A Detailed Study and Modeling of Photovoltaic Module under Real Climatic Conditions

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***Abstract*—The study of photovoltaic systems (PV) in an efficient manner requires a precise knowledge of the I-V and P-V characteristic curves of PV modules. Therefore, our work presents the modeling and simulation of PV module using the Matlab environment and taking into consideration the measurements carried out under real working conditions in Tetouan (Northern Morocco). The model is developed based on the mathematical model of the PV module, which is based on that of an elementary PV solar cell. A particular PV module is selected for the analysis of developed model. The essential parameters required for modeling the system are taken from datasheets. I-V and P-V characteristic curves highly depend on some climatic factors such as solar radiation and temperature that are locally measured for the typical clear day of two months June (summer) and December (winter), are obtained by simulation for the selected module and discussed. This tool will also be used to determinate the optimal design of such a system for many applications.**

***Index Terms*—photovoltaic cell and module, IV-PV curves, modeling, simulation**

I. INTRODUCTION

Currently, the sources of energy and harmful increase in greenhouse are problems of actuality. The additional danger is that excessive consumption of natural resources stock reduced the reserves of this type of energy in a dangerous way for future generations. To conserve our globe, the scientific community gave evidence that mankind has to decrease the green house gases emissions, mainly CO^2 and methane, by 60-70% as a minimum until the year 2050 [1] In order not to harm our natural living spaces and threaten their resilience, a renewed compatibility would require a suitable form of energy alternatives sources that should be independent, easily accessible, and low in cost and should be environmentally clean. Renewable energy, and in particular power generation from solar energy using Photovoltaic (PV) has emerged in last decades since it has the aforesaid advantages and less maintenance, no wear and tear. This Photovoltaic energy is the fact of producing the electrical energy by solar panels [2]. The main applications of PV systems are in either stand-alone systems such as water pumping, domestic and street lighting, electric vehicles, military and space applications or grid-connected configurations like hybrid systems and power plants [3] The increase in a number of Photovoltaic system installed all over the world brought the need for proper supervision and control algorithms as well as modeling and simulation tool for researcher and practitioners involved in its application.

The modeling and electrical characterization of panels currently marketed are needed to optimize the operation of photovoltaic systems using these PV panels. This may considerably reduce the cost of the PV system [4] and increase the efficiency of PV generators. The major problem of the production of electrical energy by this technique is the optimal functioning of the PV panels (modules). However, the development of profitable conversion systems and economically viable pass necessarily by the understanding of different components of the system whose the fundamental unit is the solar PV module. The latter is composed of several solar cells that require study and understanding.

The main aim of this paper is to provide the reader with the fundamental knowledge on modeling and simulation of photovoltaic generator blocks based on mathematical equations. Modeling and simulation of physical system in computer become more attractive than ever due to advanced software like Matlab. The principle of operation of the PV cell and its fundamental characteristics are presented. Afterwards, the mathematical model of the ideal PV cell and also the practical PV cell are discussed. Finally, the measurement results and simulation model developed in Matlab environment based on First Solar FS Series 3 Black PV module [5] are presented and discussed.

II. OPERATION AND CHARACTERISTICS OF PV SOLAR CELLS

A. Principle of Operation of PV Solar Cells

An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity. The solar cell which is the fundamental element of a photovoltaic system is mainly made out of semiconductor material and silicon being the most abundantly used semiconductor, currently, fundamentally, three type of technology are used in the production of solar cells: monocrystalline silicon, polycrystalline silicon and

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amorphous silicon. The efficiency is 15%, 13% and 7% respectively [6].

Solar cells directly convert solar energy into electrical energy. This physical phenomenon (called photoelectric effect which is to establish an electromotive force when the surface of the cell is exposed to light) occurs in materials which have the property of capture photon and emit electrons. The physical principle governing the behavior of a photovoltaic cell, can be explained, based on a p-n junction of a semiconductor material sensitive to sunlight, Being exposed to the sunlight, photons with energy greater than the band-gap energy of the semiconductor creates some electron-hole pairs proportional to the incident irradiation. The electrical behavior of a PV cell is essentially that of a diode. This transformation is without mechanical action, without noise, without fuel and nonpolluting.

The generated voltage can vary from 0.3V to 0.7V depending on the material used and its disposal as well as the temperature and the aging of the cell [7]. Solar cells are connected in series to increase the output voltage. Similarly, the cells in parallel will yield a higher current.

B. Characteristics of PV Solar Cell

The nonlinear Current-Voltage and Power-Voltage characteristics of the solar cell which present how the PV cell reacts to all possible loads under specific solar radiation and temperature conditions is shown in Fig. 1.

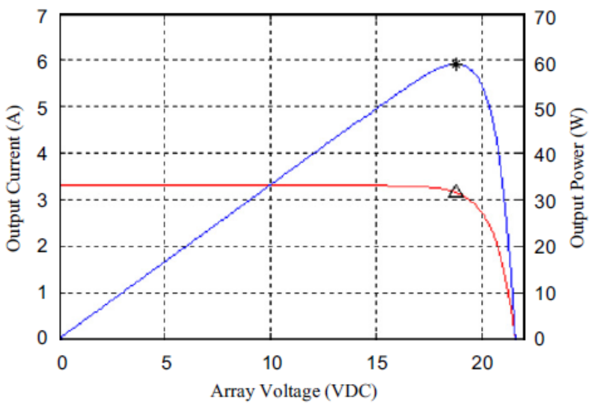

Figure 1. Current-Voltage and power-voltage characteristics of solar cell.

The current-voltage characteristic of a module is easy to obtain: just multiply the voltage of a cell by the number of cells in series Ns, and the current by the number of cells in parallel Np.

The fundamental parameters related to solar cell [8] are open circuit voltage (Voc), short circuit current (Isc), fill factor (FF) and efficiency of solar cell (η).

Open Circuit Voltage (Voc): Voc is the voltage across the cell when it is not connected to a load or when connected to a load of infinite resistor and there is no current passing through the cell. Its value decreases with temperature and changes slightly with radiation. The Open circuit voltage is calculated when the current equals to zero.

$$V\ (at\ I=0) = Voc \quad (1)$$

Short Circuit Current (Isc): Isc is the current corresponds to the short circuit condition when the impedance of the solar cell is low or zero and is the maximum current value that the cell can provide. It is a function of the illuminated surface, the solar irradiation spectrum and the temperature. This current increases linearly with the light intensity of the cell. And it is obtained when the voltage is zero.

$$I\ (at\ V=0) = Isc \quad (2)$$

Fill Factor (FF): FF is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power that can be delivered to the cell Pmax to the theoretical power (Pt) by multiplying the open-circuit voltage by the short-circuit current. It is defined by the relation:

$$FF = \frac{P\max}{Vco.Icc} \quad (3)$$

where *Pmax* = *Vm.Im*

Vm, *Im*: Voltage (V) et Current (A) corresponding to the maximum power.

It therefore represents the difference between the actual cell and a cell for which $Rs = 0$ and $Rp = \infty$ (ideal cell). The fill factor diminishes as the cell temperature is increased. Typical fill factors range from 0.5 to 0.82, and the closer it is to 1, the cell is close to ideal.

Efficiency (η): η is the main parameter of photovoltaic cells. It is the power conversion efficiency. And it is defined as the ratio between the maximum power supplied by the cell Pmax and the power of the incident light Pin. It is defined by the relation:

$$\eta = \frac{P\max}{Pin} = \frac{FF.Icc.Vco}{Pin} \quad (4)$$

Pin: incident power (light power received by the cell in W), and is taken as the product of the solar radiation of the incident light (G=λ/1000), measured in W/m^2, with the surface area (Ac) of the solar cell in m^2.

$$Pin = G.\ Ac \quad (5)$$

This efficiency can be improved by increasing the form factor, the short-circuit current and the open-circuit voltage.

III. Methodology

There exist several mathematical models in the literature to describe photovoltaic cells, from simple to more complex models ranging that account for different reverse saturation currents. The two-diode equations with the saturation currents I_{01} and I_{02} and with the diode factors A_1 and A_2 describe diffusion and recombination characteristics of the charge carriers in the material itself and in the space-charge zone [8]. To simplify parameter adjustment, the two-diode model can be reduced to a one-diode model as proposed [9], in which, according to the Shockley theory, recombination in the space-charge zone is neglected, so the second diode term is omitted [8].

Furthermore, the single-diode equivalent circuit is the most commonly adopted model for PV cells, accounting for the photon-generated current and the physics of the p-n junction of a PV cell.

Firstly, we consider an electrical circuit with a single diode (single exponential) as the equivalent photovoltaic cell circuit in the present paper. Secondly, we define the characteristic equations from this circuit; and finally, we insert these equations in matlab environment and we obtain the simulation results.

As the PV module is composed of group of cells, its model is based on that of a PV solar cell.

A. Mathatematical Model of PV Cell (Ideal Cell Case)

The equivalent circuit of an ideal PV cell is shown in Fig. 2. It includes a current source Iph, which models the photocurrent associated with a diode in parallel, which models the PN junction which its polarization determines the voltage (Fig. 2) [9]

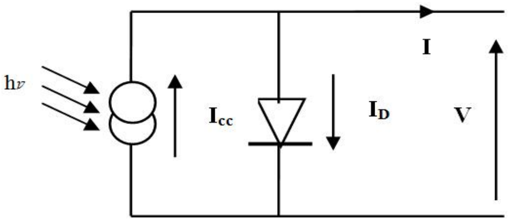

Figure 2. Equivalent circuit of ideal solar cell

The characteristic equation of the ideal cell is given by (6) and (7).

$$I = Icc - I_D \tag{6}$$

I, V: Current and voltage provided by the cell.

I_D : Diode current given by:

$$I_D = I_0 (e^{(\frac{qV}{KT})} - 1) \tag{7}$$

B. Mathematical Model of PV Cell (Real/Practical Cell Case)

A more complete equivalent circuit of the photovoltaic solar cell is shown in Fig. 3. Series resistors Rs and parallel (shunt) Rp that limit the performance of the cell are added to the model to take into account the dissipative phenomena at the cell (internal losses) [10].

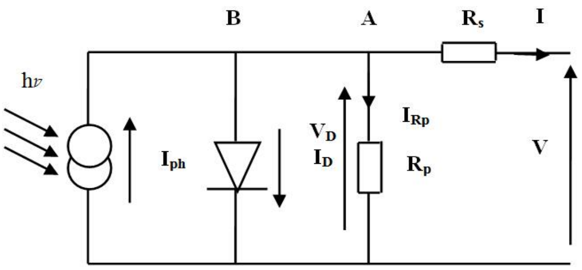

Figure 3. Equivalent circuit of real solar cell with Rs and Rp

Rs: Series resistor, mainly due to losses by Joule effect through grids collection and to the specific resistor of the semiconductor, as well as bad contacts (Semi conductor, electrodes).

Rp: Parallel resistor, called 'Shunt' comes from the recombination losses mainly due to the thickness, the surface effects and the non-ideality of the junction.

Rs and Rp modify the short-circuit current of the cell in photocurrent Iph, we will have the following equivalent electrical circuit [9].

According to the law of Kirchhoff to the nodes A and B, we have:

$$I = I_{ph} - I_D - I_p \tag{8}$$

I_{ph} : Photocurrent independent of V (or RS), it is proportional to the incident flux (rate of generation-recombination) and the carrier diffusion length, and it is linearly dependent on the solar radiation and is also influenced by temperature according to the following equation:

$$I_{ph} = \left[I_{SCr} + K_i \left(T - T_{ref} \right) \right] \frac{G}{1000} \tag{9}$$

where:

I_{SCr} is the short circuit current (at STC).

K_i is the short-circuit current/temperature co-efficient of cell, T and T_{ref} are the working temperature of cell and reference temperature respectively in K.

G is the solar radiation on the cell surface, (1000W/m ² is the nominal radiation).

I_p: Current through Rp, it is given by:

$$I_p = \frac{V_D}{R_p} = \frac{V + R_S I}{R_p} \tag{10}$$

I_D : Diode Current, it is of the same order of magnitude as I_p for the low voltages and it becomes very high around Voc, and it is given by:

$$I_D = I_0 (e^{(\frac{qV_D}{AKT})} - 1) \tag{11}$$

where,

q: Electron Charge constant, 1.6 10-19 C.

K: Boltzmann's constant (1.386503.10^{-23}J/K).

T: Cell temperature, in Kelvin.

I_0 is the reverse saturation current of the diode and it is given by:

$$I_0 = I_{rs} \left[T/T_{ref} \right]^3 exp\left[\left(q * E_{g0}/Ak \right) \left(1/T_{ref} - 1/T \right) \right] \tag{12}$$

Irs: is the diode saturation current and it is given by:

$$I_{rs} = \frac{I_{SCr}}{\left[exp(qV_{OC}/N_S kAT) - 1 \right]} \tag{13}$$

Replacing in (8), (10) and (11), the characteristic equation becomes:

$$I = Iph - I_0(e^{(\frac{q(V+R_S I)}{AKT})} - 1) - (\frac{V + R_S I}{R_p}) \quad (14)$$

A: is the ideality factor of the cell depends on recombination mechanisms in the space charge zone.

In the ideal case, Rs tends towards 0 and Rp to infinity. And in the real case, these resistors provide an assessment of the imperfections of the diode; considering that the resistance Rs has a low value. Using a numerical method and under illumination, the slopes of the I-V characteristics are calculated at I=0 open circuit and short circuit V=0 and respectively give the inverse of series and shunt resistance values [11].

C. Reference Model

In order to apply these concepts to developments of a solar cell model, the First Solar FS Series 3 Black PV module has been chosen for modeling. This module consists of 154 CdS/CdTe semiconductor active cells. The key specifications are shown in Table I.

TABLE I. ELECTRICAL CHARACTERISTICS DATA OF PV MODULE AT STC

Parameters	value
Maximum Power (Pmax)	90W
Voltage at Maximum Power (Vmp)	47.4V
Current at Maximum Power (Imp)	1.90A
Open Circuit voltage (Voc)	60.5V
Short Circuit current (Isc)	2.06A
Nominal operating cell temperature (NOCT)	45 ℃

The performance of solar cell is normally evaluated under the standard test condition (STC), where an average solar spectrum at AM 1.5 is used, the solar radiation is normalized to 1000W/m^2, and the cell temperature is defined as 25 ℃.

IV. SIMULATION RESULTS

In order to have a model to simulate the operation of our associated cells, we developed a model in Matlab environmen by using the equations given previously and also the First Solar FS Series 3 Black PV module is taken as reference module, and we obtained the Current-Voltage and Power-Voltage characteristic curves.

A. Solar Radiation Effects on PV Module Characteristics

The response of a PV cell at different levels of solar radiation and at constant temperature 25 ℃ Shows that solar radiation has a significant effect on the short-circuit current (Fig. 4 and Fig. 5), while the effect on the voltage in open circuit is quite low. Regarding the power, we can clearly see the existence of the maximum on the power curves (Fig. 6 and Fig. 7) corresponding to the Maximum Power Point Pmax.

When the solar radiation is high, the cell generates more power.

These figures show the generated current and power by one PV module of the typical clear day of two months, June (summer) and December (winter).

The PV power increases during the first hours of the day and gradually decreases, as we can see in the figures below.

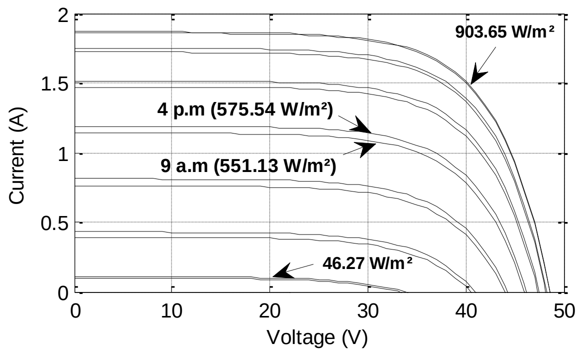

Figure 4. I-V characteristic - varying solar radiation - constant temperature (25 ℃) in June (summer)

The figure above shows that in typical clear day of summer (June), the current reaches its maximum at 1pm (1.86A) whereabouts the solar radiation is 903.65W/m^2, then decreases progressively to zero at 7pm whereabouts the solar radiation is 51.7W/m^2.

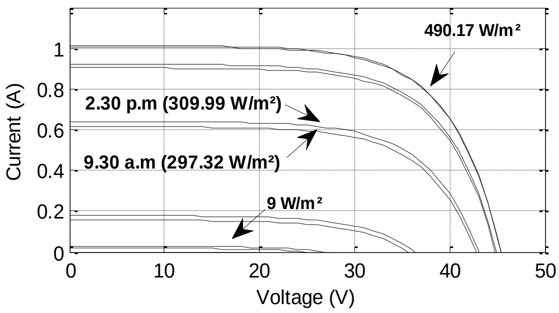

Figure 5. I-V characteristic - varying solar radiation - constant temperature (25 ℃) in December (winter)

The figure above shows that in typical clear day of winter (December). The current reaches its maximum at 12.30am (1.012A) whereabouts the solar radiation is 490.17W/m^2, then decreases progressively to zero at 6.30pm whereabouts the solar radiation is 00W/m^2.

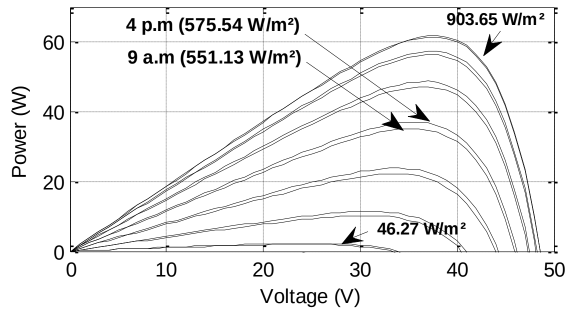

Figure 6. P-V characteristic - varying solar radiation - constant temperature (25 ℃) in June (summer)

The figure above shows that in typical clear day of summer (June), the power reaches its maximum at 1pm (61.74W) whereabouts the solar radiation is 903.65W/m^2, then decreases progressively to zero at 7pm whereabouts the solar radiation is 51.7W/m^2.

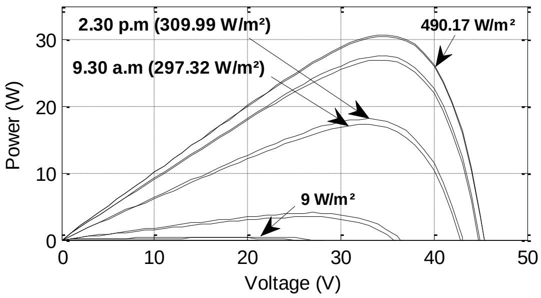

Figure 7. P-V characteristic - varying solar radiation - constant temperature (25 °C) in December (winter)

The figure above shows that in typical clear day of winter (December). The power reaches its maximum at 12.30am (30.7W) whereabouts the solar radiation is 490.17W/m²; then decreases progressively to zero at 7pm whereabouts the solar radiation is 00W/m².

B. Temperature Effects on PV Module Characteristics

The temperature is an important parameter in the behavior of solar cells. The temperature has also an influence on the characteristic of a PV generator. Fig. 8, Fig. 9, Fig. 10 and Fig. 11 show the variation of the characteristics of a PV module at different levels of temperature and at a given solar radiation (fixed at the maximum of the typical clear day of the two months, June and December) So, we can clearly see that the temperature has a very important effect on the open circuit voltage and a no remarkable effect on both the short circuit current (Fig. 8 and Fig. 10) and the power of the module (Fig. 9 and Fig. 11).

When the temperature is low, the cell generates more power. These figures show the generated current and power by one PV module of the typical clear day of two months, June (summer) and December (winter).

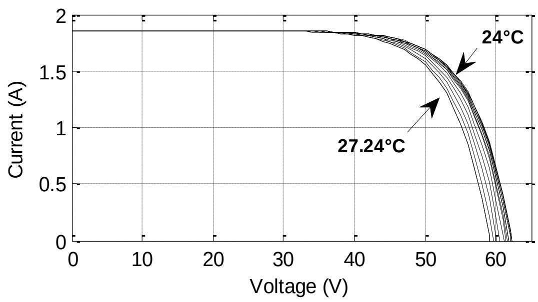

Figure 8. I-V characteristic - constant solar radiation (903.65W/m^2) - varying temperature in June (summer)

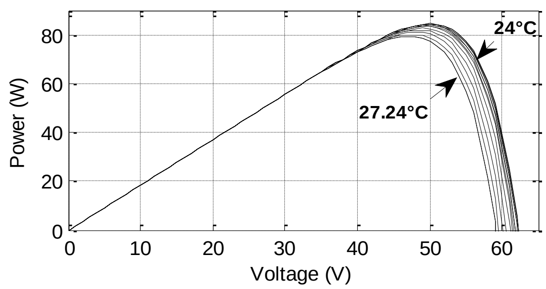

Figure 9. P-V characteristic - constant solar radiation (903.65W/m^2) - varying temperature in June (summer)

The figures above show that in typical clear day of summer (June), the power is inversely proportional to the temperature (the solar radiation is fixed at his maximum 903.65W/m²). So, when the temperature is equal to 24 °C the power reaches its maximum 84.41W, then decreases progressively to 79.27W whereabouts the temperature is equal to 27.24 °C. The same for the voltage, 62V for 24 °C, then decreases to 59V for 27.24 °C. While the current still in the same value 1.86A for different value of the temperature.

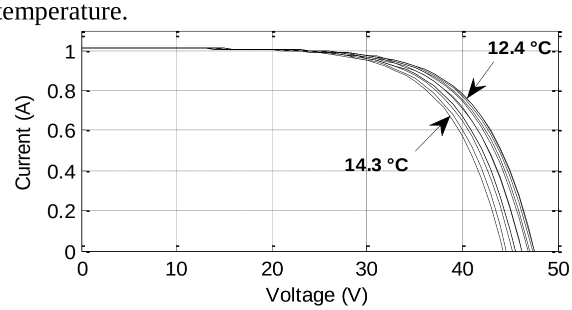

Figure 10. I-V characteristic - constant solar radiation (490.17W/m^2) - varying temperature in December (winter)

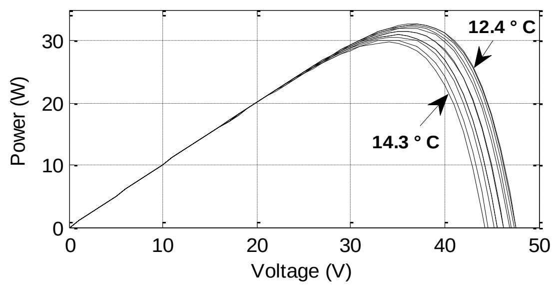

Figure 11. P-V characteristic - constant solar radiation (490.17W/m^2) - varying temperature in December (winter)

The figures above show that in typical clear day of winter (December), the power is inversely proportional to the temperature (the solar radiation is fixed at his maximum 490.17W/m²). So, when the temperature is equal to 12.4 °C the power reaches its maximum 32.69W, then decreases progressively to 29.73W whereabouts the temperature is equal to 14.3 °C. The same for the voltage, 47.5V for 12.4 °C, then decreases to 44 V for 14.3 °C. While the current still in the same value 1.01A for different value of the temperature.

V. Conclusions

In this work, we presented a study and modeling of the PV module to understand its electrical operation depending on climatic factors. The essential parameters are taken from the datasheet for the typical 90W module selected for analysis. The simulation of the module based on mathematical equations using Matlab environment and the real meteorological data collected from Tetouan, showed that the Current-Voltage and Power-Voltage characteristic curves are highly influenced by temperature and solar radiation. The following of this work is based on optimizing the performance of PV modules using commands and techniques to minimize the influence of these meteorological parameters.

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Her research interests include modeling of photovoltaic Modules and their Optimization to obtain the maximum of Energy.