Effects of a Thermal Nonlinear Resistance on the Power Output of the PV Cell

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Abstract

Within the existing approaches aiming to ameliorate the performances of the photovoltaic (PV) cell, we note that the nonlinear behaviour of the PV cell components is not exploited. In this paper, we examine the effects of a thermal nonlinear resistance on the characteristics of a PV cell known as the current-voltage *I-V* and power-voltage *P-V*. This thermal nonlinear resistance is constituted of a series resistance whose value varies as a quadratic function of the temperature across it. In the standard test condition and around this proposed model of the PV, analytical study and numerical simulations in MATLAB as well as experimental investigations with Multisim environment are made. A comparative study of the *I-V* and *P-V* characteristics of the PV cell with both constant and thermal nonlinear resistances is also done. We note that the nonlinear character of the series resistance conserves the shape of the characteristic curves *I-V* and *P-V* and, show an optimization of about 3.6% of the power output of the PV cell. Extension of our founding is made to a PV module constituted of N_S and N_p units of PV cells associated in series and parallel. The established results exhibit a considerable increment of the output power and conservation of the fill factor of the characteristic graphs.

Keywords: Series resistance; Photovoltaic (PV) cell; Thermal nonlinear resistance; Power output; optimization

1. Introduction

Day-by-day the energy demand is increasing and thus the need for a renewable source that will not harm the environment are of prime importance. Among several renewable energy resources, energy harvesting from the photovoltaic (PV) is the most essential and sustainable way because of abundance and easy accessibility of solar radiant energy around the earth. From that, there is an increasing trend for the use of solar cells in industry and domestic appliances. PV cell around the various technologies of manufacturing are the fundamental power conversion unit of a PV generator system. Despite the ease of setting a photovoltaic solar system, its weak environmental impact and the little care necessary to optimize the expected output, we note that demands are never met because they are far greater than the output of such a system.

In an attempt to resolve this energy insufficiency and alarming high demands, several researchers carried out experiments aiming at optimizing electrical characteristics (voltage, power and current) of a photovoltaic cell to ameliorate such outputs. This can be seen from the works of the following. Osueke (2011) carried out experiment based on external parameters like tilt angle, azimuth degree, PV module size and size of the inverter, to optimize the power output. Zitouni-Amini (1999) optimized the solar cell by adding a uniform surface field behind the solar cell plate. In 2008, Brest Bosma optimized the power generated by forcing automatically the solar panel to operate at the combination of current and voltage which was achieved by tracking Maximum Power Point (MPP) using a power converter to adjust either the current or the voltage. Ten years early, Zerga (1998) presented the insufficiency of one model exponential of PV cell to entirely describe its behavior**.** With the use of poly (3-hexylthiophène), Hatem (2009) contributed to improve the output and stability of the organic PV cell**.** Wolf and Rauschenbusch (1963) in their works looked through the effects of the internal series resistances of the PV cell on the solar cell measurements. Those works traduce the great desire to deeply master the dynamics of the PV cell in order to propose approaches that assure their stabilities and improve their yield. Following the same objective and strongly motivated by the fact that nonlinear elements through their dynamics generate new harmonics in the system, we plan to investigate the dynamics of PV cells in which the internal series resistance is replaced by a nonlinear series resistance whose values varyas a quadratic function of temperature across it. We are also motivated by the fact that the effects of the internal series resistances of the PV cell highlight a significant level in the flattening of the PV output characteristics such as the maximum power generated by the cell.

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This paper is outlined as follows. In section 2, we introduce the mathematical background and present the simulation results (obtained in MATLAB and MULTISIM) of the current-voltage and power-voltage characteristics of the PV cell based on a proposed circuit pattern of the cell with a constant series resistance. In section 3, the dynamics of a PV cell as well as a PV module built with a nonlinear series resistance are investigated. Comparison and discussions of the obtained results are made for the cases of constant and nonlinear series resistances. Section 4 is essentially devoted to discussions and concluding remarks.

2. Study of a photovoltaic generator

The photovoltaic cell remains the basic element of any photovoltaic generator no matter the power required. Owing to this and for better understanding, it is significant to know the electrical model of a PV cell as well as its mathematical modeling for good appreciation of its performances.

2.1. PV cell model

Boisvineau (1982), Ould (2008) and Zaamta (2009) achieved the real equivalent circuit of a photovoltaic cell given by figure 1. This circuit consists of a power source assembled in parallel with a diode, as well as series resistances R_S , and parallel R_{Sh} (shunt) which are primarily related to the phenomena of dissipation at the level of the cell. In this figure, the diverse electrical components have the following meanings:

I_{ph} : is the photocurrent,

I_D : is the current passing through the diode,

I_{Sh} : is the current which passes via the resistance of shunt (R_{Sh}),

I : is the output current of the PV cell

V : is the output voltage delivered by PV cell

V_D : is the terminal voltage of the diode

The series resistance is due to the contribution of basic resistances and the face of the junction and the contacts front and back face. Parallel resistance accounts for the effects, such as the leakage current at the edges of the cell; it is reduced because of the penetration of the metal impurities in the junction (Ould 2008 ; Zaamta 2009). This circuit can be used for a basic cell as well as for a module or a panel made up of several modules. The resistances R_S and R_{Sh} are selected so that the resistance of shunt is larger than that of series to maximize the current which crosses series resistance and to protect the diode from high current. The mathematical relation enabling us to establish a link between the current delivered by the PV cell and the voltage on its terminal is obtained by the following equation:

$$I_{ph} = I_D + I_{sh} + I \tag{1}$$

By drawing I from relation (1) we have:

$$I = I_{ph} - I_D - I_{sh} \tag{2}$$

in which the current through the diode is taken as $I_D = I_s\left[exp(V_D/V_T) - 1\right]$ where I_s and V_T designate respectively the saturation current and the thermal voltage and, $I_{sh} = (V + R_s I)/R_{sh}$. Hence, the relation (2) becomes:

$$I = I_{ph} - I_s\left[exp\left(\frac{V + R_s I}{V_T}\right) - 1\right] - \frac{V + R_s I}{R_{sh}} \tag{3}$$

Owing to the MAPLE environment, resolution of equation (3) leads to the following relation between current and voltage:

$$V = \left(I_{ph} + I_s - I\right)R_{sh} - V_T \times Lambertw\left(\frac{U}{V_T}\right) - R_s I \tag{4}$$

in which $Lambertw$ designates the Lambert function and the quantity U is defined below.

$$U = R_{sh} I_s \, exp\left(\frac{\left(I_{ph} + I_s - I\right) R_{sh}}{V_T}\right)$$

The value of V_T is considered at the temperature $T = 25°C$. In the case of a PV module constituted of N_s and N_p PV cells respectively in the series and parallel branches, expression (4) takes the form :

$$V = \left(I_{ph} + I_s - I\right) N_s R_{sh} - N_s V_T \times Lambertw\left(\frac{U}{V_T}\right) - \frac{N_s R_s I}{N_p} \quad (5)$$

Multisim model of the PV cell used for experimental purposes in this paper is given by figure 2. This Multisim model contains a voltage-controlled current source which associated to the DC voltage source enables the production of the photocurrent I_{ph}.

2.2. Results of Numerical simulations

Firstly, simulations are carried out for one PV cell through the analytical expression (4) and using the Standard Test Conditions (STC) where an average solar spectrum at the atmospheric mass (**AM)** is used, the irradiance is normalized to $1000W/m^2$ and the cell temperature is defined as $25°C$. For the value of the parameters $I_{ph} = 30mA$, $I_s = 1.41nA$, $R_s = 0.16\Omega$ and $R_{sh} = 700\Omega$ .Results of the simulations of the current-voltage characteristics $I = f(V)$ and those of the power-voltage $P = f(V)$ are respectively given by figures 3 and figures 4.In accordance with the results obtained from the simulations in both MATLAB and Multisim environments, the electrical specifications of the PV cell are summarized in the Table 1.

For applications, power usually delivered by the PV cell is not enough to feed a charge. For this reason, the possibility of building the PV module which consists of series and parallel arrangements of the cells is considered. Suitably with the workspace available in Spice, we realize the PV module constituted of $N_s = N_p = 3$ PV cells as shown on figure 5. On this circuit, the bypass diodes play a great role on the performance of the PV module, especially during the shading effect. In fact the bypass diodes allow current to pass around shaded cells and thereby reduce the voltage loss across the module. The importance of these bypass diodes is clearly mentioned by Ricaud (2008) and Singh (2011) in their work.

Based on the analytical expression (5), simulations of the dynamics of the PV module with the parameters defined above yield the plots of figures 6 and figures 7.

Let us stress that the electrical specifications of this PV module are greater than those of one PV cell (Table 2). Thus, decently at the application, the choice of the association of the cells is consequently made.

3. Effect of thermal nonlinear resistance on the PV cell

In telecommunication commonly, many oscillators integrate nonlinear elements in sight of to produce a chaotic behavior, good for the masking of the information. Beyond this application, the nonlinear circuits have offered very often advantages to provide the energy of the system. Motivated by this positive effect of the nonlinearity, we choose to replace the series resistance of the PV cell by a nonlinear resistance expressed as a quadratic function of the temperature across it since it is well known that any conductor crosses by a current is the siege of Joule effects usually neglected. Here, we plan on the nonlinear character of the resistance to minimize this effect and perform the behavior of our series conductor.

3.1 Circuits and Characteristic Equations

X. Xin (2012) has defined the mathematical expression of the nonlinear resistor as :

$$R_s = f(T) = R_{so}\left(1 + \alpha T + \theta T^2\right) \quad (5)$$

Wherein θ is an arbitrary constant and consequently chosen. R_{s0}, T and α are respectively the normalization resistance, temperature and thermal dilation coefficient of the material. Substitution of (6) into the relation (5) leads to the following general analytical expression for the current-voltage characteristic a PV module of $N_s \times N_p$ PV cells :

$$V = \left(I_{ph} + I_s - I\right) N_s R_{sh} - N_s V_T \times Lambertw\left(\frac{U}{V_T}\right) - \frac{N_s R_{so} I}{N_p} - \frac{\alpha N_s R_{so} IT}{N_p} - \frac{\theta N_s R_{so} IT^2}{N_p} \qquad (7)$$

The Multisim software offer the advantage to include the possibility to configure in its platform a resistor obedient at the mathematical expression of the nonlinear resistor mentioned above. Thus with the configuration of the series resistance as a function of temperature given in expression (6) in the electronic circuits given by the figure 2 and figure 5, the electronic circuits including thermal nonlinear resistance as much for one PV cell and the module keep the same profile.

3.2 Results and Discussions

Owing to the SCT conditions, numerical simulations of the mathematical expression (7) are made under MATLAB environment for the system parameters $R_{so} = 0.16\Omega$, $\alpha = 2.6 \times 10^{-6} K^{-1}$, and $\theta = -5.802 \times 10^{-5} K^{-2}$. We have considered the case of silicon material justified by the chosen value of α. In order to appreciate the effects of the thermal nonlinear series resistance on the power output of the PV cell, analytical and experimental investigations carried out respectively in MATLAB and Multisim environments lead to the simulation results plotted on figures 8 and 9.

With the glance of different characteristic curves given on those figures for the PV cell, it clearly appears that the shape and by consequence the fill factor is not reduced, though according Tarak Salmi *et al* (2012), Markvart and Castaner (2003) have denoted in their works the flattening effects of the PV output characteristics with the growth of series resistance values. For a better investigation of the effects of the thermal nonlinear resistance on the PV cell dynamics, we proceed to the presentation of the characteristic curves of the PV cell for the constant and nonlinear cases of the series resistance. The results of our simulations are presented on figures 10 and 11. The maximum power output evaluated on figure 11 helps to appreciate an analytical optimization of 3.68% and an experimental optimization of 3.53% for the case of the constant and nonlinear series resistances respectively. Therefore, the substitution of the constant series resistance by a thermal nonlinear resistance contributes significantly to the optimization of the power delivered by the PV cell.

Extension of our investigations to the dynamics of a PV module made of (3×3) PV cells leads to the curves of figure 12 for the power output of the PV module. The range of optimization is practically preserved. The little difference observed between the analytical and experimental inquiries can be easily understood by the parasitic effects of the components in the real situation. Nevertheless, effects of the thermal nonlinear resistance used in this workbring a positive contribution for the optimization of the power output of the cell. The results which effectively show that though the researchers as Bouzidi (2012), Xiao *et al* (2007) operate on the external parameters (like tilt angle of the PV module and its methods of arrangement) to optimize the output of the PV cell, it is also possible to act on the internal structure of the PV cell to improve its power output.

4. Conclusion

In that work, we have examined the effects of a thermal nonlinear series resistance on the dynamics of a PV cell. This nonlinear resistance has been expressed as a quadratic function of the temperature across it. We have proceeded to analytical and experimental investigations in the STC conditions and around the specific values of the parameters. We have established that the use of a thermal nonlinear series resistance induced an optimization of the power output of about 3.6%. Moreover, this thermal nonlinear series resistance has induced a growth of the fill factor without altered the shape of the characteristic curves of the PV cell. These studies have been extended to the case of PV module and the results obtained testified the capacity of nonlinear elements judiciously chosen to play a great role in the optimization on the power efficiency of the PV cell and PV panels. The results above offer to the PV cells manufacturers, new astuteness to be taken into consideration in order to improve the cells efficiency. For future works, we plan to investigate other aspects of the nonlinear behavior of the PV cells and PV panels.

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TABLES

Table 1: Electrical specifications of the PV cell deduced from the simulations made under MATLAB and MULTISIM environments.

Quantity Identification	Corresponding Value
Maximum power	16.398mW
Current at maximum power point	27mA
Voltage at maximum power point	0.609V
Average short-circuit current	30mA
Average open-circuit voltage	0.74V

Table 2: Electrical specifications of the PV module

Quantity Identification	Corresponding Value
Maximum power	146.5mW
Current at maximum power point	81mA
Voltage at maximum power point	1.8V
Average short-circuit current	90mA
Average open-circuit voltage	2.4V

FIGURES

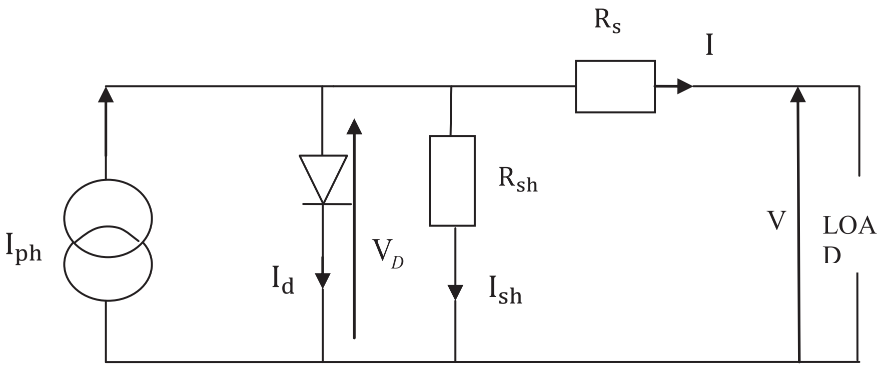


Figure 1: Equivalent electrical circuit of a photovoltaic cell

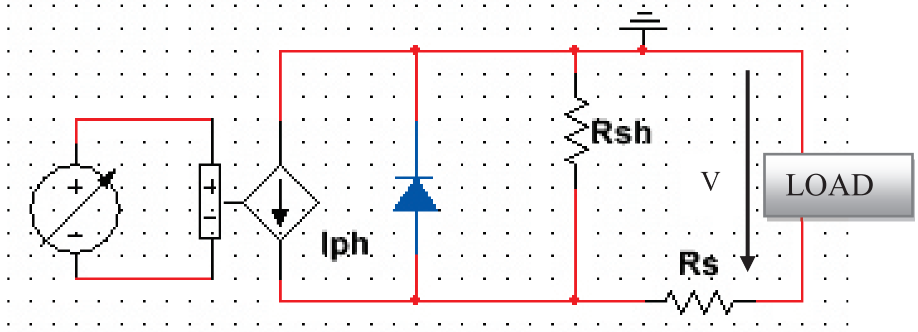
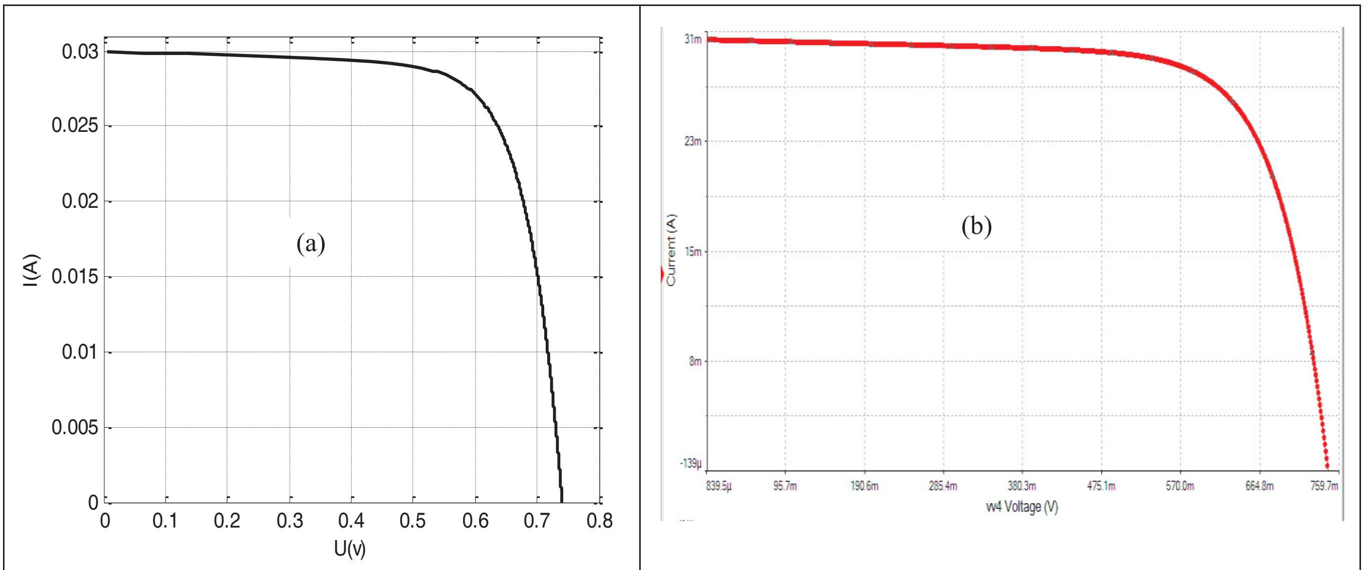
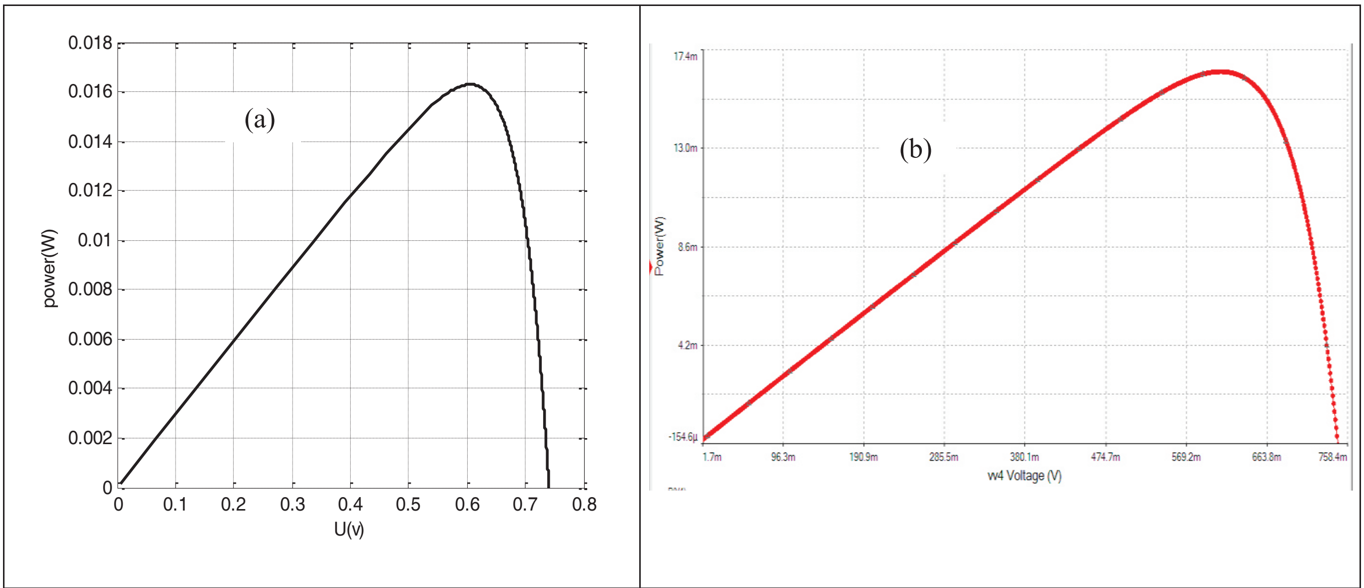


Figure 2 : Multisim model of the PV cell



Figures3: Current-voltage (I-V) characteristics for a PV cell. (a) Numerical simulations in MATLAB; (b) Simulations in Multisim environment.



Figures4: Power-voltage (P-V) characteristics for a PV cell. (a) Results from MATLAB, (b) Results from Multisim environment

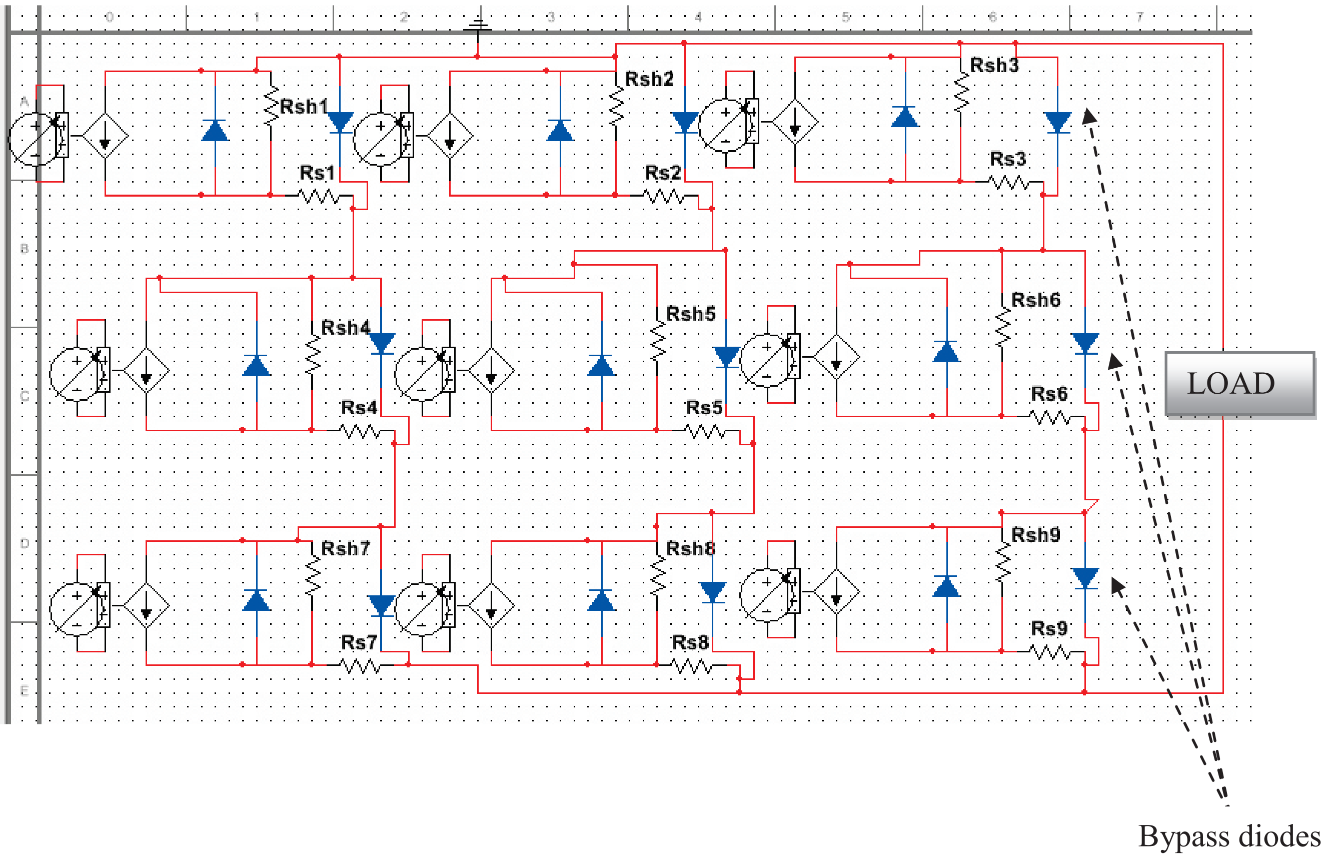


Figure 5: Multisim model of the PV module made of nine PV cells.

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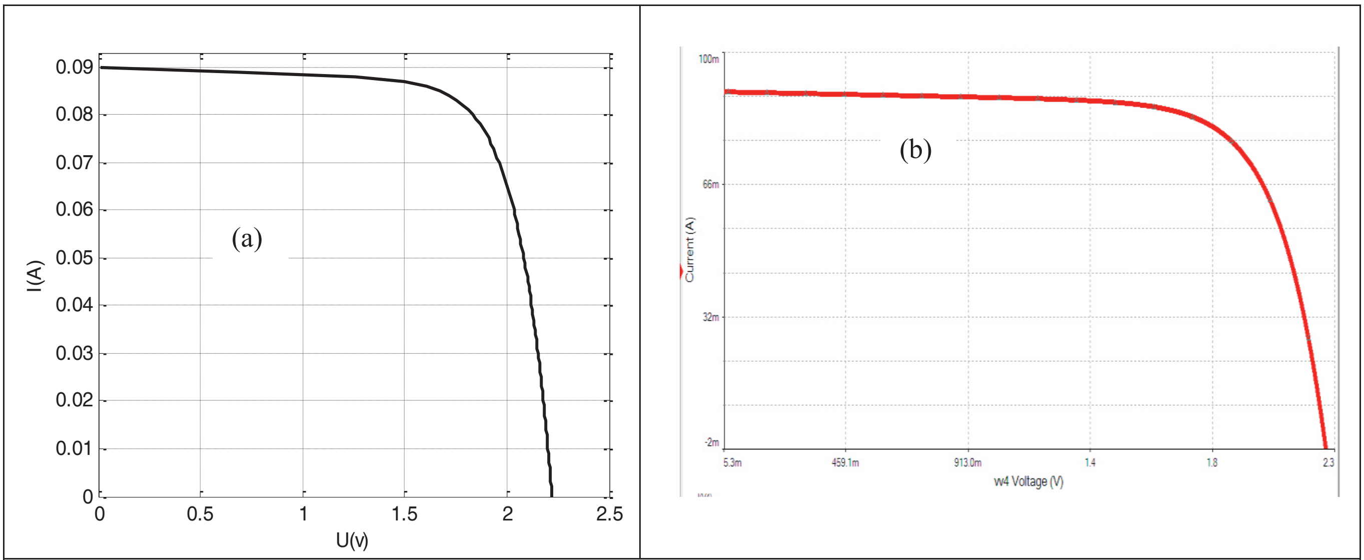
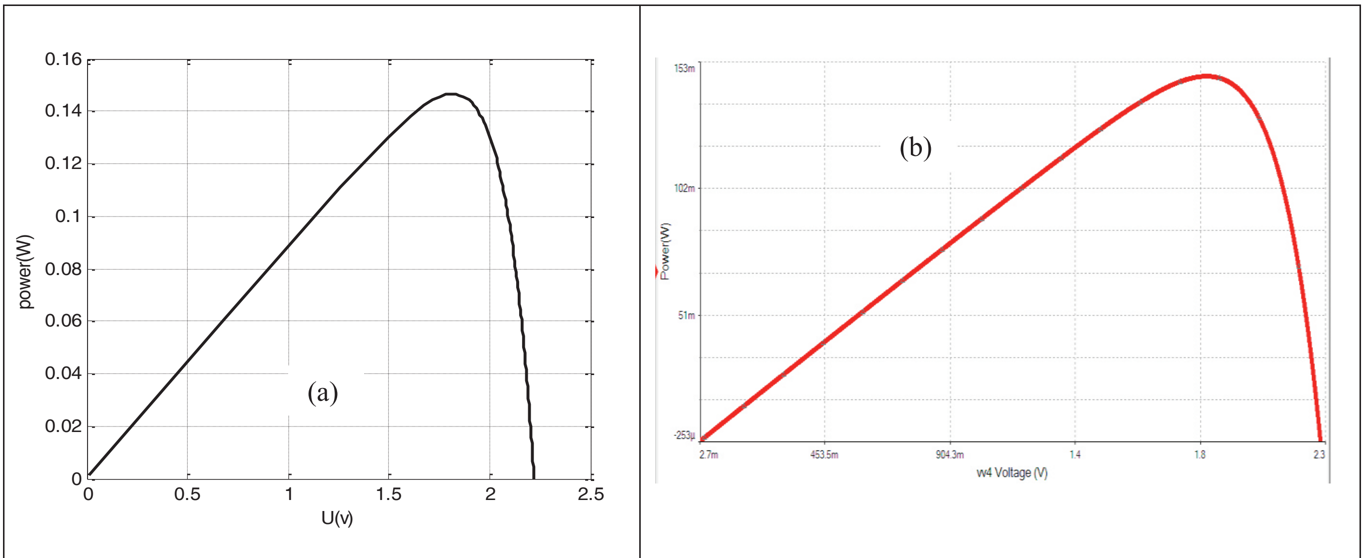
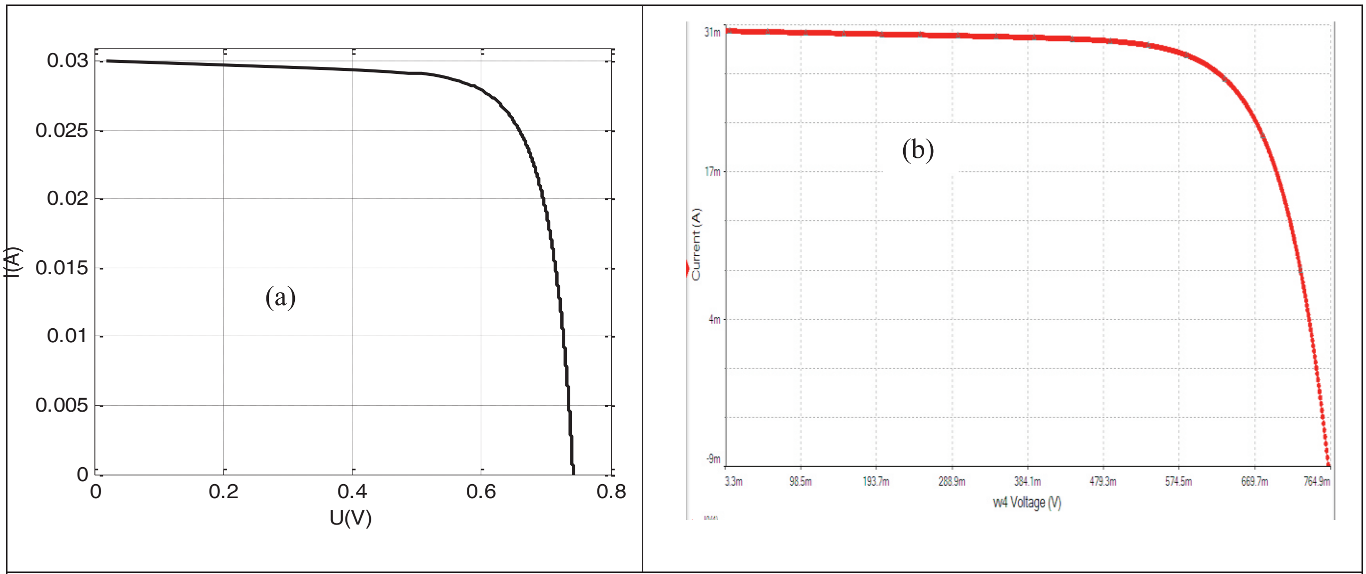


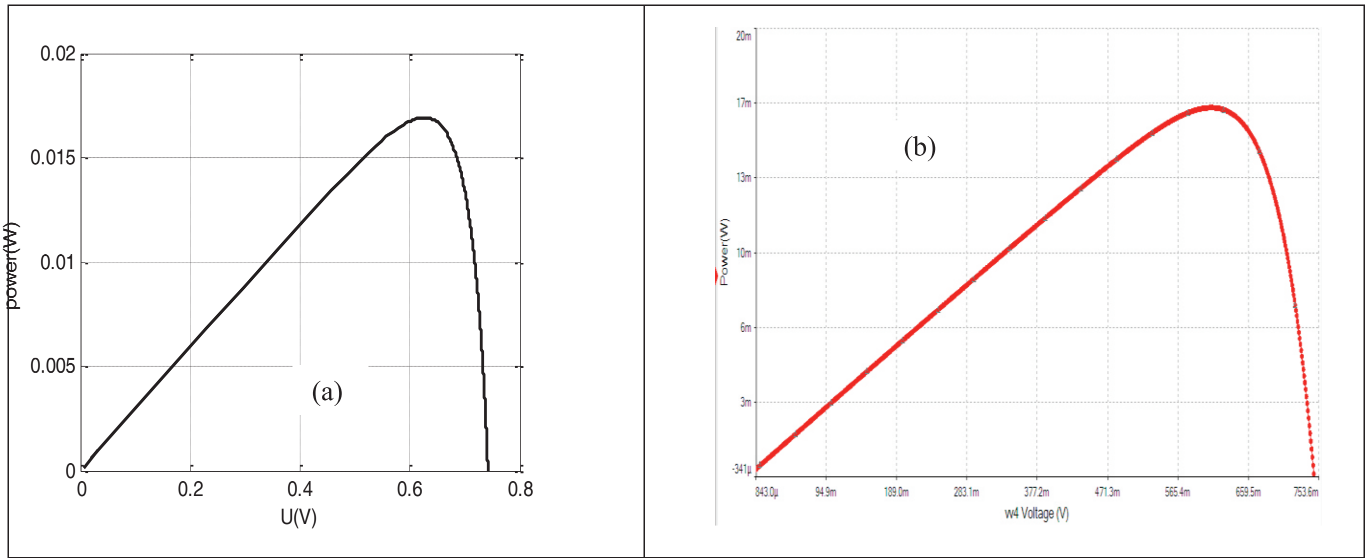
Figures 6: I-V curves for the PV module of 3×3 PV cells. Simulations (a) in MATLAB and (b) in Multisim



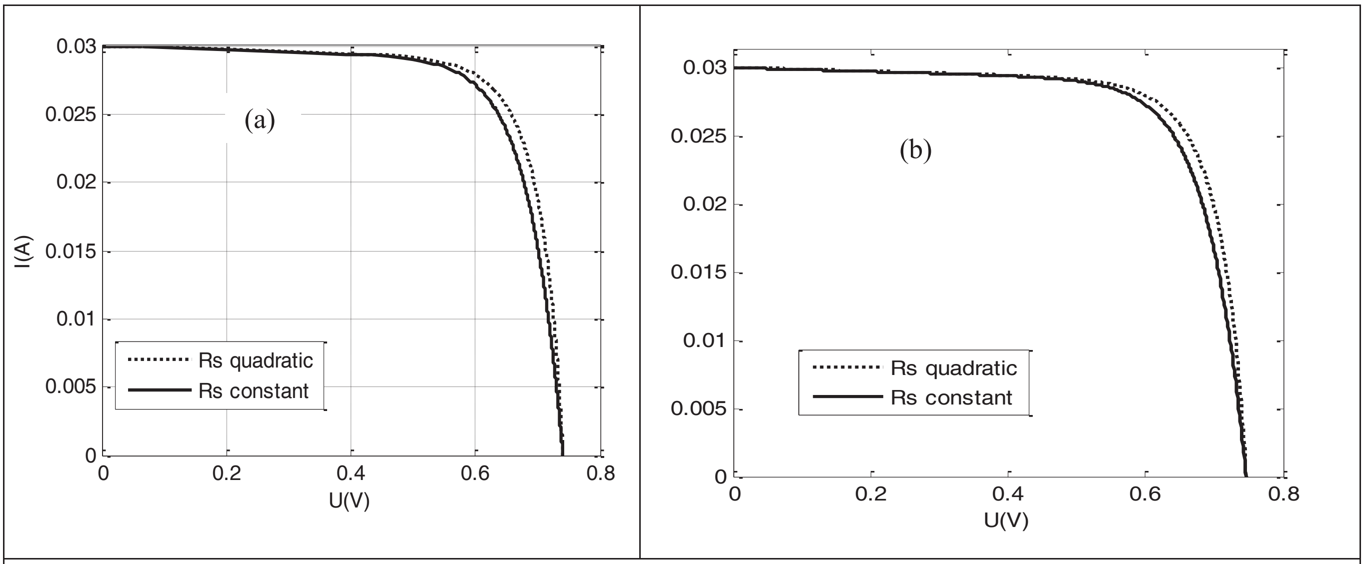
Figures7: Power-voltage (P-V) characteristics for a PV module. (a) Results from MATLAB, (b) Results from Multisim environment



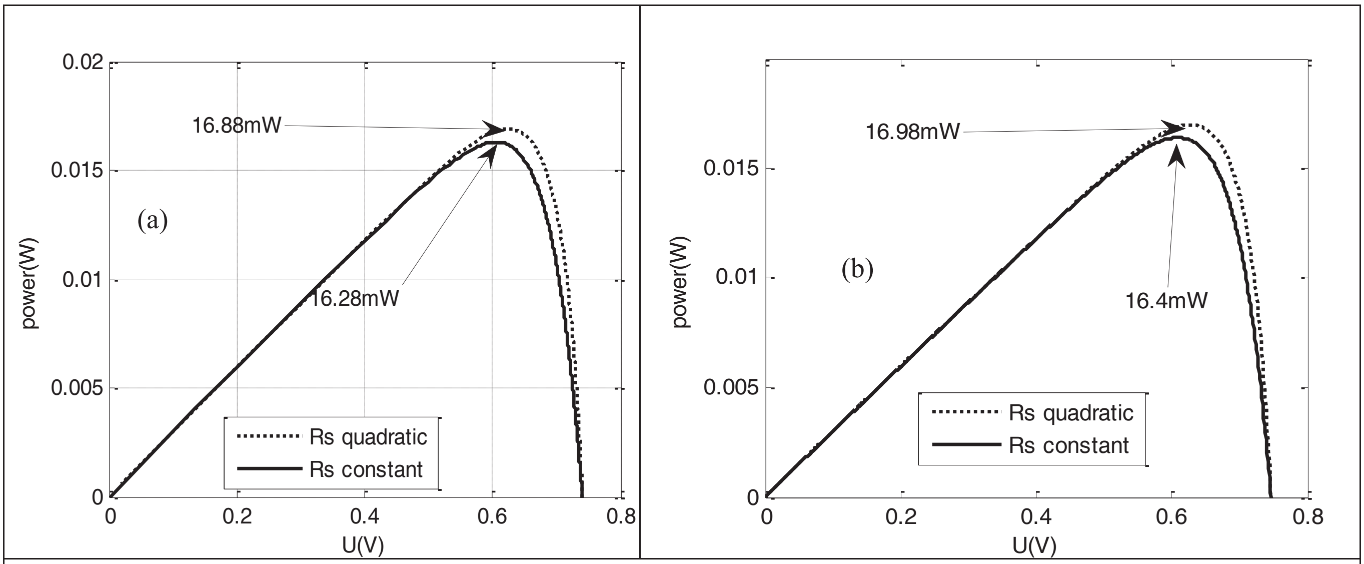
Figures 8 : *I-V* characteristics for a PV cell. *(a) :* Results from MATLAB, *(b) :* Results from Multisim environment



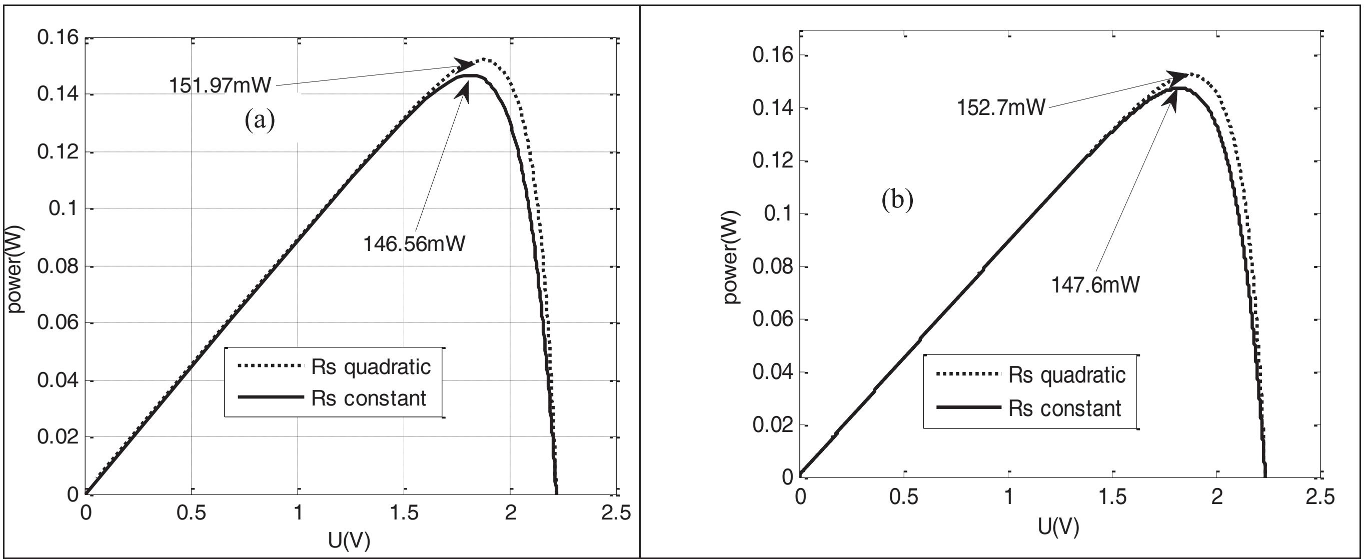
Figures 9 : *P-V* characteristics for a PV module. *(a) :* Results from MATLAB, *(b) :* Results from Multisim environment



Figures 10 : *I-V* superposition curve for a PV cell. *(a) :* Results from MATLAB, (b) Results from Multisim environment



Figures 11 : *P-V* superposition curve for a PV cell. *(a) :* Results from MATLAB, *(b) :* Results from Multisim environment



Figures 12 : *P-V* superposition curve for a PV module of 3x3 PV cells. *(a) :* Results from MATLAB, *(b)* : Results from Multisim environment.