

# A Model for Photovoltaic Module Optimisation

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**Abstract** Electricity generation from fossil fuels for general use is posed with problems such as greenhouse gas (GHG) emissions, environmental threats and energy crisis. However, renewable energies have become the best possible alternatives to fossil fuel, in terms of generating electricity, and they have lower impact on the environment. Photovoltaic (PV) technology is the fastest growing renewable energy technology but it's very expensive and not as efficient compared to traditional energy conversion systems. In this paper, we introduce an optimisation model to ensure efficient use of photovoltaic modules. We build a one diode model using blocks from the **MATLAB**/Simulink library. Simulations were carried out for varying irradiance intensity from  $400\text{Wm}^{-2}$  to  $1000\text{Wm}^{-2}$ . We process the simulations data in Matlab and the results is that the irradiance incident on the module directly affects the current supplied by the module, and this in turn affects its Fill Factor and efficiency. There exist also a relationship between the series resistor of the PV module and the Maximum Power delivered, and we obtain a mathematical expression linking the series resistor and the intensity of the irradiance incident.

**Keywords** Photovoltaic (PV), Module, Irradiance, Series resistor, Efficiency

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## 1. Introduction

Globally, electricity is accorded the most multipurpose energy carrier. The significance of the contribution of electricity to human and economic development cannot be moderated. Studies by several researchers confirm immense contribution of electrical energy to economic development of a nation [1-4].

Electricity is mostly generated from fossil fuels (oil, gas, coal, nuclear etc). However, there are a lot of problems associated with the use of fossil fuels: energy crisis, Greenhouse Gas (GHG) emissions and environmental threats [5]. Renewable energy technology is an alternative and considered as the optimum solution because of its lower environmental impact than fossil fuels. Research has shown that the use of renewable energy sources is beneficial to counteracting the dangers and effects associated with the use of fossil fuels [2, 4-8].

Photovoltaic technology is one of the fastest growing pollution free renewable energy technologies. El-Negamy et al. [7] maintain that 'photovoltaic energy is a clean, renewable, energy with long service life and high reliability. However, it is observed that the utilisation and contribution of the PV generated electricity is less than other energy

sources [7]. This is as a result of the high cost; however, it has low efficiency of photovoltaic modules. Anchored on the advantages and the disadvantages of the PV modules (no noise associated with their use, no or little maintenance, no health nor environmental hazards and high cost coupled with low efficiency), it is imperative to optimise them.

It is emphasise that photovoltaic systems will continue the future development in a direction to become a key factor in the production of electricity for households and buildings in general [9]. This is because PV systems contribute to reducing energy consumption in buildings as well as lower environmental impacts.

Most studies conducted on the performance of PV modules [4, 10-14] have shown that the efficiency of solar panels is directly affected by irradiance and the temperature on its surface. The peculiarity of this research is that it seeks to eliminate the influence of the temperature at the surface of the module by regulating its internal resistance.

In this paper we define and propose a model for optimisation of PV modules. Our proposed model is based on the influence of irradiance and the series resistor.

### 1.1. PV System and PV Simulation Model

A PV solar system consists of solar panels or a solar array, the balance of system (BOS) and a load. The solar cell is the basic unit of a PV system. According to Zeman [15], for solar cells to be able to generate electricity for practical applications, a number of cells must be connected together. A module refers to a group of cells that are electrically

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connected together in series and/or parallel in a sealed laminate. Modules are the building blocks of a PV power generating system. Modules are put together to form a panel and the panel in turn form an array [12].

There are several models for simulation of PV system operation and behaviour. The model postulated by Borowy and Salameh is a simplified model for calculating maximum power output for known irradiance and temperature [16]. Jones and Underwood also defined a simplified model of the maximum power output. According to them, the maximum power output is inversely proportional to the cell temperature and has a logarithmic relationship with the solar radiation absorbed by the PV cells [17]. There are significant variations in the methods of calculations, accuracy and the number of parameters used for the determination of the current-voltage characteristics. Yang, Lu, & Zhou [18] established a model for ascertaining the optimum power output of PV modules with particular emphasis on the theory of equivalent circuit of solar cells through the use of eight parameters which can be identified by regression with the Downhill Simplex Method. The accuracy of this model was validated with experimental data.

However, Selmi, Abdul-niby, & Alameen [12] posit that photovoltaic cell modelling is possible through the use of equivalent circuits. Further, the authors observed that there are two key parameters that characterise a photovoltaic cell. The first parameter is the short-circuit current ( $I_{sc}$ ), obtained by short-circuiting both terminals of the photovoltaic cell. Thus, the photovoltaic current is expected to reach its maximum value, while the voltage between the two terminals ( $V_{sc}$ ) is null. The second parameter is the open circuit voltage ( $V_{oc}$ ). Here the two terminals of the cell are unconnected, the photovoltaic current is shunted by an intrinsic diode and there is no current in the external ( $I_{oc} = 0A$ ).

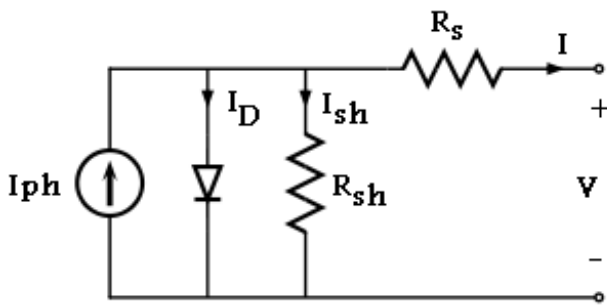


Figure 1. Single-diode equivalent circuit of a PV cell

PV system simulation models require information that mainly relates the electrical output of its constituent modules to various environmental and operating conditions [19]. Understanding the environmental and operating conditions undoubtedly provide means to integrate sustainably the required model for simulation and maximum energy production. A Single diode equivalent circuit model is viewed and considered the appropriate and simplest form of representing the electrical performance of a PV module [10, 12, 20]. The single-diode model is formulated through

the extension of best diode law to account for parasitic series ( $R_s$ ) and shunt resistances ( $R_{sh}$ ) as well as the addition of various equations which appropriately describe how photocurrent and other terms of the models vary with irradiance and temperature. [10]

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

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

Where  $I_{PH}$  is a light-generated current or photocurrent,  $I_S$  is the cell saturation current,  $q$  is the electron charge,  $K$  is Boltzmann's constant,  $T_C$  is the cell's working temperature,  $A$  is an ideal factor,  $R_{SH}$  is a shunt resistance, and  $R_S$  is a series resistance. The photocurrent mainly depends on the solar insolation and cell's working temperature, which is described as

$$I_{PH} = [I_{SC} + K_I (T_C - T_{REF})] \lambda$$

Where  $I_{SC}$  is the cell's short-circuit current at a 25°C and 1kW/m<sup>2</sup>,  $K_I$  is the cell's short-circuit current temperature coefficient,  $T_{REF}$  is the cell's reference temperature, and  $\lambda$  is the solar insolation in kW/m<sup>2</sup>. Also, the cell's saturation current differs with the temperature of the cell mainly described as:

$$I_S = I_{RS} (T_C - T_{REF})^3 \exp \left[ \frac{qE_G}{k} \left( \frac{1}{T_{REF}} - \frac{1}{T_C} \right) \right] / KA$$

Where  $I_{RS}$  is the cell's reverse saturation current at a reference temperature and a solar radiation  $E_G$  is the band-gap energy of the semiconductor used in the cell [13].

## 1.2. PV Power Output Optimization and Efficiency

Singh et al. observed that a typical PV cell produces less than 2W at 0.5V. According to the authors, in order to ensure high power output and efficiency, the cells of the PV must be connected in series-parallel configuration. Further, it is observed that the PV optimisation and efficiency is sensitive to a small amount change in  $R_s$  but insensitive to changes in  $R_{sh}$ . [13]

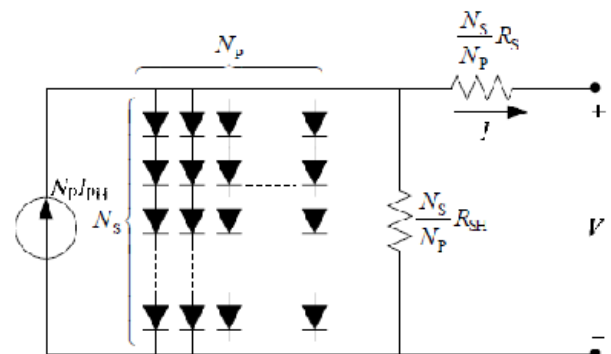


Figure 2. A generalised model for optimum PV power output

For a PV module, the series resistance becomes apparently important and the shunt resistance approaches infinity which is assumed to be open. PV cells are generally connected in series to form a PV module primarily to produce adequate working voltage [21]. PV modules are then arranged in series-parallel structure to attain a desired power output.

Figure 2 depicts the connection of PV cells to ensure maximum power output where  $NS = NP = 1$  for a PV cell,  $NP = 1$  and  $NS$ : series number of cells for a PV module, and  $NS$  and  $NP$ : series-parallel number for a PV array [13].

## 2. Methodology

The PV model for optimisation in this paper was developed using Matlab/Simulink. The model is based on a one diode model of a photovoltaic cell. With the aid of Shockley's diode equation, the model was established. Simulink was used to build and simulate the equivalent electrical circuit of the model. We simulate for varying irradiance from a  $100\text{Wm}^2$  to a  $1000\text{Wm}^2$  to investigate the effects of solar irradiance on a module. We then use Matlab to analyse the simulation results.

## 3. Modelling and Simulation

The simulation was carried out using the characteristics of the BP 365U photovoltaic module acquired from its manufacturer's data sheet. The module consists of 36 Silicon Nitride Multicrystalline cells connected in series. The BP 365U module is primarily used for rural electrification, pumping and irrigation and for industrial applications such as telecommunication. The 3 characteristic points of the PV module ( $I_{sc}$ ,  $P_{max}$ ,  $V_{oc}$ ) given by the manufacturer were compared with that which was obtained from simulation to ensure that the SIMULINK model models the physical properties of the system under study.

### 3.1. Description of Model

Models of PV cells are generally represented with electrical circuits. The many existing theoretical models are differentiated using the number of diodes, the shunt resistor being finite or infinite and the numerical method used to determine the unknown parameters [2]. The unknown parameters of a model are a photogenerated current, a shunt resistor, a series resistor, the saturation current and the equivalent number of ideality factors of the diodes used. The model used in this paper is a one diode model. It consists of a parallel connection of a current source modelling the photogenerated current ( $I_{ph}$ ), a diode modelling the dark current through the p-n junction ( $I_D$ ), a parallel resistor also known as the shunt resistor ( $R_{sh}$ ) modelling possible shunts across the junction. These three elements are then connected in series with an additional resistor, the series resistor  $R_s$ , which models the ohmic losses in the device [1]. The single diode model also known as the Lumped, 1 Mechanism model has five unknown parameters but the shunt resistor or both the shunt and series resistors can sometimes be eliminated to form Lumped, 1 Mechanism model with 4 Parameters (L4P) and the Lumped, 1 Mechanism model with 3 Parameters (L3P) respectively [4-9]. These sub-models are called mathematical models. The L3P is theoretical; does not

account for the comportment of the cell under Standard Test Conditions. The L4P which is Townsend's model (used in this paper) is largely used and is so far the ideal model [10]. This model likens the module to a cell producing current that depends on only the irradiance received.

### 3.2. Mathematical Model

Firstly, we define the following parameters:

- $q$ : charge of electron  $\rightarrow 1,602 \times 10^{-19}\text{ C}$
- $K$ : Boltzmann's constant  $\rightarrow 1.38 \times 10^{-23}$
- $T$ : cell temperature in Kelvin
- $I_{ph}$ : photogenerated current
- $I_{mpp}$ : maximum power point current
- $V_{mpp}$ : Maximum power point current
- $I_{sc}$ : short circuit current
- $I_s$ : saturation current
- $n$ : ideality factor
- $I_D$ : diode current
- $I_{sh}$ : shunt current
- $R_s$ : series resistor
- $R_{sh}$ : shunt resistor

Consider figure 3, when apply Kirchoff's first law, we obtain equation (1).

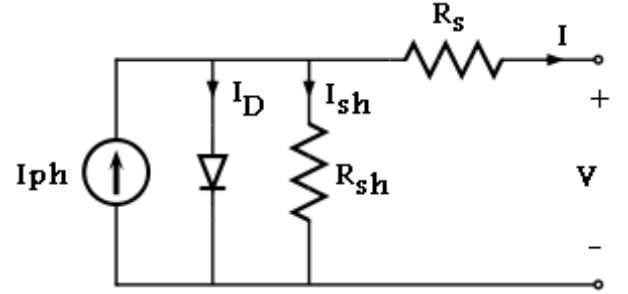


Figure 3. Circuit of a one diode model of a photovoltaic cell

$$I_{ph} = I_D + I_{sh} + I \quad (1)$$

We set two hypotheses;

- ❖ The shunt resistor ( $R_{sh}$ ) is very huge  $\Rightarrow I_{sh} \rightarrow 0$ .
- ❖ The photocurrent  $I_{ph}$  is independent of the temperature of the circuit. Its value under standard conditions is equal to that of the short circuit current  $I_{sc}$ .  
 $I_{ph} = I_{sc}$

Given the hypotheses, equation (2) is deduced from equation (1)

$$I_{sc} = I_D + I \quad (2)$$

We then consider Shockley's equation for a diode in equation (3).

$$I_D = I_s \left\{ \exp\left(\frac{qV_d}{nKT}\right) - 1 \right\} \quad (3)$$

More so, we obtain the voltage across the diode ( $V_d$ ) in equation (4) and that of the short circuit in equation (5) (i.e  $I = 0$ ):

$$V_d = V + (I \times R_s) \quad (4)$$

$$I_{sc} = I_s \left\{ \exp\left(\frac{qV_{oc}}{nKT}\right) - 1 \right\} \quad (5)$$

From equation (5) we obtain the saturation current of the cell in equation (6).

$$I_s = \frac{I_{sc}}{\left\{ \exp\left(\frac{qV_{oc}}{nKT}\right) - 1 \right\}} \quad (6)$$

if  $\left(\exp\frac{qV_{oc}}{nKT}\right) \gg 1$  so  $I_s$  becomes:

$$I_s = \frac{I_{sc}}{\left(\exp\frac{qV_{oc}}{nKT}\right)} \quad (7)$$

From equation (2), the expression of the short circuit current at the Maximum Power Point (MPP) is deduced:

$$I_{sc} = I_D + I_{m\ pp} \quad (8)$$

Replacing the expression of the diode current  $I_D$  in equation (8), equation (9) is obtained.

$$I_{sc} = I_s \left\{ \exp\left(\frac{q(V_{m\ pp} + (R_s \times I_{m\ pp}))}{nKT}\right) \right\} + I_{m\ pp} \quad (9)$$

The tension and current at the maximum power point ( $V_{m\ pp}$ ,  $I_{m\ pp}$ ) is a pair of known values. An ideal cell contains an ideal diode and an ideal diode has an ideality factor of 1.

$V_t = KT/q$  and  $n_{cell}$  is the number of solar cells in the module. Thus the value of the series resistor can be calculated from equation (10).

$$R_s = \frac{\ln\left(\frac{I_{sc} - I_{m\ pp}}{I_s}\right) n_{cell} \times V_t - V_{m\ pp}}{I_{m\ pp}} \quad (10)$$

### 3.3. Simulation

The model was built based on equation (10) using blocks from the Simulink library. The temperature of the module was fixed at 25°C while simulations were carried out for varying irradiance intensity from 400Wm<sup>2</sup> to 1000 Wm<sup>2</sup>. Table 1 compares the results obtained from simulation with that which is given on the manufacturer’s data sheet. The model chosen is suitable for optimisation of the BP 365U module because the simulation results are approximately equal to its given electrical specifications.

**Table 1.** Validation of simulation results

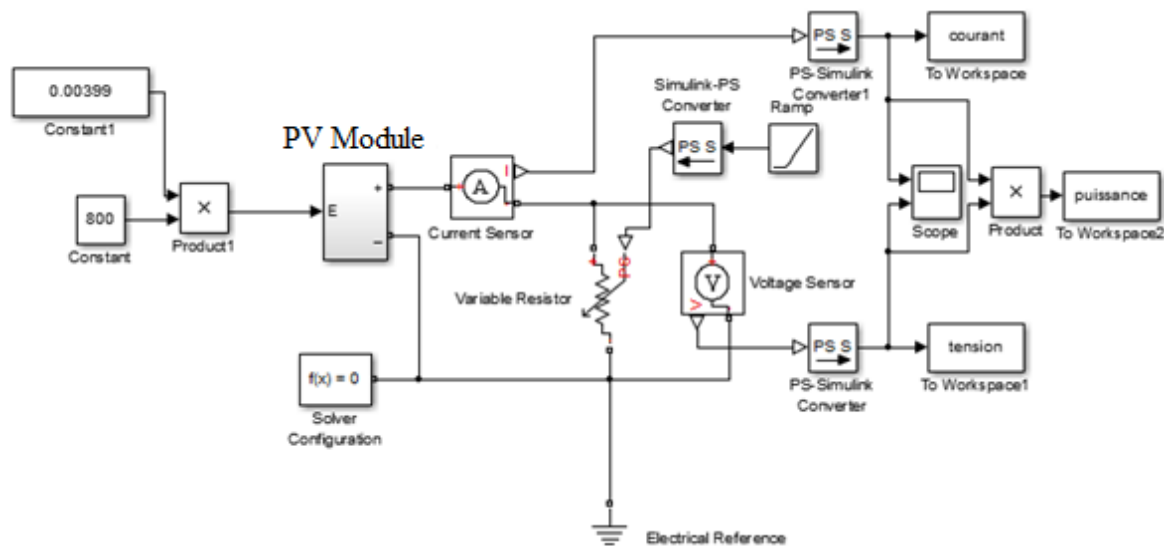
Parameter	Manufacturer’s data	Simulation result
Isc	3.99A	3.99A
Voc	22.1V	22.06V
Pmax	65W	65.08W

The  $P(V)$  illustrates that the functioning of the solar cell depends on the load associated with it: the power produced varies with the voltage across the module but there is a voltage where the electrical power produced is maximum.

## 4. Results and Discussion

### 4.1. Effects of Irradiance on Module Performance

It can be deduced from figure 7 that the irradiance received influences largely on the current delivered by the cell. The current dispersed is directly proportional to irradiance intensity. However the tension is almost not affected.



**Figure 4.** The simulation model for calculating  $R_s$

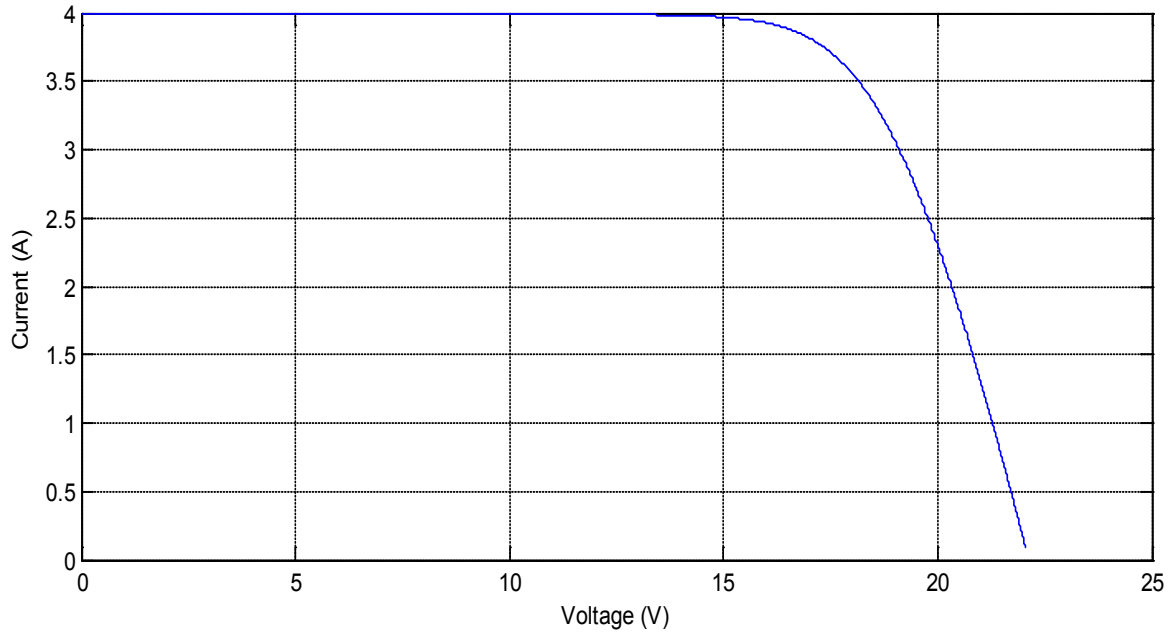


Figure 5. The current-voltage  $I(V)$  curve

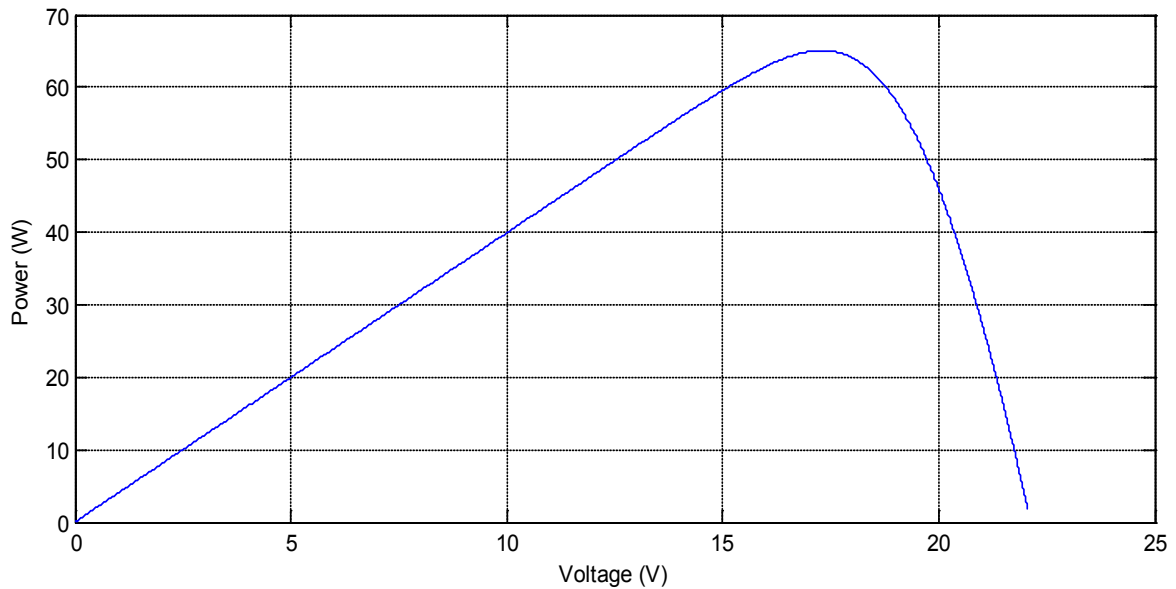


Figure 6. The power-voltage  $P(V)$  curve

Here it is important to note that the electrical power delivered by the module increases with increasing irradiance while its voltage varies slightly but the voltage of the peak power is almost fixed as shown in figure (8). This implies that to be able to produce maximum power, the voltage across the module must be around this value.

Figure 9 shows that the module’s power output increases with increasing irradiance and each irradiance value has a corresponding maximum power. Also the power delivered reduces with increasing resistance. Our aim is to find the series resistor ( $R_{opt}$ ) that corresponds with the maximum power point and its relation with the irradiance received.

- At the maximum power point:

$$P_{max} = I_{mpp} \times V_{mpp} = (I_{mpp})^2 \times R_{opt} \quad (11)$$

$$R_{opt} = \frac{P_{max}}{(I_{mpp})^2} \quad (12)$$

#### 4.2. The Optimal Series Resistor

The figure10 shows a graph illustration that the resistance at the maximum power point decreases with increasing irradiance intensity. The relationship between the optimal resistance and the irradiance is given in equation (16):

$$R_{opt} = 7.9 \times 10^{-5} G^2 - 0.12G + 49 \quad (16)$$

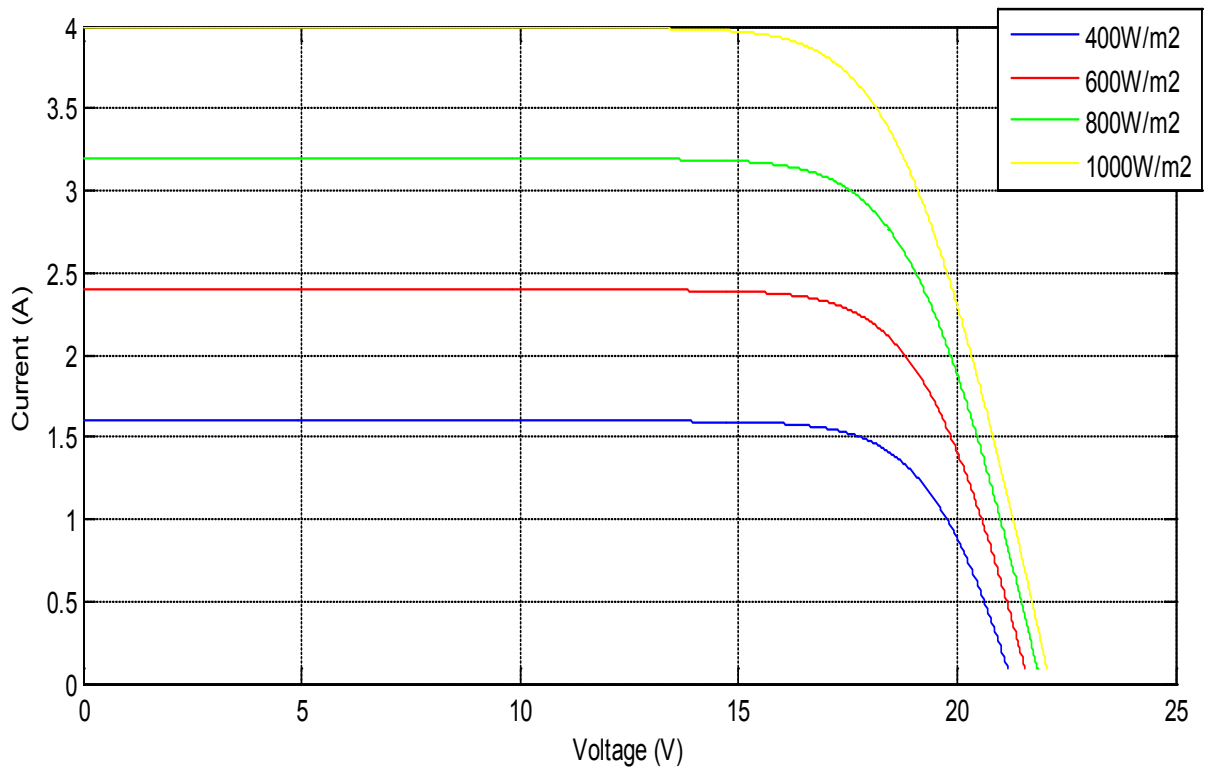


Figure 7. Evolution of the  $I(V)$  characteristic with varying irradiance

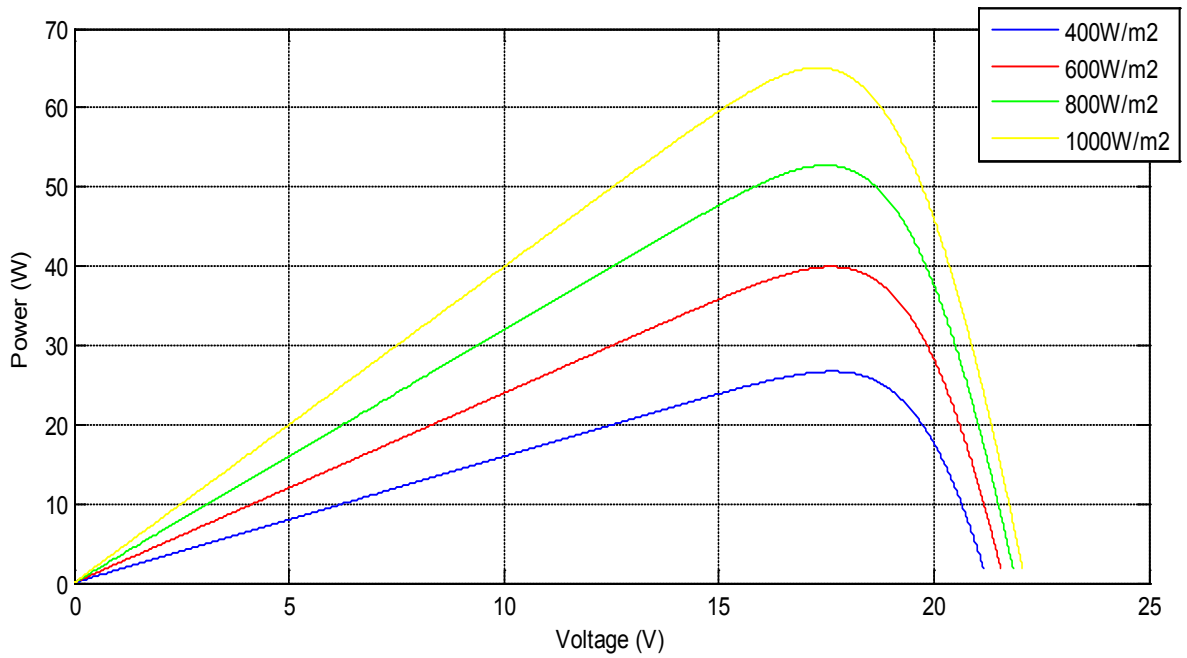


Figure 8. Evolution of the  $P(V)$  characteristic with varying irradiance intensity

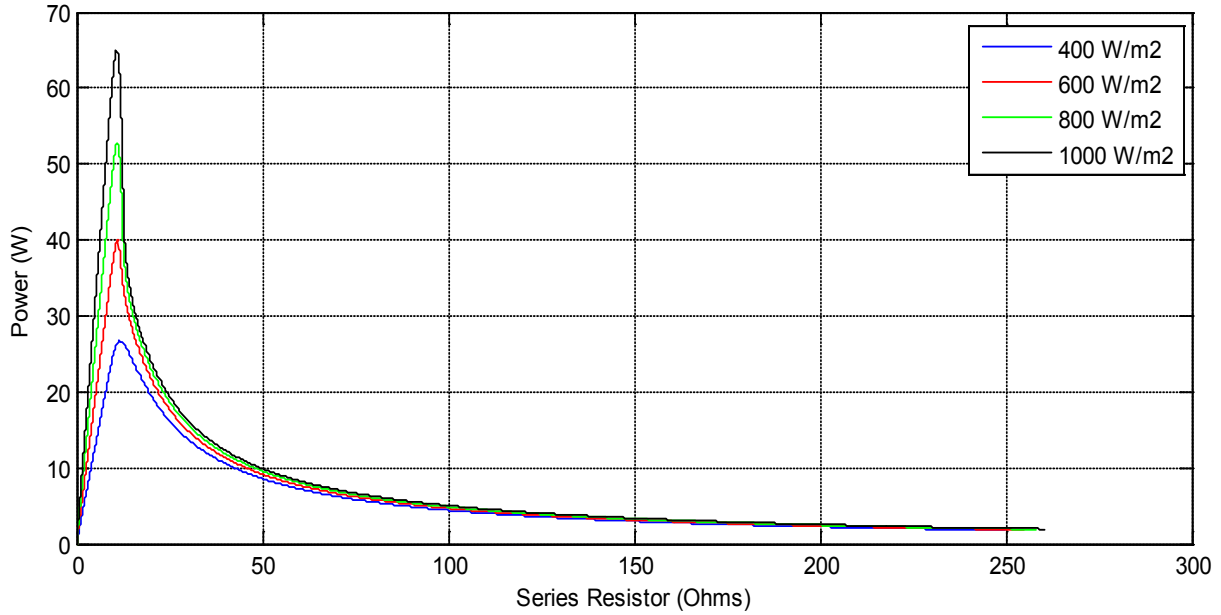


Figure 9. Power versus resistance for varying irradiance

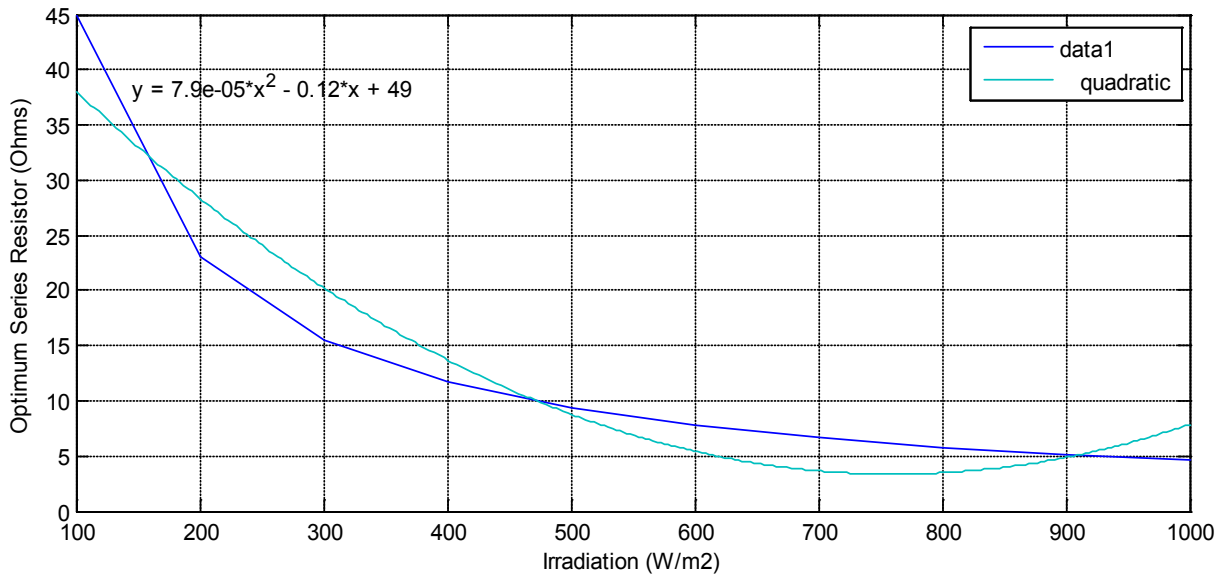


Figure 10. Series resistor at MPP versus irradiance

The coordinates of the Maximum Power Point of the optimised module is calculated from the characteristic relations obtained:

$$V_{mpp} = -2.4 \times 10^{-6} (1000)^2 + 0.0027(1000) + 17 = 17.3V$$

$$I_{m\ pp} = 0.0038(1000) + 0.0069 = 3.8069\ A$$

$$P_{max} = I_{m\ pp} \times V_{mpp} = 17.3 \times 3.8069 = 65.8594W$$

$$R_{opt} = 7.9 \times 10^{-5} (1000)^2 - 0.12(1000) + 49 = 8\Omega$$

This implies that at Standard Test conditions, the optimised module will produce a maximum power of 65.8594W on the condition that its internal resistance is

equal to 8Ω.

- Efficiency

$$\eta = \frac{I_{m\ pp} \times V_{mpp}}{G \times A} \tag{17}$$

The efficiency of the module according to the manufacturer’s data sheet is 11.7% but after optimisation we obtain 11.8%. There is 0.1% increase in efficiency after optimisation; the maximum output has been improved at standard conditions. An improvement in efficiency at standard conditions hints that other operating conditions can further be improved. It is possible that other operating conditions yield further increase in efficiency. This needs to be experimentally verified.

## 5. Conclusions

The current flow of a solar cell is directly proportional to irradiance intensity. The series resistor is a function of solar irradiance and influences on the efficiency of a solar cell; its magnitude has a direct impact on the maximum power delivered. One cannot control the irradiance but the internal resistance of the solar panel can be predetermined for a site. The model can be built by replacing the fixed series resistor in PV models with a variable resistor and a sensor.

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