Analytical Modelling, Simulation and Comparative Study of Multi-Junction Solar Cells Efficiency

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Abstract- Currently, solar energy is promising the primary source of renewable energy that has a great potential to generate power for an extremely low operating cost when compared to already existing power generation technologies. Increasing the efficiency of solar cells is a major goal and the prominent factor in photovoltaic system research. Current triple junction solar cells reach 30% and the next generation will bring 35% in 5 years to peak at 40%. These cells are used in space environment and in terrestrial systems. Nowadays, high-efficiency multi-junction solar cells are employed in many applications. In regard to terrestrial industrial applications, induction motor is being fed from the multi-junction photovoltaic systems using a boost converter and three phase inverter for variable–speed applications. Another application for multi-junction solar cells is the use in space vehicles and satellites. Indeed, solar PV array are the only non-nuclear means that enable space systems to be fed continuously. In this research work, we had simulated, investigated and correlated the performance of multi-junctions solar cells in terms of efficiency, fill factor, and other electrical parameters. Subsequently, the influence of temperature and irradiation on the electrical parameters of solar cells was investigated for terrestrial and extraterrestrial condition AM1.5G/D or AM0 to guarantee a certain level of reliability and performance of these. Then, we had made an efficiency comparison between various solar cells at constant atmospheric condition Air Mass AM0 of 0.1353 W/cm^2 to improve their performance and determine the best choice of solar cells that will be used in the design of solar array of our multi-junctions photovoltaic systems. Finally, an experimental test bench of low-cost electrical characterization system for photovoltaic solar cells array was designed using Arduino MEGA2560 board to automate the characterization performance.

Keywords- Solar energy, High-efficiency, Multi-junction Solar cells, Terrestrial and space applications, Three phase inverter, Variable speed, Induction motor, Electrical characterization.

1. Introduction

The development of terrestrial and space systems is affected especially to the field of energy. Currently, solar energy is the primary source for the generation of electricity globally [1]. The efficiency of solar cell is one of the important parameter in order to establish and grow this technology speedily in the market. Presently, extensive research work is going for efficiency improvement of solar cells for industrial use [2, 3]. Indeed, solar PV array are the only non-nuclear means that enable space systems to be fed continuously. The efficiency of these solar cells increases. Twenty years ago, silicon solar cells allowed 12%. With gallium arsenide single junction, appeared a decade ago, we rose to 20%. Now, multi-junctions solar cells reach 30% and the next generation will bring 35% in 5 years to peak at 40% [5, 6, 7]. Due to their high conversion efficiency, this type of solar cell is mainly used in solar cells array for terrestrial and space applications. Renewable energy fed induction motors have drawn the interest of many researchers. Low cost, high reliability, high robustness and high efficiency have made induction motor the most attractive in industry application. Multi-junction solar cells are used to power efficiently a boost converter to feed an induction motor through a three phase inverter to control the speed using field oriented vector control [1, 4]. In this research work, we had simulated, investigated and correlated the performance of multi-junctions in terms of efficiency, fill factor, and other electrical parameters. Subsequently, the influence of temperature and irradiation on the electrical parameters of solar cells was investigated in spatial environment to guarantee a certain level of reliability and performance of these. Then, we had made an efficiency comparison between various solar cells to determine the best choice which will bring a good performance to be used in the design of solar array of our multi-junctions photovoltaic systems. Finally, an experimental test bench of low-cost characterization system for photovoltaic solar cells array was designed using Arduino MEGA2560 board. The variation effects of solar radiation intensity, temperature and load on solar cells efficiency are improved.

2. Modelling Of Multi-junction Solar Cells

The electrical behaviour is one of the most important aspects that characterize a solar cell device and it's important to know what the fundamental equations are and how they are linked to the physics parameters. Moreover, the equation which characterizes the electrical behaviour gives the possibility to build an equivalent circuit to easily make simulations that permit to extract some important I-V and P-V curves [8].

2.1. Equivalent Electrical circuit for Single Junction Solar Cells

The model shown in figure 1 is the most popular equivalent circuit of a single junction solar cell based on a diode and resistance. In case of an ideal solar cell comprising a current source and diode in parallel, the current source models the current generated by the photons and the diode models the PN junction. The case of a real solar cell, the equivalent circuit must integrate a series resistance R_s which models the resistive losses within the photocell and a shunt resistance R_{sh} modelling the leakage currents which bypass the junction [9, 10].

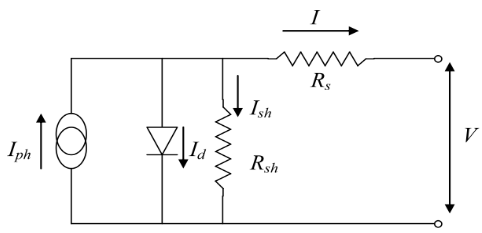

Fig. 1. Electrical model circuit of single junction solar cell.

Analyzing the equivalent circuit, total current I could be found using Kirchhoff current law [11]:

$$I = I_{ph} - I_d - \left(\frac{V + I\ R_S}{R_{sh}}\right) \tag{1}$$

Where: I_{ph}, I_d are photon current in ampere and diode's current in ampere respectively. So the total current equation is:

$$I = I_{ph} - I_s\left[\exp\left(\frac{V + I\ R_S}{n\ V_T}\right) - 1\right] - \left(\frac{V + I\ R_S}{R_{sh}}\right) \tag{2}$$

2.2. Equivalent Electrical circuit for Multi-junction Solar Cells

The structure of triple junction solar cells is demonstrated in fig. 2 [12]. Due to increasing requirement for power, mass and area traditional silicon solar cells will be more and more replaced by high efficiency multi-junction solar cells on space solar generators. Triple junction solar cells consist of sub cells, namely GaInP, GaAs and Ge junctions connected in series in a way similar to the conventional one, to get high efficiency through current-matching among the generated current from each sub cells band gap energy should be strictly combined. Moreover, layers are connected together with tunnel junction and are also provided with window layers. The current generated is highly dependent on amount of light exposure. Series resistance models the tunnel resistance between each cell and the shunt resistances represent the cell material resistance. GaAs based solar cells have the potential to reach efficiencies greater than 30% [5, 13]. Triple junction solar cells are capable to convert a huge amount of sun's energy into electrical energy at much greater efficiency and hence differ from the traditional solar cells.

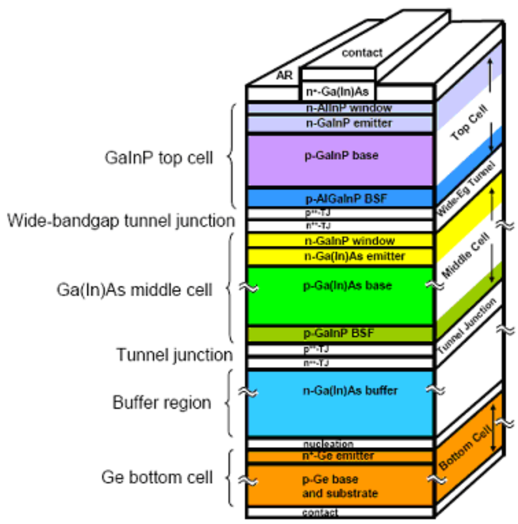

Fig. 2. Structure of Triple Junction Solar cells.

The model for the equivalent circuit of a triple junction solar cell is shown in the figure 3 below [14]:

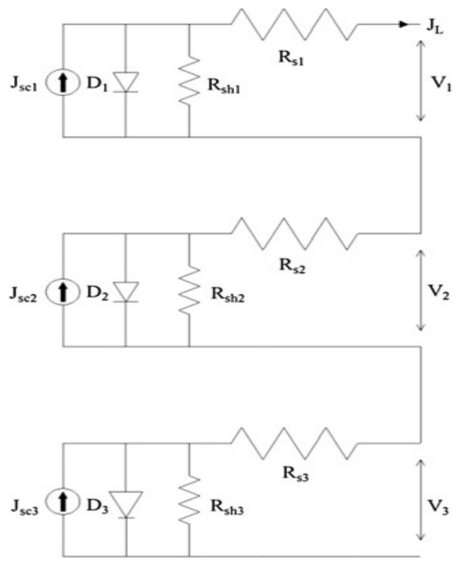

Fig. 3. Equivalent electrical circuit model of Triple Junction Solar cell

From the equivalent electrical circuit, the total current density J_L of triple junction solar cell is given by the equation:

$$J_L = J_{sc,i} - J_{o,i}\left(\frac{q\left(V_i + AR_{s,i}\, J_L\right)}{n_i\, K_B\, T} - 1\right) - \frac{V_i + AR_{s,i}\, J_L}{AR_{sh,i}} \quad (3)$$

Where: i, J_{sc}, J_o, J_L, q, V, R_{sh}, R_s, K_B, n, A, T represent the number of sub cells (1=high, 2=medium and 3=low), photon current density in A/cm^2, reverse saturation current density in A/cm^2, operating current density of cells in A/cm^2, electrical charge constant (1.602×10^{-19} C) , operating voltage per cell in V, shunt resistance in Ω, series resistance in Ω, Boltzmann constant ($1.38064852 \times 10^{-23}$ m^{2}kg s^{-2}k^{-1}), diode ideality factor (typically constant between 1 and 2), cell area in cm^2 and operating temperature in K respectively [15]. It's assumed that temperature of the cell is uniform. The diode's dark saturation current is strongly dependent on temperature and is calculated by the following [15, 16]:

$$J_{o,i} = k_i \times T^{\frac{3+\gamma_i}{2}} \times e^{\frac{-q \times E_{gi}}{n_i \times K_B \times T}} \quad (4)$$

Where: γ_i is a constant (typically between 0 and 2), K_B is Boltzmann constant and E_g is the band gap energy in eV. Band gap energy differs from one cell to another due to the difference in material used. The relation between band gap energy and temperature is described by the equation below:

$$E_{gi} = E_g(0) - \frac{\alpha_i \times T^2}{T + \sigma_i} \quad (5)$$

Where: $E_g(0)$ is the band gap energy at 0°C, α and σ are constants dependent on the materials used.

The band gap energy given in equation (6) is strongly affected by the mixture alloys of the Indium Gallium Arsenide "InGaAs" and Indium Gallium Phosphate "InGaP". However, Germanium "Ge" is referred as pure material.

$$E_{gi}(A_{1-x}\, B_x) = (1-x)\; E_g(A) + x\; E_g(A) + x\; E_g(B) - x\;(1-x)\; P \quad (6)$$

Where: A_{1-x} B_x is the composition of the alloy material and P is an alloy dependent parameter that takes into account deviations from the linear approximation in eV. The voltage at terminals of triple junction solar cell is given in equation (7) by the sum of the voltages of three sub-cells connected in series.

$$V = \sum_{i=1}^{3} V_i \quad (7)$$

Where:

$$V_i = \frac{n_i\, K_B\, T}{q}\; \ln\left(\frac{J_{sc,i} - J_L}{J_{o,i}} + 1\right) - J_L\; AR_{s,i} \quad (8)$$

Open circuit voltage per cell is achieved by canceling the operating current density J_L and it's described by the equation below:

$$V_i = \frac{n_i\, K_B\, T}{q}\; \ln\left(\frac{J_{sc,i}}{J_{o,i}} + 1\right) \quad (9)$$

The open circuit voltage is inversely proportional to temperature and can be also demonstrated using I-V curve characteristics representation. The maximum power point "MPP" is obtained by canceling the term dP/dJ_L where: $P = J_L VA$ [17].

3. Simulations Results Of Multi-Junction Solar Cells

The electrical characteristic is very important to well understand the behavior of solar cells in term of device efficiency. To do that, we had introduced programs under PSpice software to determine the electrical characteristics I-V and P-V curves of each solar sub-cells "InGaP, GaAs, Ge, Si" and that of the triple junction solar cells "InGaP/GaAs/Ge" respectively.

I-V and P-V curves were the most efficient techniques for extracting short circuit current density J_{sci}, open circuit voltage V_{oci}, maximum power P_m, Fill Factor FF and the power conversion efficiency of cell η. The influences of irradiation and temperature on the electrical parameters of cells were investigated.

A comparison between solar cells efficiency was demonstrated to determine the best choice of solar cells that are capable to convert a huge amount solar energy into electrical energy at much greater efficiency to be used in terrestrial and space photovoltaic system applications. In order to simulate and calculate the Fill Factor FF and the power conversion efficiency η of solar cells, the radiation intensity or solar constant of air mass zero (AM0) was considered equal to 1.353 Kw/m^2 and a given temperature equal to 28°C for the area of 1cm^2. Fig. 4,5,6,7 and 8 shows the simulation results of the electrical characteristics I-V and P-V curves of the "InGaP", "GaAs", "Ge", "Si" and "GaInP/GaAs/Ge" solar cells respectively [18, 19].

Simulated and calculated results of the electrical parameters extracting from the I-V and P-V curves of each solar cells are shown in table 1. Where Fill Factor is the ratio between the maximum power and the multiplication of open circuit voltage and short circuit current. Fill Factor's, maximum power are given by [20, 21, 22]:

$$P_m = V_m * J_m \tag{10}$$

$$FF = \frac{P_m}{V_{oc} * J_{sc}} \tag{11}$$

Table 1. Simulated and calculated results of electrical parameters of solar cells

Electrical Parameters of Solar cells	*InGaP*	*GaAs*	*Ge*	*Si*	*InGaP/GaAs/Ge*
Voc (V)	*1.4320*	*1.0400*	*0.2210*	*0.6300*	*2.6902*
Jsc (mA/cm^2)	*16.5000*	*28.8001*	*47.6500*	*38.4003*	*16.5210*
Vm (V)	*1.3400*	*0.9460*	*0.1645*	*0.5360*	*2.5550*
Jm (mA/cm^2)	*16.0012*	*27.9602*	*42.1277*	*37.2502*	*16.0908*
Pm (mW/ cm^2)	*21.4415*	*26.4752*	*6.9378*	*19.9979*	*41.1226*
FF (%)	*90.7445*	*88.3919*	*65,6580*	*82.6598*	*92.5333*

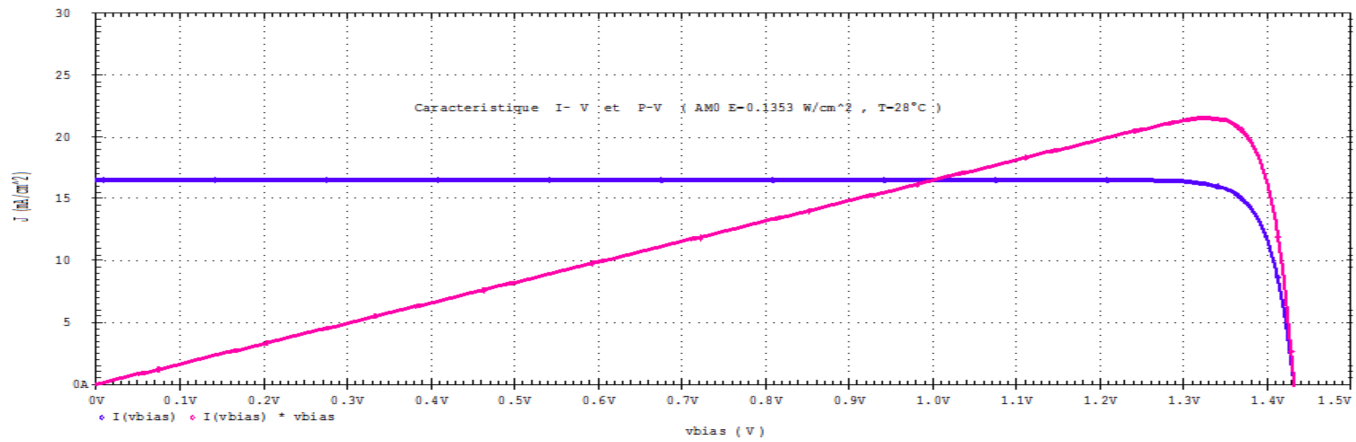

Fig. 4. Electrical characteristic curve I-V and P-V of InGaP solar cell.

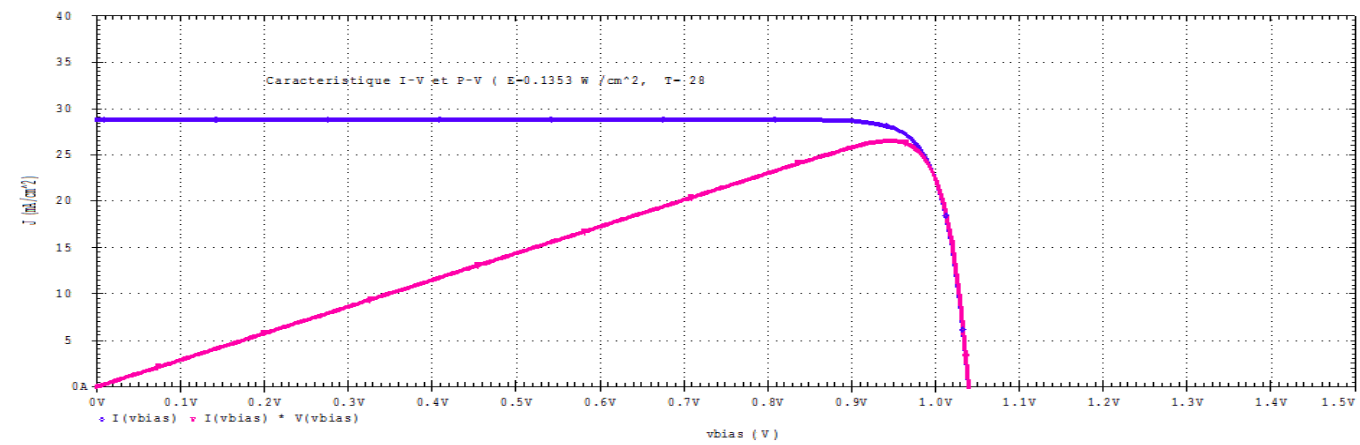

Fig. 5. Electrical characteristic curve I-V and P-V of GaAs solar cell.

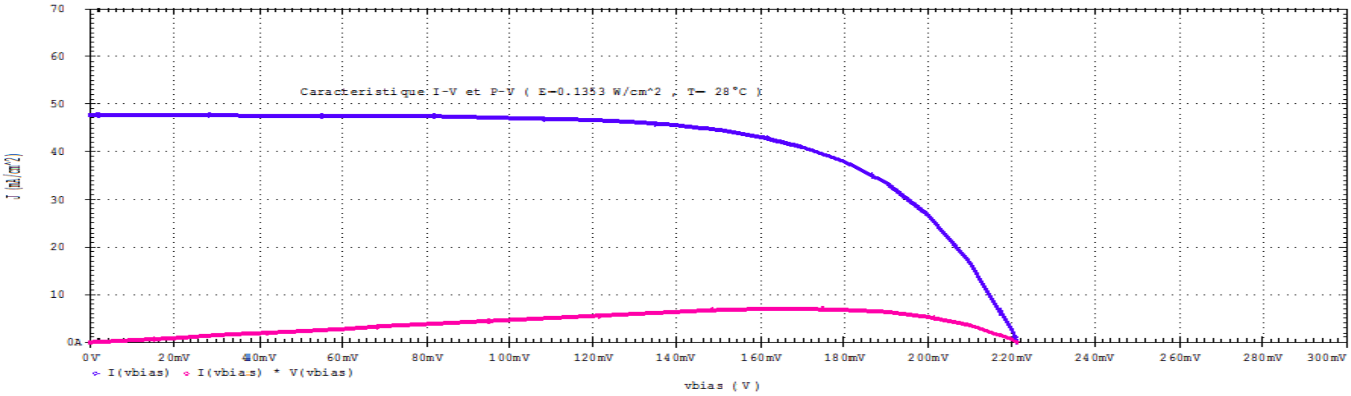

Fig. 6. Electrical characteristic curve I-V and P-V of Ge solar cell

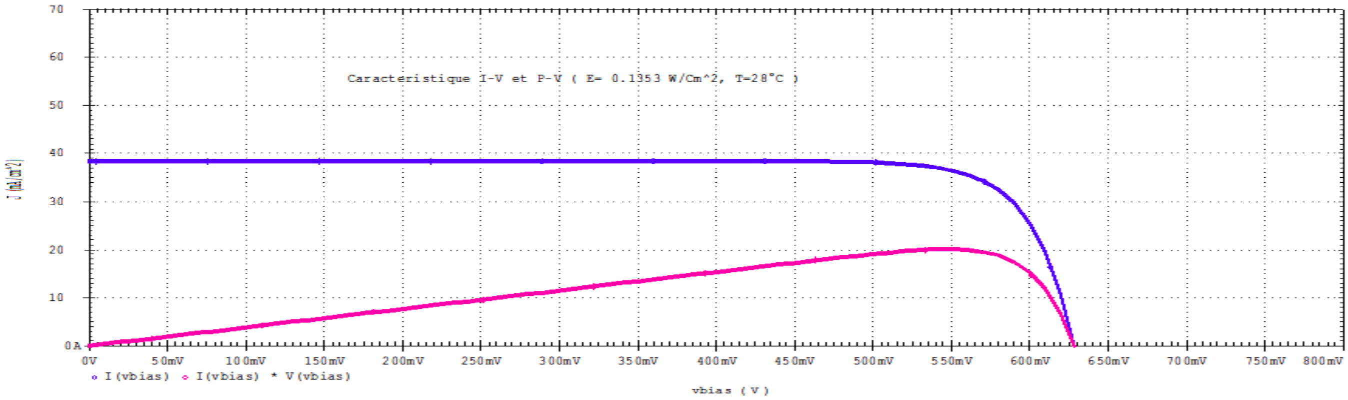

Fig. 7. Electrical characteristic curve I-V and P-V of Si solar cell.

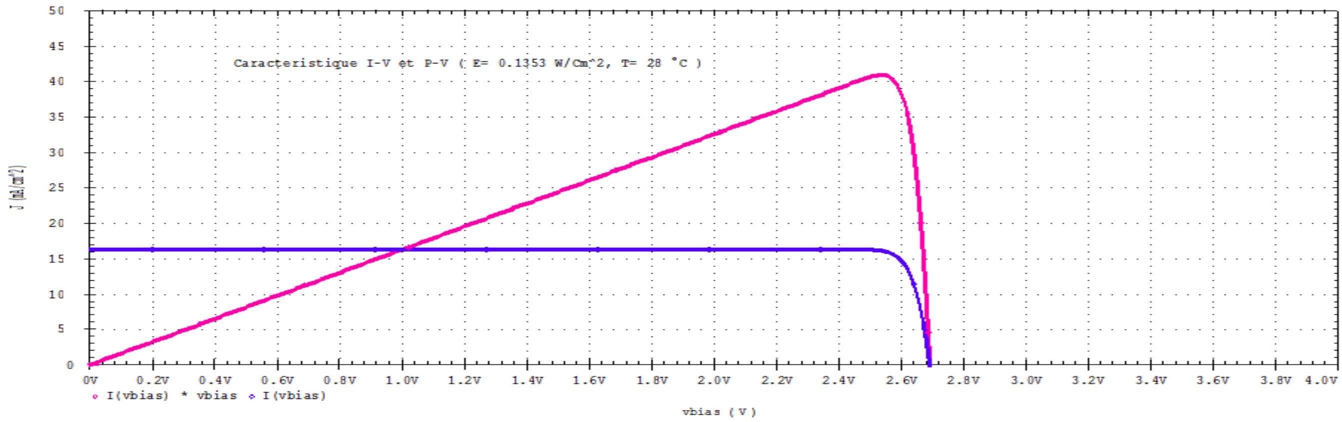

Fig. 8. Electrical characteristic curve I-V and P-V of GaInP/GaAs/Ge Triple Junction Solar cells.

3.1. Simulation Results and Discussions

The above figures show the simulation results of the electrical characteristics I-V and P-V of each solar sub-cell "GaInP, GaAs, Ge, Si" and that of multi-junction solar cell (GaInP / GaAs / Ge). From fig. 6; it can be seen that solar sub-cell of "Ge" has a higher current density than the other solar sub-cells, this is due to its low band gap which allows all absorbed photons that have an energy equal to or greater than its band gap to produce a high current density at this level. More than the band gap increases, the voltage increases, so that the photons absorbed by the solar sub-cell have insufficient energy to be all absorbed from where the density of the current decreases. Fig. 8 show that the triple junction solar cell "InGaP/GaAs/Ge" has a very small short-circuit current density (J_{sc}) and a high open circuit voltage (V_{co}), this is due to series connection of solar sub-cells that keeping the current constant while added their voltages.

3.2. Typical Comparison Performance of Solar Cells

A typical comparison of performance between the various types of solar cells at given temperature equal to 28 °C and constant radiation intensity equal to 0.1353 W/cm^2 are shown in Table 2. The power conversion efficiency of solar cells equation is given by:

$$\eta = \frac{P_m}{P_{incidente}} \tag{12}$$

Table 2. Typical performance comparison between various types of solar cells.

Comparative table of solar cells efficiency		
Power Conversion Efficiency (%)	***GaInP/GaAs/Ge***	***30.40***
	GaInP	***15.84***
	GaAs	***19.56***
	Ge	***05.12***
	Si	***14.78***
Temperature (°C)	***28***	
Radiation Intensity (W/cm²)	***0.1353***	

It is noted that the triple junction solar cells have a high-efficiency compared to other solar cells. It is the superiority and the outstanding efficiency of these cells with which they are gaining attention of many researchers to improve their performance for terrestrial and space applications. The output of multi-junction solar cell is fed to a boost converter through three phase inverter which converts the dc output to ac input that used to drive an induction motor for terrestrial applications or space systems applications [23, 24].

3.3. The effect of varying temperature on the electrical characteristic of multi-junction solar cells

The current-voltage characteristic I-V of multi-junctions solar cells is nonlinear and, importantly, it's also greatly impacted by variations in temperature and irradiance (changing environment conditions). Simulation results of varying temperature effect on the energy gap of triple junction solar cells at constant solar irradiation are seen in figure 9. We fixed the solar irradiation at constant value of 1.353 kw/m^2 and we varied the temperature of solar cells between -80 to 90 °C. We observed that more the temperature decreases, the open circuit voltage V_{co} increases and the short circuit current J_{sc} decreases with a very small drop or the maximum power of multi-junction solar cells increases. The reverse saturation current density depends on the band-gap and temperature, if the temperature is increased reverse saturation current density is also increase. So, the temperature has a direct influence on the efficiency of solar cells. Multi-junction solar cell has a good performance when the temperature is low and solar irradiation is important [25].

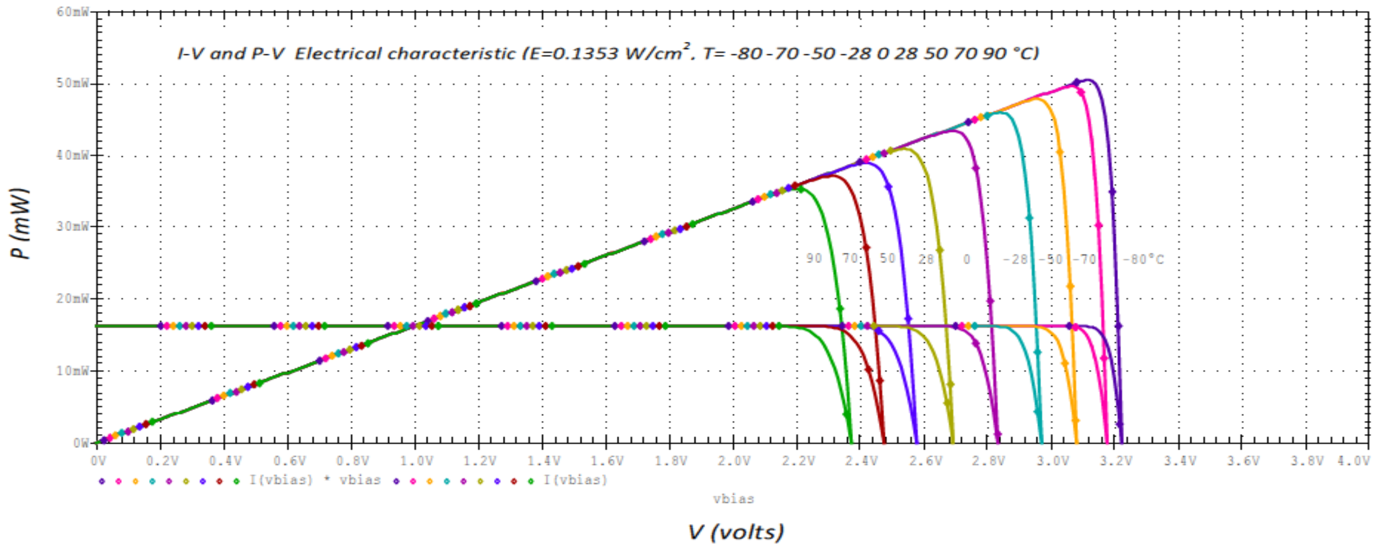

Fig. 9. The effect of varying temperature on the electrical characteristic P-V of multi-junction solar cells.

4. Experimental Results of Photovoltaic Characterisation System

In this part, some diagnostics systems use Arduino board based devices is required to obtain the parameters of solar cells. An experimental test bench of low-cost characterization system for photovoltaic solar cells array was designed to study, measure and perform the electrical characterization I-V and P-V under variation effect of solar radiation intensity, load and temperature using Arduino MEGA2560 board and a Laptop as shown in figure 10. The picture in figure 11 shows the designed prototype, it is able to test and obtain the parameters of solar cells array automatically in short time that approaches real time conditions. To draw the current-voltage I-V and power-voltage P-V characteristics, the solar cells array sees a variable load at its terminals.

The implementation has been divided into electronic realization, programming of the Arduino MEGA2560 board and the development of a software interface on a Laptop to present the measured voltage and current of solar cells array in graphical form. During the acquisition phase, Arduino board transmits the different measurements of solar cells array to a graphical interface using USB communication with the Laptop. The tests were carried out with different irradiance and temperature values. The designed prototype can be used for reading, storing and analyzing a data acquisition from several solar cells array to compare their characteristics, performance and confirm the best solar cells that will be used for design of terrestrial and space photovoltaic systems [26, 27, 28].

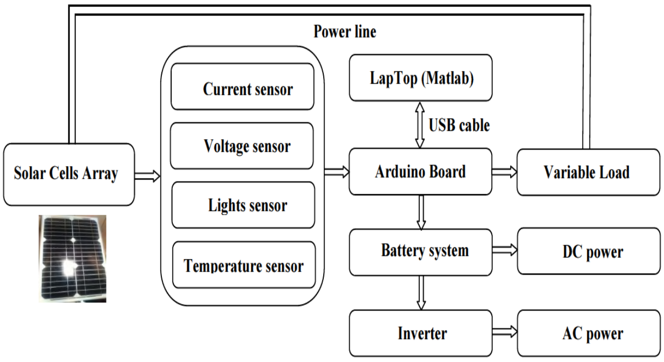

Fig. 10. Diagram of solar cells array power measurement and characterization system using Arduino Mega 2560 board.

Fig. 11. Photo of the experimental platform of solar cells array electrical characterization system.

The measured current-voltage I-V and power-voltage P-V characteristics performance curve according to the variation of solar radiation intensity, temperature and load are presented in fig. 12 and 13. The electrical power value was calculated for each measuring point. It can be seen that the power which the solar cells array can provide depends on the intensity of solar radiation, load and temperature variation. Through analysis of the test results obtained, the programmed Arduino board and designed prototype were employed to verify, test and automate the characterization performance of the required photovoltaic solar cells array parameters that will be used for terrestrial and space applications photovoltaic systems [29].

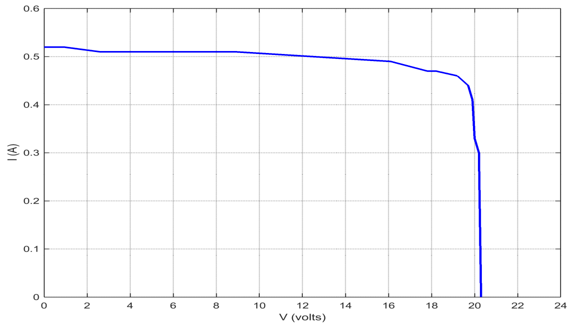

Fig. 12. Electrical characteristic I-V curve according to solar radiation of 400 W/m^2 and temperature of 25°C.

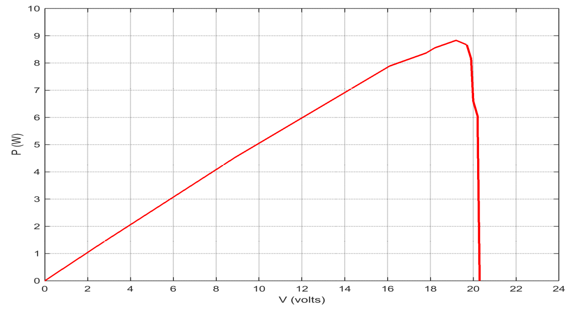

Fig. 13. Electrical characteristic P-V curve of solar cells array for solar radiation of 400 W/m^2

5. Conclusion

The goal of this research work was an analytical modeling, simulation and comparative study of multi-junction solar cells efficiency that will be contributed and used in the design of high efficiency photovoltaic systems in terrestrial and space applications. To do this task, we started by a theoretical study to understand the multi-junction solar cells works. Secondly, we had simulated various types of solar cells under PSpice software to determine the best characteristics and performance of these in terms of efficiency, Fill Factor, and other electrical parameters. From the comparison and simulation results obtained of the electrical characteristics I-V and P-V of each solar cell, we observed that the triple junction solar cells deliver a highly efficient compared to other solar cells. Due to their high cost, multi-junction solar cells are primarily used in the design of photovoltaic systems in outer space, satellites, and space vehicles, and as concentrator cells where a large amount of sunlight is reflected onto the cell. The performance of these must be high in space environment in order to have a minimum mass at equal power. Multi-junction solar cells had a good performance for low temperature and high radiation. The irradiation is the main component for producing the electricity from solar energy; they have the advantage of improved performance. It's estimated that have an incredible efficiency for more than 40%.

We concluded also that high-efficiency multi-junction solar cells find their use in terrestrial applications when exposed to high light concentrations and in space applications under low light concentrations. The simulation results of multi-junction solar cells was very satisfactory for further exploration in future applications contributions and attempted to combine it with an induction motor drive to speed digital vector field oriented control trough a three phase inverter and boost converter for high efficiency terrestrial industrial applications.

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