INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. Seck et al., Vol.12, No.4, December 2022

Comparative Study of Photovoltaic Models Using Simulation and Experimental Studies

Assane Seck*‡, Mouhamadou Thiam*, Maguette Sarr**, Ibrahima Ka*, Mamadou Wade*

* Laboratoire des Sciences et Techniques de l'Eau et de l'Environnement (LaSTEE), Ecole Polytechnique de Thiès (EPT) Thiès, Sénégal

** Laboratoire des Energies Renouvelables (LER), Ecole Supérieure Polytechnique (ESP), Dakar, Sénégal

(assanemiftah2@gmail.com, mthiam@ept.sn, setekan@gmail.com, ika@ept.sn, mwade@ept.sn)

‡ Corresponding Author; Assane Seck, Laboratoire des Sciences et Techniques de l'Eau et de l'Environnement (LaSTEE), Ecole Polytechnique de Thiès (EPT) Thiès, Sénégal, Tel: +221 77 236 97 56,

assanemiftah2@gmail.com

Received: 25.04.2022 Accepted:08.06.2022

Abstract- Recently, many photovoltaic (PV) models have been found in the market. The choice of the PV model is a crucial step in the operation and design of such a system. Therefore, this article presents a comparative study of different PV cell models. The modeling and simulation of each model such as 2M7P, 2M6PRs, 2M6PRsh, L5P, L4PRs, L4PRsh and L3P, under different levels of solar irradiance and temperatures were carried out. This part allows to see the behavior of the models under the variation sunshine and temperature. The comparison of these models with the real behavior of the polycrystalline module SPP030501200 allowed us to distinguish the 2M6PRsh model from the L5P model among the most faithful models of reality.

Keywords Single diode model, two diode model, I-V and P-V characteristics, photovoltaic module.

1. Introduction

Solar energy is one of the most potentials among renewable energy sources in terms of ecology and socio-economic [1]. The photovoltaic (PV) module is made up of a solar cell that converts sunlight into electricity. The electricity produced by a PV depends on several parameters, such as sunshine, temperature, etc. So that, it is necessary to define a model that considers these influencing factors to predict the behavior of a PV.

Many research studies have been focused on modeling a PV module to determine the most suitable and efficient model that takes into consideration all possible weather conditions to describe the real behavior of a PV cell. An experimental analysis was conducted by Olivier and al. [2] using three models, i.e. five-parameter diode model (L5P), two diodes seven parameters model (2M7P) and the polynomial model. The objective was to find a model that can precisely follow the PV conversion chain. The polynomial model was distinguished by its simulation speed. The models with one and two diodes needed several minutes to achieve the computational while the polynomial model only required a few hundred milliseconds. Ishaque and al. [3] adopted the 2M7P model to analyse the partial shading of a PV system. A comparative study between the ideal one-diode model (L3P) and the four-parameter one-diode model with series resistance (L4PRs) was conducted by Rodrigues and al. [4]. This study proves that the L4PRs model presents the most realistic behavior. Ritesh and al. [5] have conducted a comparative study between the one-diode and the two-diode models. Saban and al. [6] demonstrated the performance of a 2M7P model in modeling the PV system. Ali and al. mentioned that the one-diode model is the most used in the literature due to its simplicity as compared to the two-diode model [7]. Tanvir and al. [8] evaluated the performance of the L5P and 2M7P models by varying model parameters, irradiation and temperature. The Bishop model and the L5P model have also been compared by Abdesslam and al. [9]. The study was conducted between the cases without defects and with defects (shading of a single cell at 50% for all configurations). The simulation results show that Bishop's model is the most effective for detecting the faults in PV systems. Vincenzo and al. [10] studied the two-diode model of a PV module. This study was based on an assessment of the utility and accuracy of two-diode models developed by some authors in the literature. The results obtained were compared with current-voltage characteristic data from two solar panel manufacturers. This work aims to help researchers and designers working in the field of PV systems to choose and use a model that could be adapted for research purposes. After evaluation, the two-diode model developed by Ishaque and al. [3] has been found as the best option among two-diode models. Saad and al. [11] modeled a PV cell based on an L5P model. Authors studied model behavior by varying external and internal parameters.

In this paper, we analyze different models of PV cells found in the literature. Additionally, we provide the mathematical model of these PV cells with a comprehensive insight. To the best of the authors' knowledge, this is the first attempt to identify the most coherent model found in the literature by comparing it to the experimental study.

The remainder of the paper is organized as follows: In Section 2, the modelling of the PV cell is presented. Additionally, mathematical models are described. Section 3 describes the experimentation study. Section 4 presents the comparison results and discussion. Finally, the conclusion and remark are presented in Section 5.

2. Modelling of PV Cells

The modelling of PV cells involves a judicious choice of equivalent electrical circuits. To develop an accurate equivalent circuit for a PV cell, it is necessary to understand the physical configuration of the elements of the cell as well as the electrical characteristics of each element. According to this, several mathematical models are developed to represent a strong nonlinear behavior, resulting from that of the semiconductor junctions which are on the basis of their realizations. These models differ from each other by the mathematical model and the number of parameters involved in the calculation of the voltage and current of the PV module.

Several models will be presented in this study including their simulation results obtained by Matlab, under the variation of the sunshine and temperature. Table 1 presents the characteristics of the module used in this study under standard conditions (1000 W/m2, optical masse: AM 1.5, Temperature of the cell: 25 °C).

Table 1. Characteristics of the module used for the simulation

Photon-current (Iph)	Iph (A)
Thermal coefficient (Ki)	0.0032 A/°C
Short circuit current (Isc)	3,120 A
Operation temperature	T (K)
Nominal temperature (Tn)	298 K
Solar irradiation	G (W/m2)
Electron charge (q)	1,6 e-19 C
Open circuit voltage (Voc)	21,6 V
The ideality factor of the diode (n)	1,3
Boltzmann's constant (K)	1,38 e-23 J/K
Band gap energy of the semiconductor (Eg0)	1,1 eV
Number of cells connected in series (Ns)	54
Serie resistance (Rs)	0,739 Ω
Shunt resistance (Rsh)	198 Ω
Rated power (Pmp)	50 W
Voltage at maximum power (Vmp)	17,50 V
Current at maximum power (Imp)	2,858 A

2.1 Two-Diode Model

2.1.1 Seven-Parameter Model (2M7P)

It is also known as a 2M7P (Lumped, 2 Mechanism model with 7 Parameters) model. The operation of a PV cell can be modeled by the equivalent electrical diagram as shown in Fig. 1. The mathematical formula is written as the parallel connection of two diodes which have identical saturation currents I01 and I02, diode factors (n), a current source producing a photo-current Iph which depends on solar irradiance. The series resistance Rs represents the resistivity of the material, the electrodes, and the semiconductor-metal contact. This value should as low as possible to limit its influence on the cell current. This can be achieved by optimizing the metal/ semiconductor contact and reducing the resistivity of the material used. However, too high doping will increase the recombination of the carriers. The parallel (shunt) or short-circuit resistance Rsh represents the leakage current through the emitter, caused by a fault. It is the case when the diffusion of high-temperature metal contacts pierces the transmitter. It can also be due to a short circuit on the edges of the cell. This value should be as high as possible.

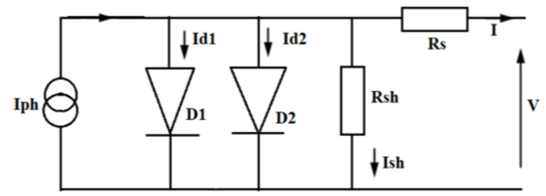


Fig. 1. Equivalent circuit of the 2M7P model

The equation of the current is obtained by Kirchhoff's law [6]:

$$I = I_{ph} - I_{d1} - I_{d2} - I_{sh} \tag{1}$$

Where Id1 and Id2 are the current of a diode 1 and 2, respectively.

Fig. 2 gives the simulation results of the current-voltage and power-voltage characteristics by varying the sunshine and temperature.

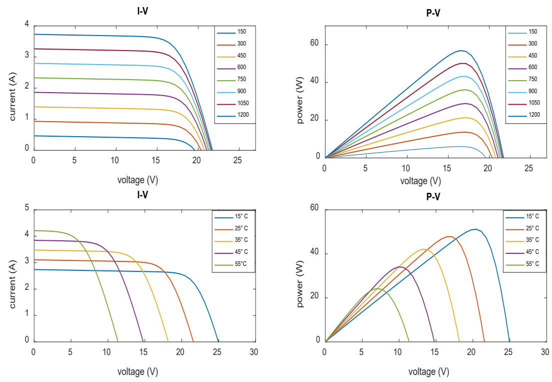


Fig. 2. Simulation results of the 2M7P model, under the variation of the solar irradiance and temperature

2.1.2 Six-Parameter Model With Series Resistance (2M6PRs)

If the shunt resistor is considered infinite (Rsh = ∞), there exist six parameters to be determined, which refer to the 2M6PRs model (Lumped, 2 Mechanism model with 6 Parameters). This simplification is justified by the fact that the shunt resistance is usually much larger than other resistors, so the current flowing through it becomes negligible. The electric circuit is described in Fig. 3. It represents by the parallel connection of two identical diodes which have the same saturation current, the same diode factor (n), a current source producing a photo-current. The latter depends on the solar irradiance and the series resistance Rs.

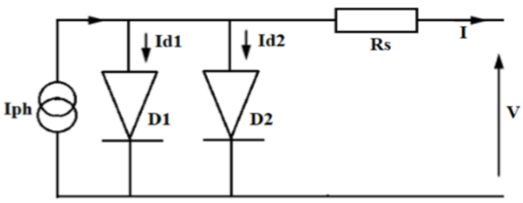


Fig. 3. Equivalent circuit of the 2M6PRs model

The equation of the current is written as

$$I = I_{ph} - I_{d1} - I_{d2} \qquad (2)$$

Fig. 4 depicts the simulation results of the current-voltage and power-voltage characteristics in accordance with the variation of the sunshine and temperature, respectively.

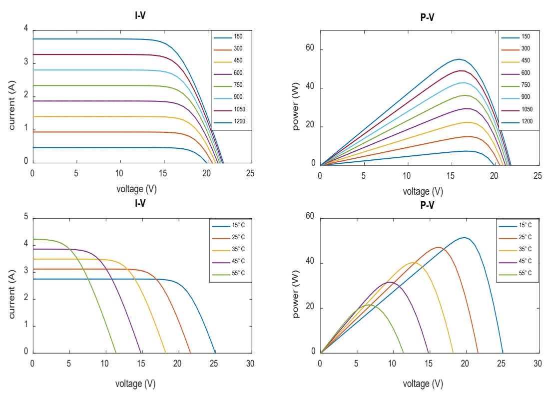


Fig. 4. Simulation results of the 2M6PRs model, under the variation of the solar irradiance and the temperature

2.1.3 Six-parameter model with a shunt resistor (2M6PRsh)

Fig. 5 represents the equivalent circuit of a six-parameter model in which a current source is used to model the light flux and the losses are modeled by a shunt resistor.

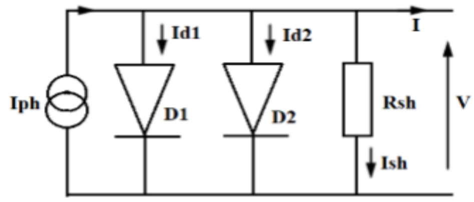


Fig. 5. Equivalent circuit of the 2M6PRsh model

The equation of the current is expressed by

$$I = I_{ph} - I_{d1} - I_{d2} - I_{sh} \qquad (3)$$

In Fig. 6, the simulation results of the current-voltage and power-voltage characteristics are presented, following the variation of the sunshine and temperature, respectively.

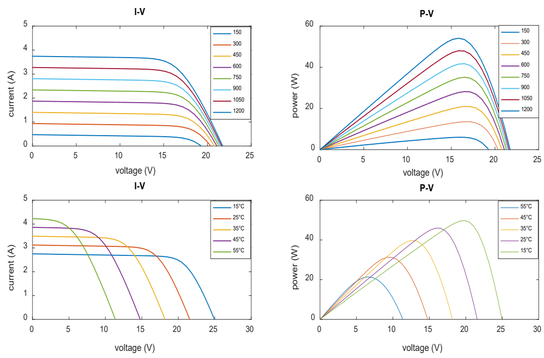


Fig. 6. Simulation results of the 2M6PRsh model, under the variation of the solar irradiance and temperature

2.2 Single diode models

The operation of a PV module is described by the “standard” one-diode model, which is defined by Shocky, for a single PV cell. It is a PV module assuming as a set of identical cells connected in series or parallel. A simpler description is obtained from the one-diode model. This model has one less diode compared to the two-diode model.

2.2.1 II.2.1 Five-parameter model (L5P)

This model is known as an L5P (Lumped 1 Mechanism model with 5 Parameters) five-parameter model. This is the most classic model and involves a current generator to model the incident light flux, a single diode for cell polarization phenomena, and two resistors (series and shunt) for losses [12] [1]. The model involves the five unknown parameters, i.e. n, Iph, Rs, Rsh, and I0. Its equivalent circuit is depicted in Fig. 7.

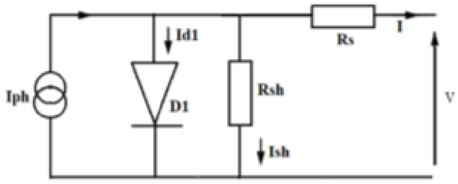


Fig. 7. Equivalent circuit of the L5P model

The equation of the current is represented as [11].

$$I = I_{ph} - I_d - I_{sh} \tag{4}$$

with

$$I_{sh} = \frac{V + I * R_s}{R_{sh}} \tag{5}$$

$$I_d = I_0 \left[\exp\left(\frac{q(V + I * R_s)}{n * Ns * K * T}\right) - 1\right] \tag{6}$$

$$I_0 = Irs \left(\frac{T}{Tn}\right)^3 exp \left[\frac{qE_{go}}{nK}\left(\frac{1}{Tn} - \frac{1}{T}\right)\right] \tag{7}$$

Where Irs is obtained by using the same assumption as the 2M7P model.

$$I_{rs} = \frac{Isc + Io\left[exp\left(\frac{q * Isc * Rs}{n * Ns * K * T}\right) - 1\right] + \frac{Isc * Rs}{Rsh} - \frac{Voc}{Rsh}}{\left[exp\left(\frac{q * Voc}{n * Ns * K * T}\right) - 1\right]} \tag{8}$$

The simulation results of the current-voltage and power-voltage characteristics are plotted in Fig. 8, under the variation of the sunshine and the temperature, respectively.

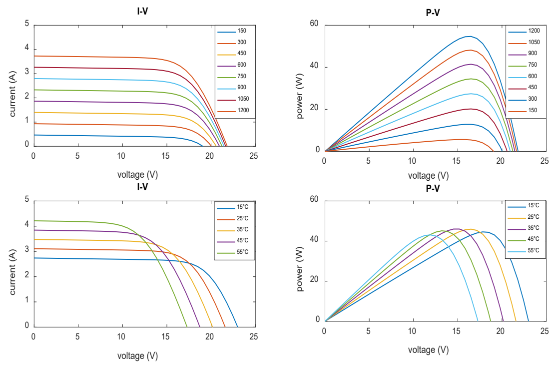


Fig. 8. Simulation results of the L5P model, under the variation of the solar irradiance and temperature

2.2.2 Four-parameter Model with Series Resistance (L4PRs)

The four-parameter model is one of the most widely used in previous research studies. This model considers the PV cell as a current source that depends on the solar irradiance, connected in parallel with a diode and series with a series resistor. The four parameters represented in the I(V) consist of the photon current Iph, the series resistance Rs, and two characteristics of the diode I0 and n [13]. They must be determined from the I(V) equations under different operating points given by the manufacturers. The equivalent electrical diagram of the PV cell for this model is shown in Fig. 9.

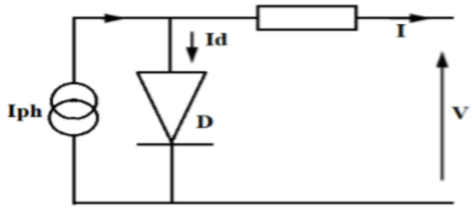


Fig. 9. Equivalent circuit of the L4PRs model

We can define the current equation as

$$I = I_{ph} - I_d \tag{9}$$

Figure 10 provides the simulation results of the current-voltage and power-voltage characteristics under the variation of sunshine and temperature.

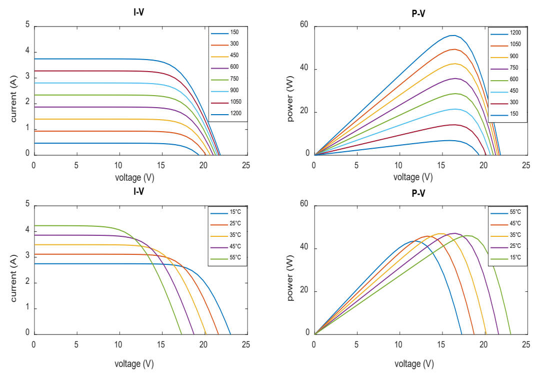


Fig. 10. Simulation results of the L4PRs model, under the variation of the solar irradiance and temperature

2.2.3 Four-Parameter Model with a Shunt Resistor (L4PRsh)

The PV cell is represented by the electrical circuit as shown in Fig. 11. It consists of a current source representing the irradiance while the losses are modeled by a shunt resistor.

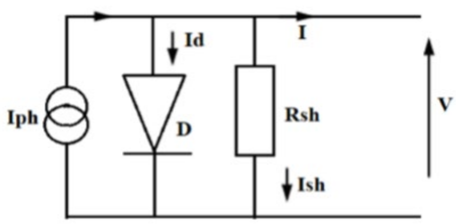


Fig. 11. Equivalent circuit of the L4PRsh model

The current equation is

$$I = I_{ph} - I_d - I_{sh} \tag{10}$$

In Fig. 12, the simulation results of the current-voltage and power-voltage characteristics are presented, under the variation the solar irradiance and temperature.

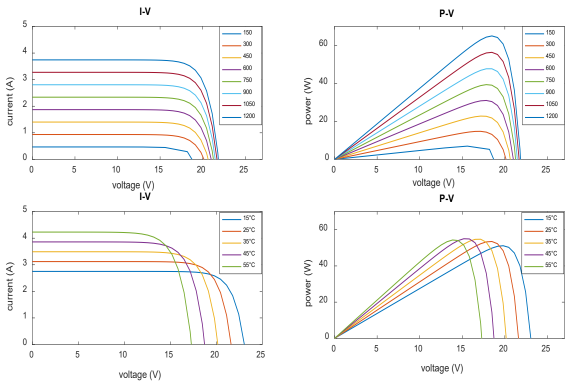


Fig. 12. Simulation results of the L4PRsh model, under the variation of the solar irradiance and temperature

2.2.4 Three-Parameter Model (L3P)

A PV cell can be described as an ideal current source in parallel with a diode. The current source generates a current Iph which is proportional to the solar irradiance, where a diode corresponds to the P-N transition area of the PV cell. This model is called the L3P (Lumped, 1 Mechanism model with 3 Parameters) model. For an ideal PV, the voltage across the resistor is equal to that across the diode [3]. This model is too theoretical and does not take into account the behavior of a PV cell under real operating conditions. However, it remains valid under certain assumptions (i.e. without considering voltage losses, leakage current, etc.). The equivalent electrical diagram is shown in Fig. 13.

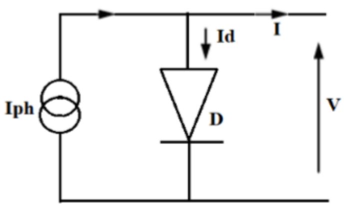


Fig. 13. Equivalent circuit of the L3P model

The current equation is described by

$$I = I_{ph} - I_d \tag{11}$$

The simulation results of the current-voltage and power-voltage characteristics is presented in Fig. 14, under the variation the sunshine and temperature.

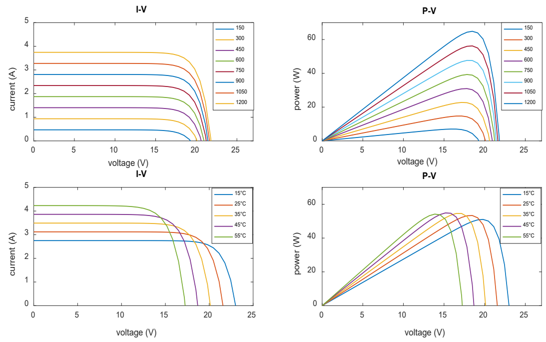


Fig. 14. Simulation results of the L3P model, under the variation of the solar irradiance and temperature

The simulation results show that the models listed above are all sensitive to the variation of irradiation and temperature. The increase in sunshine generates an increase in the intensity of the cell and a slight increase in the voltage. The voltage varies strongly decreases with the increase of the temperature compared to the variation of the intensity.

3. Experimentation

In this section, a polycrystalline panel of 50 Wp is chosen to carry out experimental measurements under different solar irradiance based on an I-V 400 W, as shown in Fig. 15. Their characteristics are listed in Table 2. In this regard, we can draw the I-V and the P-V curves and compare them with the models in literature. The objective is to determine the most realistic model that presents the real behavior of a PV module.

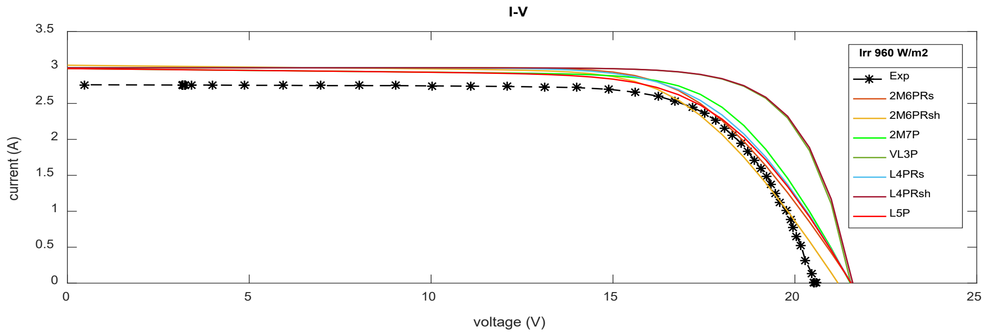
Table 2. Characteristics of the module SPP030501200

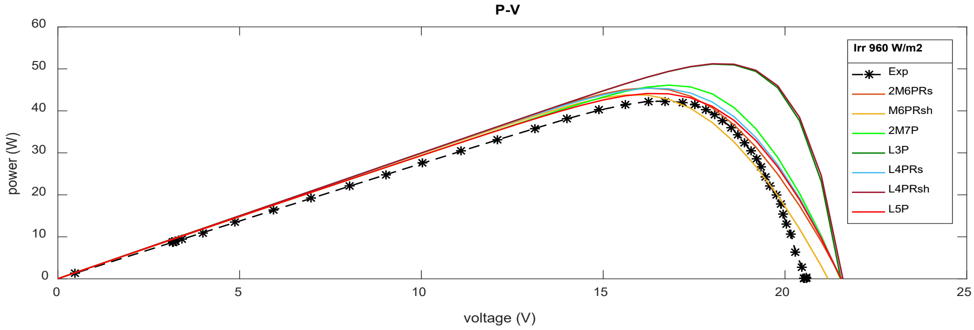
Maximum Power Pmp	50 Wc
Optimum operating voltage Vmp	17,50 V
Optimum operating current Imp	2,858 A
Open circuit voltage Voc	21.6 V
Short circuit current Isc	3,120 A
Temperature coefficients of Pm (%)	-0,48
Temperature coefficients Voc (%)	-0,34
Temperature coefficients of Isc (%)	0,037
Serial resistor Rs	0,739 Ω
Shunt resistor Rsh	198 Ω

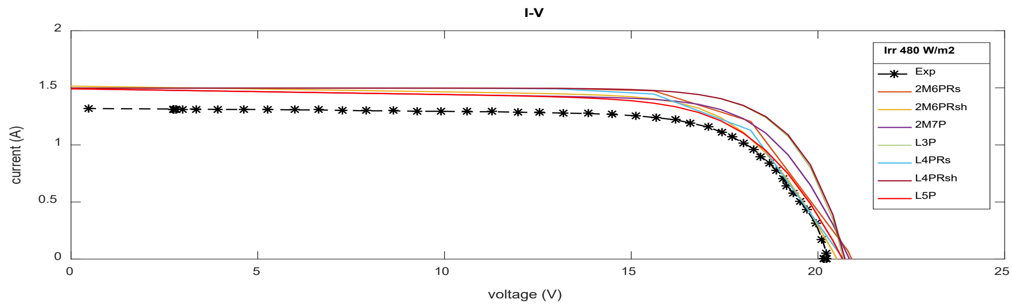
Fig. 15. I-V measurements of the PV module 50W with an I-V 400 W

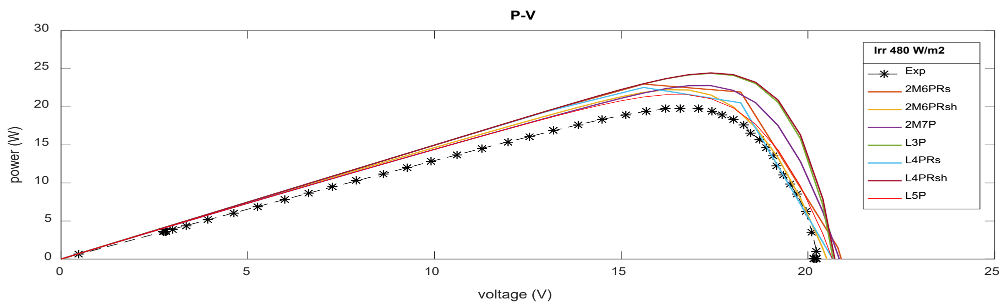
4. Results and Discussion

The I-V curves have been plotted in Matlab/Simulink to compare different models with the experimental data.









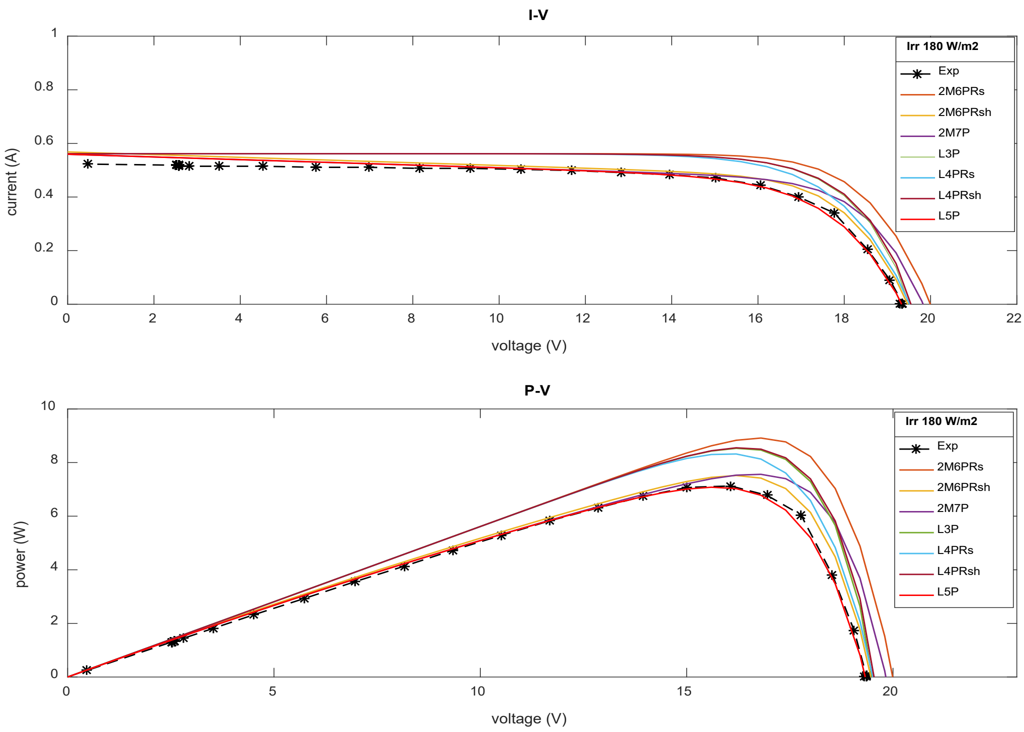


Fig. 16. I-V and P-V curves under each solar irradiance

The simulation results proved that all the models presented in this study describe the perfect behavior of a PV cell under different irradiation and temperatures. So, it is essential to compare these results with the real behavior obtained by an I-V curve of a 400 W module. We can notice that the L5P and 2M6PRsh models are more realistic to the actual behavior of the module. In addition, we have evaluated the deviations of each model from the actual behavior to compare the accuracy of each model. So that, the root of the root mean square error (RMSE) is calculated to analyze the deviations, as given in Table 3.

Table 3. Comparison of different models

Irradiation 960 W/m^2							
	2M7P	2M6PRs	2M6PRsh	L5P	L4PRs	L4PRsh	L3P
RMSE	0,7103	0,6223	**0,5310**	**0,**6451	0,6697	1,0166	1,0174
Irradiation 480 W/m^2							
	2M7P	2M6PRs	2M6PRsh	L5P	L4PRs	L4PRsh	L3P
RMSE	0,4768	0,5005	0,4269	**0,4213**	0,4651	0,5584	0,5521
Irradiation 180 W/m^2							
	2M7P	2M6PRs	2M6PRsh	L5P	L4PRs	L4PRsh	L3P
RMSE	0,1467	0,5265	0,1646	**0,1302**	0,1593	0,1646	0,1499

From this table, it can be seen that under the irradiation levels of 480 W/m2 and 180 W/m2, the L5P model is the most consistent with reality. On the other hand, for a higher irradiation such as 960 W/m2, the 2M6PRsh model gives a lower RMSE. We can see through the table that with a low irradiation (less than 500 W/m2) the models with a L5P diode give results more faithful to reality. The model with two diodes 2M6PRsh gives one of the interesting results with a strong irradiation (about 900 W/m2).

5. Conclusion

In this work, a review of PV cell models was made. A simulation of the models under the variation of irradiation and temperature allowed to see the behavior of these models through I-V and P-V curves. The models were also confronted with the data obtained by measurement using the IV400 under three different irradiation values. The results allowed us to conclude that the L5P model is the closest to reality and also for a significant irradiation, we have the 2M6PRsh model.

Acknowledgment

I would like to thank Mr. Seye from the Institut Superieur d'Education Professionnelle de Thies.

References

[1] H. Kamelia, Modélisation D'une Cellule Photovoltaique: Etude Comparative, Tizi-Ouzou, 2012, Pp. 50-60.

[2] A. M. Humada, M. Hojabri Et S. Mekhilef, "Solar Cell Parameters Extraction Based On Single And Double-Diode Models: A Review", Renewable And Sustainable Energy Reviews, N° %156, Pp. 494-509, 2015.

[3] B. Abdesslam, F. Krim, A. Arabi Et M. Ayad, "Comparaison Entre Les Modèles À Une Seule Diode Et De Bishop De La Cellule Solaire", Chez Conference Paper, Sétif, 2016.

[4] A, Birhane, E. Salilih Et Yilm, "Modeling And Analysis Of Photo-Voltaic Solar Panel Under Constant Electric Load", Hindawi, Pp. 01-10, 2019.

[5] J. Bikaneria, S. P. Joshi Et A. Joshi, "Modeling And Simulation Of Pv Cell Using One-Diode Model", Ijsrp, Vol. 3, N° %110, 2013.

[6] K. Ishaque, Z. Salam, H. Taheri Et Syafaruddin, "Modeling And Simulation Of Photovoltaic (Pv) System During Partial Shading Based On A Two-Diode Model", Simulation Modelling Practice And Theory, N° %119, Pp. 1613-1626, 2011.

[7] O. Gergaud, B. Multon Et H. B. Ahmed, "Analysis And Experimental Validation Of Various Photovoltaic Ssystem Models," Hal, Vol. 6, N° %100674669, Pp. 1-6, Aout 2002.

[8] R. Dash Et S. Ali, "Comparative Study Of One And Two Diode Model Of Solar Photovoltaic Cell", International Journal Of Research In Engineering And Technology, Vol. 3, N° %110, Pp. 190-194, 2014.

[9] H. Tchakounté, C. B. N. Fapi, D. Tchakounté, M. Kamta, H. Djalo Et P. Woafo, "Performance Predictions Accuracy Of A Smart Sun Tracking System For Photovoltaic Applications", International Journal Of Renewable Energy Research, Pp. 195-208, December 2021.

[10] S. Motahhir, A. El Ghzizal Et A. Derouich, "Modélisation Et Commande D'un Panneau Photovoltaique Dans L'environnement Psim", Hal, Pp. 01-16, 2018.

[11] M. Rodrigues Et C. Mendes, "Simulation Of A Solar Cell Considering Single-Diode Equivalent Circuit Model", Re&Pqj, Vol. 1, N° %19, Pp. 369-373, Mai 2011.

[12] S. Yilmaz, A. Yilmaz, M. Günes Et H. R. Ozçalik, "Two-Diode Model Performance Analysis Of Photovoltaic Panels", Ijett, Vol. 4, Pp. 2890-2895, 2013.

[13] T. Ahmad, S. Sobhan Et F. Nayan, "Comparative Analysis Between Single Diode And Double Diode Model Of Pv Cell: Concentrate Different Parameters Effect On Its Efficiency", Journal Of Power And Energy Engineering, N° %14, Pp. 31-46, 2016.

[14] V. Franzitta, A. Orioli Et A. D. Gan, "Assessment Of The Usability And Accuracy Of Two-Diode Models For Photovoltaic Modules", Energies, Vol. 10, N° %1564, Pp. 1-32, 2017.

[15] A. I. Nusaif Et A. L. Mahmood, "Mppt Algorithms (Pso, Fa, And Mfa) For Pv System Under Partial Shading Condition, Case Study: Bts In Algazalia, Baghdad", International Journal Of Smart Grid, Vol. 10, N° %103, Pp. 101-110, 2020.