
R_S	Series resistance, Ω
R_{sh}	Shunt resistance, Ω
T_C	Cell temperature, K
$T_{C,ref}$	Cell temperature at STC, K
V	Output voltage of PV module, V
V_m	Maximum voltage of PV module, V
V_{oc}	Open circuit voltage, V
$V_{oc,ref}$	Open circuit voltage at STC, V
V_T	Thermal voltage of diode, V
Greek Symbols	
η_m	Module efficiency, %
Abbreviations	
EVA	Ethylene vinyl acetate
PV	Photovoltaic
STC	Standard test condition

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