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An experimental analysis of illumination intensity and temperature dependency of photovoltaic cell parameters

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HIGHLIGHTS

- R_{sh} is rather sensitive to the variations in T_c.
- For higher G values, G^* is not affected from the variations in light intensity.
- Ideality factor decreases linearly with increasing T_c.
- A linear decrease of R_s and R_{sh} has been observed with increasing T_c.
- Fill factor increases exponentially with G while it decreases linearly with T_c.

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ABSTRACT

It is well known that accurate knowledge of photovoltaic cell parameters from the measured current–voltage characteristics is of vital importance for the quality control and the performance assessment of photovoltaic cells/modules. Although many attempts have been made so far for a thorough analysis of cell parameters, there are still significant discrepancies between the previously published results. In this regard, a detailed investigation of cell parameters through a comprehensive experimental and statistical work is important to elucidate the aforementioned contradictions. Therefore in the present work, effects of two main environmental factors on performance parameters of mono-crystalline and poly-crystalline silicon photovoltaic modules have been experimentally investigated. The experiments have been carried out under a calibrated solar simulator for various intensity levels and cell temperatures in the range 200–500 W/m^2 and 15–60 °C, respectively. The results indicated that light intensity has a dominant effect on current parameters. Photocurrent, short circuit current and maximum current increase linearly with increasing intensity level. A new term, solar intensity coefficient, has been defined first time to characterize the solar radiation dependency of current parameters. On the other hand, it has been observed that cell temperature has a dramatic effect on voltage parameters. Open circuit voltage and maximum voltage considerably decrease with increasing cell temperature. Temperature coefficients of voltage parameters have been calculated for each case. Shunt resistance has also been found to be rather sensitive to the variations in cell temperature. Shunt conductance of photovoltaic modules has almost remained constant as light intensity level changed. A linear decrease of series resistance has been observed with increasing cell temperature. Thermodynamic performance assessment of photovoltaic modules has also been done in the study.

1. Introduction

Solar energy is regarded as one of the most promising renewable energy technologies since it provides an unlimited, clean and environmentally friendly energy [1–6]. Renewable technologies based on solar power include solar heating, solar photovoltaics, solar thermal electricity and solar architecture which can make considerable contributions to solving some of the most urgent problems the world now faces such as climate change, energy security, and universal access to modern energy services [7]. Within a variety of solar energy applications in progress, photovoltaics (PVs) draw attention with its rapidly developing technology and remarkable potential to meet the energy demands of the world in the upcoming future. Conversion of sunlight directly into electricity by PV cells is also a key item for environmental issues. As reported by Cuce and Cuce [3], PVs

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Nomenclature

a, b, c	model constants	c	cell
G	illumination intensity (W/m^2)	ds	diode saturation
G^*	conductance (Ω^{-1})	en	energy
I	current (ampere, A)	ex	exergy
k	Boltzmann constant (1.381×10^{-23} J/K)	m	maximum
n	ideality factor	mpp	maximum power point
P	power (watt, W)	oc	open circuit
q	electronic charge (1.602×10^{-19} Coulomb)	pc	power conversion
R	resistance (ohm, Ω)	ph	photo
T	temperature (°C)	s	series
V	voltage (volt, V)	sc	short circuit
		sh	shunt
Greek letters		voc	open circuit voltage
β	inverse thermal voltage ($=q/kT$)	vm	maximum voltage
δ	temperature coefficient (V/°C)		
η	efficiency	*Abbreviations*	
μ	solar intensity coefficient (Am^2/W)	CF	curve factor
		FF	fill factor
Subscripts		PVs	photovoltaics
amb	ambient		

notably contribute to the CO_2 emission reduction. Moreover, PV systems are silent and free of moving parts. Therefore, operation and maintenance costs of these systems are very low. The most challenging point of PVs may be considered the high upfront investment cost and intensive efforts are made to reduce the cost per peak power obtained from PV cells. These efforts aim at narrowing the gap between PV and conventional power sources. Besides the importance of developing new manufacturing processes related to PVs, it is quite significant to provide the most appropriate operating condition for a PV system [1]. Performance parameters of a PV module strongly depend on the environmental parameters such as temperature, illumination intensity level and wind speed. An accurate knowledge of these parameters is of vital importance for the quality control and the performance evaluations of PV modules. Several methods are proposed for extracting the performance parameters that describe the nonlinear electrical model of PVs [8–12].

The steady state current–voltage (I–V) characteristics of a p–n junction silicon PV cell are often described based on one diode model as given in Eq. (1) [13–16]. PV cell equation consists of five parameters called light generated current (I_{ph}), reverse saturation current (I_o), diode ideality factor (n), series resistance (R_s) and shunt resistance (R_{sh}). These cell parameters have a dominant impact on the shape of I–V characteristics of a PV cell at any given illumination intensity and cell temperature and thus decide the values of the performance parameters such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), curve factor (CF) and efficiency (η) of the PV cell [13].

$$I = I_{ph} - I_o\left[\exp\left(\frac{\beta}{n}(V + IR_s)\right) - 1\right] - G^*(V + IR_s) \quad (1)$$

In Eq. (1), $\beta = q/kT$ is the usual inverse thermal voltage and $G^* = 1/R_{sh}$ is the shunt conductance. In recent years, several attempts have been made to investigate the dependency of PV cell parameters to main environmental factors, viz. the light intensity, ambient temperature and wind speed. It has been underlined by many researchers that the values of performance parameters change significantly as the illumination intensity level changes [17–20]. Similarly, cell temperature is of vital importance for performance of PV cells and thus temperature dependence of performance parameters and energy conversion in PV cells has been investigated by many authors [21–26,28–30,47–59]. Recently Cuce and Cuce [3] have presented a novel model for PV modules to estimate performance parameters and to perform a thermodynamic assessment. A simple one-diode model has been proposed to estimate the electrical parameters of PV modules considering the series resistance and shunt conductance. The model results have been compared with the manufacturer's data report and an excellent agreement has been observed. Despite the theoretical, numerical and limited experimental attempts for parameter extraction of PV cells, a comprehensive experimental and statistical analysis has not been conducted up to now.

In the present work, a detailed experimental and statistical analysis has been carried out to analyse light intensity and temperature dependency of silicon PV module parameters. Most silicon PV modules are designed to work under standard test conditions that correspond to $G = 1000\ W/m^2$, $T_c = 25$ °C and AM = 1.5. However, as reported by previous studies, illumination intensity, cell temperature and wind speed always vary with time under real operating conditions and these environmental factors play a significant role on performance characteristics of PV modules. Therefore, an accurate knowledge of interaction between environmental factors and PV module parameters is crucial.

2. Experimental study

The experimental setup devised in the present work consists of a solar simulator, a control room (darkroom) and measurement devices.

2.1. Solar simulator

A solar simulator was manufactured in order to carry out the experiments under any constant illumination intensity. It is well-documented in literature that the xenon lamps are very efficient to simulate the solar spectrum. However, they are very expensive compared to the alternative light sources like halogen lamps. Hence in this study, a halogen lamp based solar simulator was

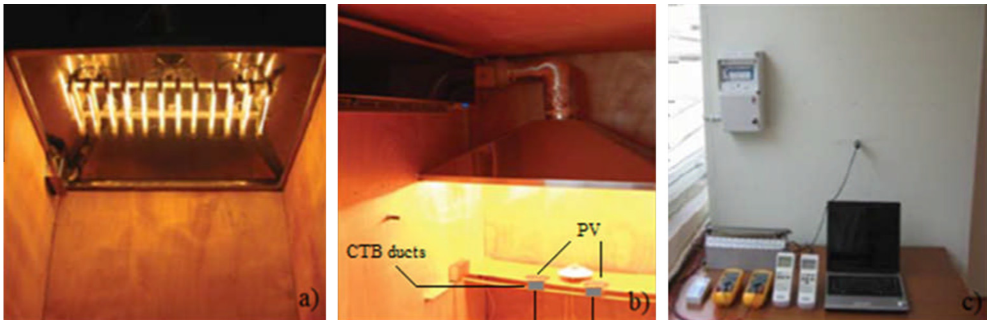

Fig. 1. Experimental setup: (a) solar simulator, (b) control room, and (c) measurement devices.

utilized. The solar simulator illustrated in Fig. 1a consists of 12 tungsten halogen bulbs. The maximum power of the illumination system is 12 suns. It was placed in a hood and was mounted on the top of the control room. An electronic circuit was manufactured and it was placed in an electrical panel. The illumination intensity could be adjusted to any constant value using a potentiometer which was connected to the electrical panel. Before the tests the calibration of the solar simulator was performed with respect to the solar spectrum.

2.2. Control room

A control room with air-conditioning system was constructed to carry out the experiments under constant ambient temperature (T_{amb} = 25 °C). The control room has 1000 mm length, 1500 mm width and 2000 mm height. During the manufacturing of the control room, 10 mm thick glass wool was used between two 20 mm thick plywood plates in order to provide insulation. An air conditioner with 15,000 BTU cooling capacity was assembled on one side of the control room as it is seen in Fig. 1b. In addition, control room was supported with a constant temperature bath unit to provide constant cell temperature at different solar intensities and to perform experiments for various cell temperatures.

2.3. Measurement devices

Kipp & Zonen CMP 11 Pyranometer with high linearity and low tilt error was used to measure illumination intensity. The electrical parameters of the PV cell were evaluated using FLUKE 87 V multimeters with a measuring error of 0.2% for DC current and 0.06% for DC voltage. As reported in literature [45,46], FLUKE multimeters have internal resistance. However, the experiments were carried out in the high sensitivity option. A 1100 V, 0.8 A rheostat was used to vary the resistance of the circuit. A LUTRON HT 3006HA humidity–temperature metre was utilized for temperature and humidity measurements of the control room. An EXTECH infrared high-temperature thermometer was used in order to measure the cell temperature. Measurement devices are illustrated in Fig. 1c. Calibration of the solar simulator is very significant in terms of the accuracy of the experimental results. The distance at which the PV modules are positioned from the solar simulator has been optimized to prevent the modules from overheating due to the waste heat from halogen lamps. Afterwards, the electrical characteristics of the PV modules presented by the manufacturer for standard test conditions have been verified experimentally. The simulation results showed good agreement with the manufacturer's data report. The experiments were carried out in the illumination intensity range 200–500 W/m^2. Temperature of the control room was adjusted to 25 °C. On the other hand, the experiments were performed for four different cell temperatures in the range 15–60 °C. A NUMAN D 100 constant temperature bath was used to provide constant photovoltaic cell temperatures. High sensitive temperature sensors were utilized to measure lower surface temperature of the PV modules. All tests were performed after the aforementioned test conditions were achieved.

3. Statistical study

Statistical analysis has followed the experimental study. After *I–V* characteristics have been determined with high accuracy for all cases, a well-known PV cell parameter extraction method by Bouzidi et al. [12] has been utilized to obtain the performance parameters statistically for each case. The prescribed method is based on determining model parameters (a,b,c) via nonlinear estimation and then calculating the values of cell parameters by the following relations where I_{pA} and G_A are the linear regression constants:

$$R_s = -b \tag{2}$$

$$n = \beta c \tag{3}$$

$$I_o = I_{pA}\exp(-a/c) \tag{4}$$

$$I_{ph} = \frac{I_{pA}}{1 - G_A R_s} \tag{5}$$

$$\frac{1}{R_{sh}} = \frac{G_A}{1 - G_A R_s} \tag{6}$$

4. Results and discussion

4.1. Results for different illumination intensity levels

A mono-crystalline and a poly-crystalline silicon PV module with the same nominal power output (10 W) have been investigated as test units in the study. The characteristics of PV modules were very similar. The nominal power, open circuit voltage, maximum voltage, short circuit current, maximum current, dimensions and weight have been given by the manufacturer at standard test conditions as 10 W, 21.9 V, 17.6 V, 0.68 A, 0.56 A, 355 × 250 × 18 mm and 1 kg, respectively. After the calibration of solar simulator, temperature of the control room (T_{amb}) has been set to 25 °C via the air conditioning system. Afterwards, cell temperatures of the PV modules have been adjusted to 25 °C via the constant temperature bath unit. Under the steady-state conditions, *I–V* characteristics have been obtained for each PV module as it is illustrated in Fig. 2.

At first glance, it can be easily said that current parameters of silicon PV modules are highly dependent on the illumination intensity level. Although I_{sc} of the m-Si and the p-Si PV module for G = 200 W/m^2 was only 0.0767 and 0.0717 A, respectively, they

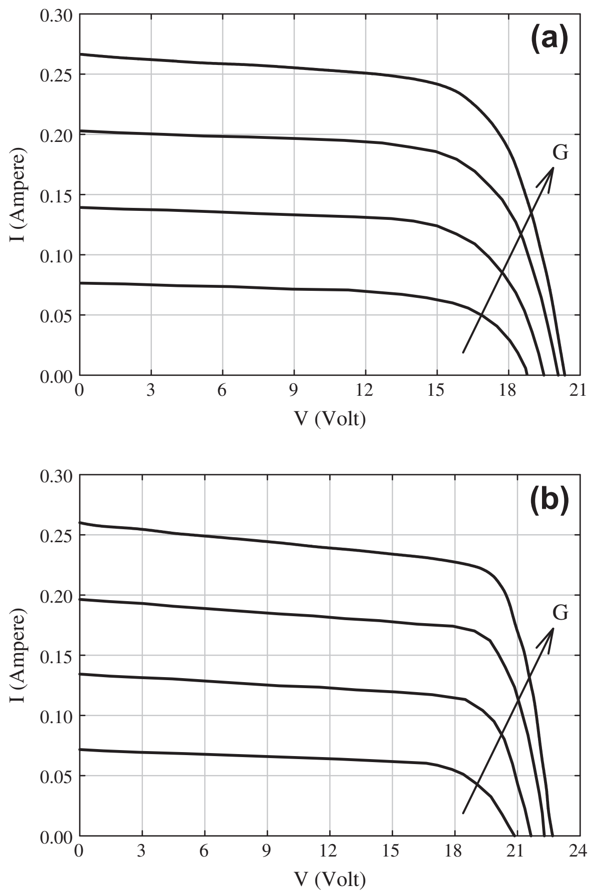

Fig. 2. *I–V* characteristics of (a) m-Si and (b) p-Si PV module for T_{amb} = 25 °C and G = 200, 300, 400 and 500 W/m^2.

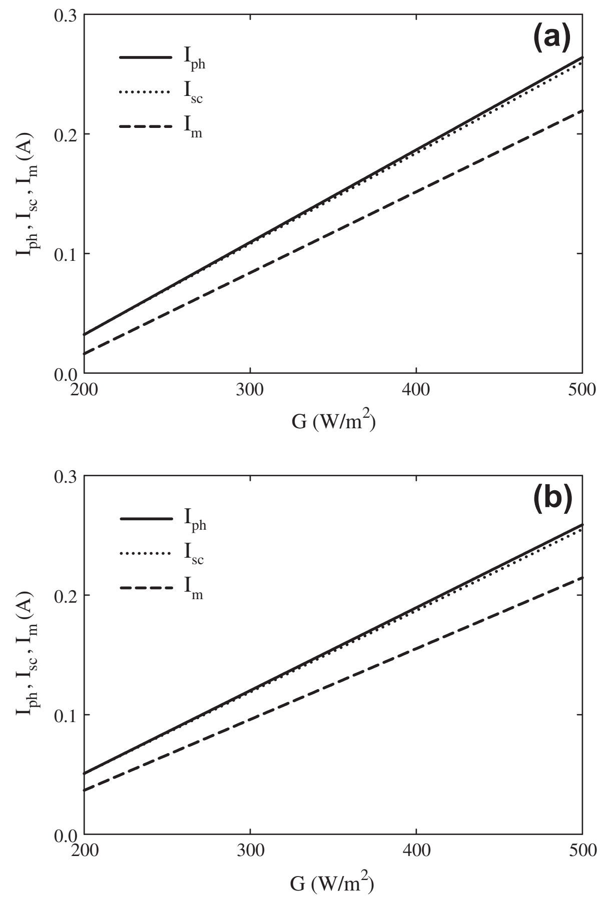

Fig. 3. Light intensity dependency of current parameters of (a) m-Si and (b) p-Si PV module.

have been measured to be 0.2658 and 0.2591 A for G = 500 W/m^2. In order to specify the level of dependency, a new term namely solar intensity coefficient has been defined as follows:

$$\mu = \frac{\text{Current}}{\text{Solar Intensity}} = \frac{\text{Am}^2}{\text{W}} \tag{7}$$

For m-Si PV module, μ values have been calculated to be 0.000773, 0.000758 and 0.000674 for I_{ph}, I_{sc} and I_m, respectively. For p-Si PV module, those values have been found to be 0.000693, 0.000681 and 0.000593, respectively. On the other hand, an exponential growth of voltage parameters has been observed with the light intensity level. About a 9% enhancement in V_{oc} of PV modules has been observed while G varied from 200 to 500 W/m^2. After determining *I–V* characteristics with high accuracy, a statistical analysis has been performed via STATISTICA software and light intensity dependency of current parameters, voltage parameters and the other performance parameters have been investigated. Fig. 3 depicts the variation of photocurrent, short circuit current and maximum current of PV modules with light intensity. Current parameters increase linearly with increasing light intensity. This result has been theoretically and experimentally verified by numerous works [3,6,13,42], and hence, there is already a consensus among scientists about the solar intensity dependency of current parameters. I_{ph} and I_{sc} values are very close to each other or even the same for both m-Si and p-Si PV module. Having close values of I_{sc} and I_m shows that the test modules utilized in the study reflect the characteristics of an ideal PV cell.

Switching from current parameters to voltage parameters, it has been found that both open circuit voltage and maximum voltage of PV modules demonstrated an exponential rise with increasing G as shown in Fig. 4. For m-Si PV module, V_{oc} and V_m have been determined to be 18.66 and 14.78 V, respectively for G = 200 W/m^2 whereas they were 20.32 and 16.18 V for G = 500 W/m^2. Similarly, for p-Si PV module, V_{oc} and V_m have been measured to be 18.32 and 15.19 V, respectively for G = 200 W/m^2 whereas they were 19.92 and 17.30 V for G = 500 W/m^2. It can be noted from the results that light intensity level has a crucial impact on current parameters of a PV module rather than the voltage parameters. From this point of view, concentrating systems may be regarded a key choice to enhance the maximum power output (P_m) of PV systems.

Fig. 5 illustrates the illumination intensity dependency of ideality factors of PV modules. Through the statistical analysis it has been found that n values show a linear decrease with increasing G. The trend of n shows a very good agreement with a recent experimental work that has been carried out by Khan et al. [13]. Macdonald and Cuevas [31] has also found n decreasing with V_{oc} monotonically in silicon solar cells made from 1.5 Ω-cm resistivity material which implied decrease of n with G. In a silicon PV cell, the value of n is governed by the combination of space charge recombination, bulk recombination and surface recombination mechanisms. The space charge recombination is more dominant at low illumination intensity levels and junction voltages. Hence, the higher n values at lower solar intensities as shown in Fig. 5 can be attributed to the larger contribution of space charge recombination to the total recombination in the solar cell. Cuce and Cuce [3] have clearly shown in their recent work that ideality factor only affects a limited area around the 'knee' position which is commonly called maximum power point. In addition they have clarified that

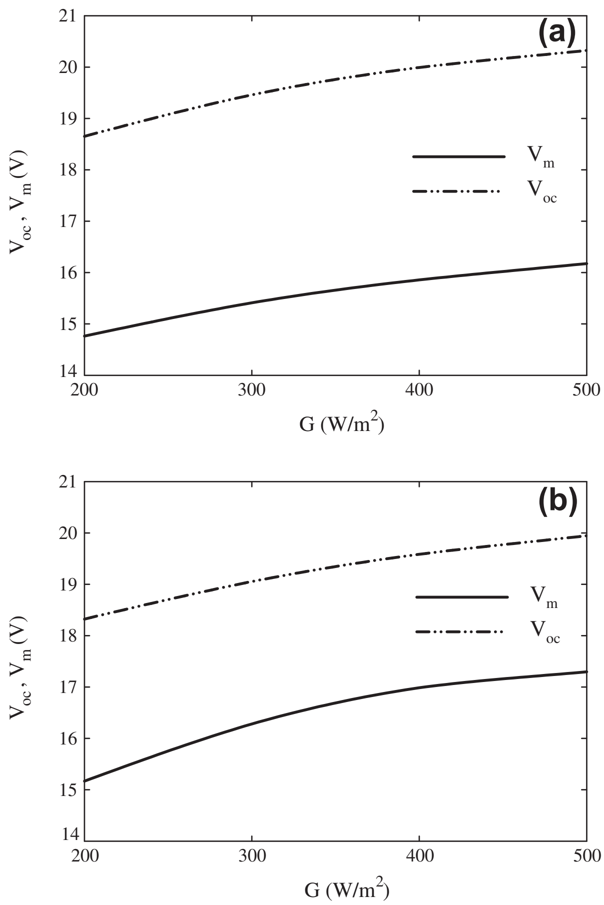

Fig. 4. Light intensity dependency of voltage parameters of (a) m-Si and (b) p-Si PV module.

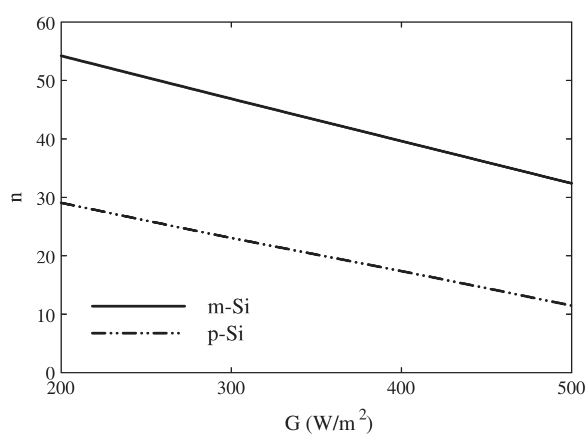

Fig. 5. Light intensity dependency of ideality factor of m-Si and p-Si PV module.

higher values of n soften the *I–V* characteristic curve. Hence, it can be concluded that P_m slightly decreases with increasing *n*.

The shunt resistance represents any parallel high conductivity paths (shunts) across the solar cell p–n junction or on the cell edges [27]. The shunt conductance (=1/R_{sh}) is also used to represent this loss term of the PV circuit. For an ideal PV cell, R_{sh} is considered infinite (G_{sh} = 0). As reported by Cuce and Cuce [3], the slope of the line between mpp and I_{sc} increases with decreasing R_{sh} thus the maximum power output of the PV module notably reduces. Therefore behaviour of R_{sh} for any operating condition is quite significant in terms of η and P_m of the system. Fig. 6 shows

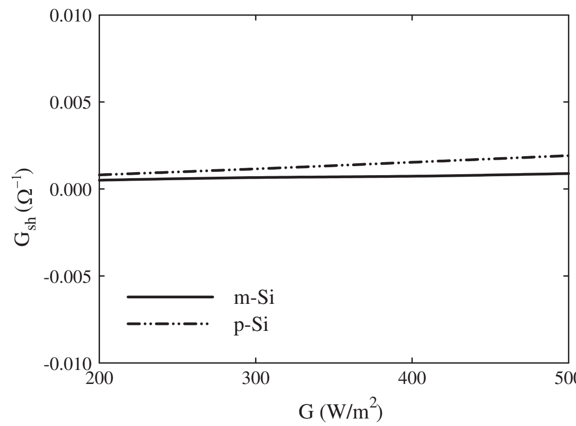

Fig. 6. Light intensity dependency of shunt conductance of m-Si and p-Si PV module.

that variation of G_{sh} with G can be neglected for both PV modules. In other words, R_{sh} of the PV modules is independent from the variations in *G*. Especially at higher values of *G*, R_{sh} completely becomes constant as reported by previous researchers [13,15]. On the other hand, for the lower solar intensities (G < 200 W/m^2), a slight increase of R_{sh} with *G* has been reported in several previous works [32–35]. This slight increase can be attributed to the existence of local inhomogeneities leading to non-uniform current flow [32] or to the charge leakage across the p-n junction in the cell [33]. Shunt resistance is commonly associated with the localized

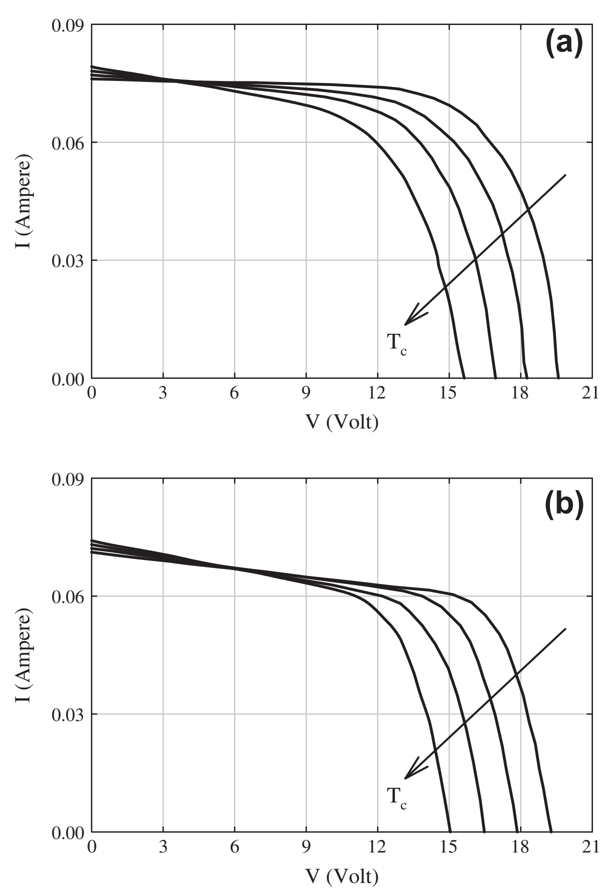

Fig. 7. *I–V* characteristics of (a) m-Si and (b) p-Si PV module for G = 200 W/m^2 and T_c = 15, 30, 45 and 60 °C.

defect regions which in turn have a larger concentration of traps that make them electrically active. These traps behave as sinks for majority carriers or light-generated minority carriers depending on the nature of the traps [34,35]. They capture carriers from the neighbouring regions [35]. The electrical activity of the aforementioned traps is stronger at lower values of G. As the solar intensity increases the traps start getting filled and this reduces the shunt current and thus increases the shunt resistance of the cell [13]. After all traps get filled, shunt resistance becomes constant. However, some other effects like heating of the cell can cause a decrease in R_{sh} as reported by Singh et al. [36].

4.2. Results for different cell temperatures

Similarly to the tests carried out for different illumination intensity levels, at first the calibration of the solar simulator was performed and T_{amb} has been adjust to 25 °C via the air conditioning system. The tests were conducted for $G = 200\ W/m^2$. Different cell temperatures were provided by using a constant temperature bath. After the cell temperatures remained constant, I–V characteristics have been obtained for each PV module as it is illustrated in Fig. 7. At first glance, it can be easily said that cell temperature has a dominant impact on voltage parameters whereas its effect is almost negligible for current parameters. Potential energy content of the PV modules remarkably decreases with increasing T_c.

Fig. 8 depicts the cell temperature dependency of current parameters of PV modules. While I_{ph} and I_{sc} of PV modules increase linearly with increasing T_c, I_m values decreases. Increase of I_{ph} and I_{sc} with increasing cell temperature can be attributed to the decrease in band gap and correspondingly increase in band-to-band absorption coefficient across the spectrum as similarly reported by Green [37]. On the other hand, the decrease in I_m arises from the dramatic drop in voltage parameters [21,26]. For any value of cell temperature, the difference between I_{sc} and I_m of m-Si PV module has been found to be smaller than that of the p-Si PV module. This result indicates that the m-Si PV module is more appropriate for the ideal cell definition.

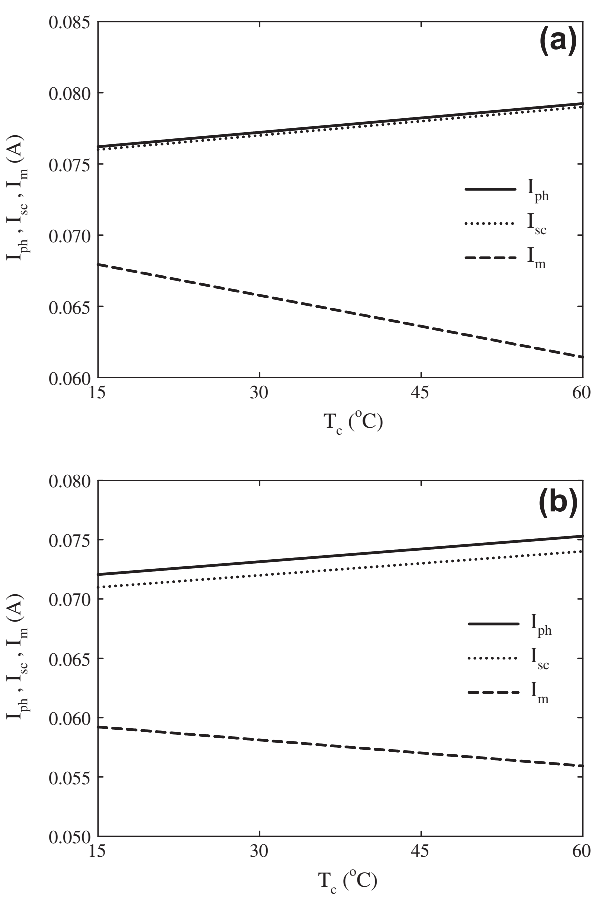

Fig. 8. Cell temperature dependency of current parameters of (a) m-Si and (b) p-Si PV module.

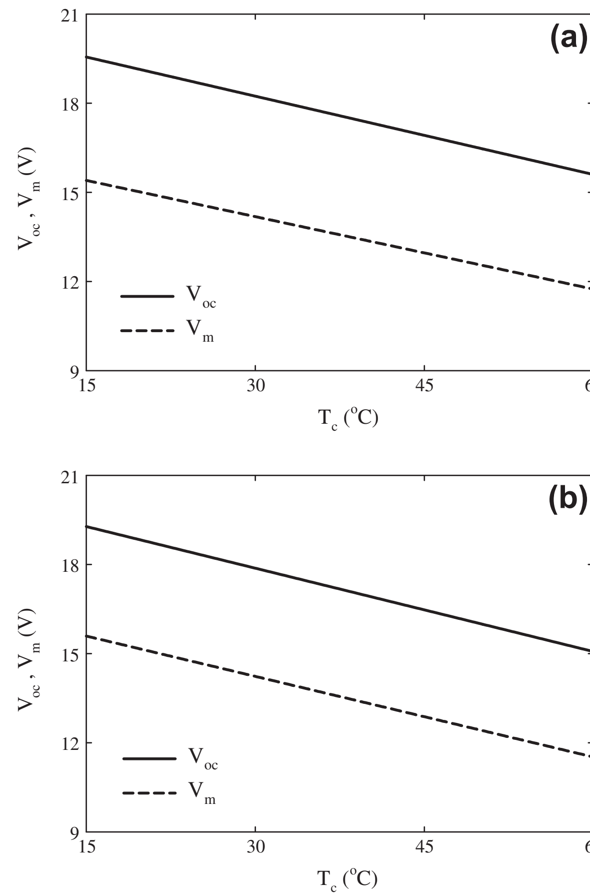

Fig. 9. Cell temperature dependency of voltage parameters of (a) m-Si and (b) p-Si PV module.

Temperature dependency of voltage parameters of PV modules is illustrated in Fig. 9. For both PV modules, it has been observed that voltage parameters dramatically decrease with increasing T_c. For m-Si PV module, V_{oc} and V_m have been determined to be 19.54 and 15.48 V, respectively for $T_c = 15$ °C whereas they were 15.61 and 11.62 V for $T_c = 60$ °C. About 20% and 25% decrement in V_{oc} and V_m, respectively has been determined. Similarly for p-Si PV module, V_{oc} and V_m have been found to be 19.25 and 15.65 V, respectively for $T_c = 15$ °C while they were 15.05 and 11.42 V for $T_c = 60$ °C. About 22% and 27% decrement in V_{oc} and V_m, respectively have been observed. In terms of temperature coefficient, δ_{voc} and δ_{vm} have been calculated to be −0.0873 and −0.0857, respectively for m-Si PV module; −0.0933 and −0.0940, respectively for p-Si PV module. The trend of the temperature coefficient has been found very similar with the results of King et al. [38].

Fig. 10 shows that ideality factor of PV modules decreases linearly with increasing T_c. Temperature dependency of ideality factor has shown a good agreement with the previously published results [36,39,40]. The decrease in the n value with increasing temperature can be explained due to the decrease in resistance of the active layer of the semiconductors thereby sending more current in the

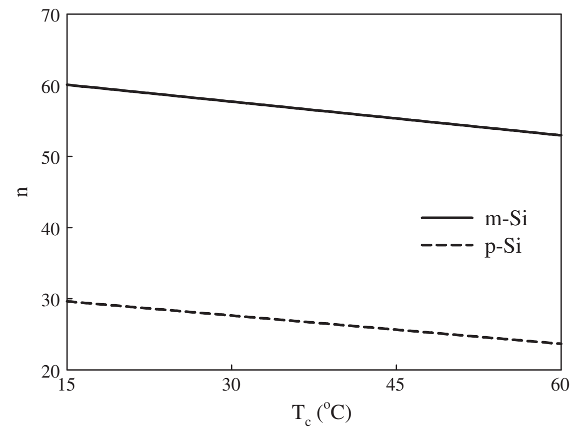

Fig. 10. Cell temperature dependency of ideality factor of m-Si and p-Si PV module.

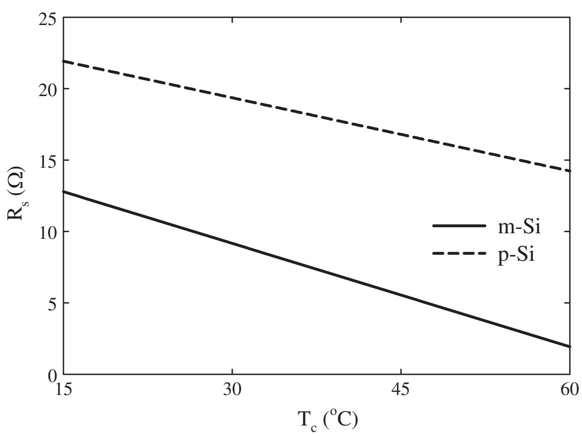

Fig. 11. Cell temperature dependency of series resistance of m-Si and p-Si PV module.

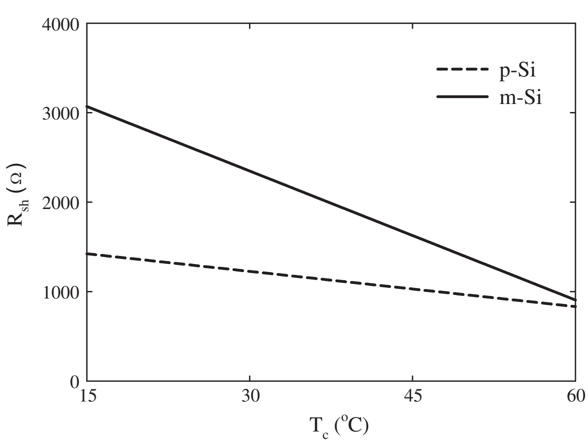

Fig. 12. Cell temperature dependency of shunt resistance of m-Si and p-Si PV module.

forward direction [41]. Temperature dependency of series resistance and shunt resistance of PV modules are given in Figs. 11 and 12, respectively. It has been observed that R_s values of PV modules decrease linearly with increasing T_c. This result can be verified through the experimental study performed by Singh et al. [36]. Cuce and Bali [6] found that there is a linear relationship between R_s and T_c. If the loss term due to the R_s reduces in a PV cell, that

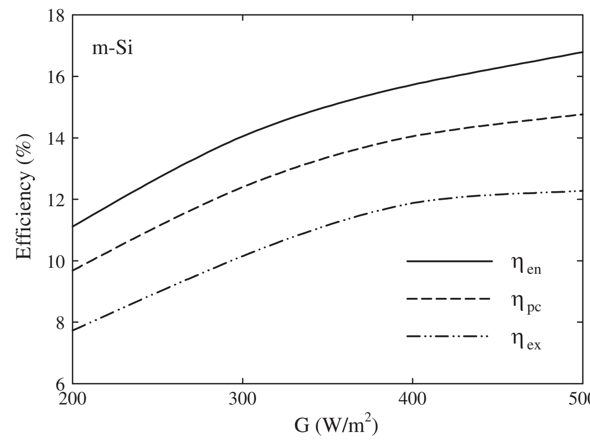

Fig. 13. Illumination intensity dependency of efficiencies for m-Si PV module.

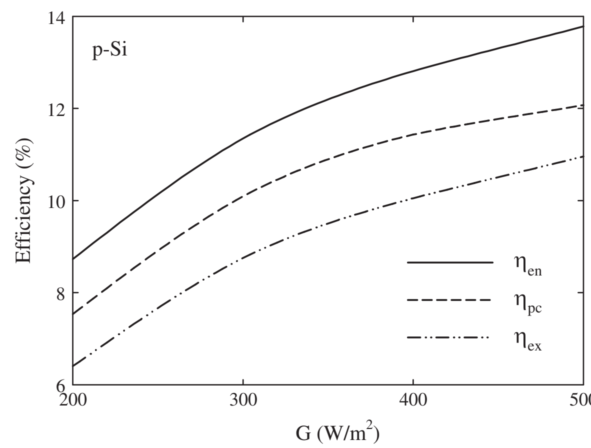

Fig. 14. Illumination intensity dependency of efficiencies for p-Si PV module.

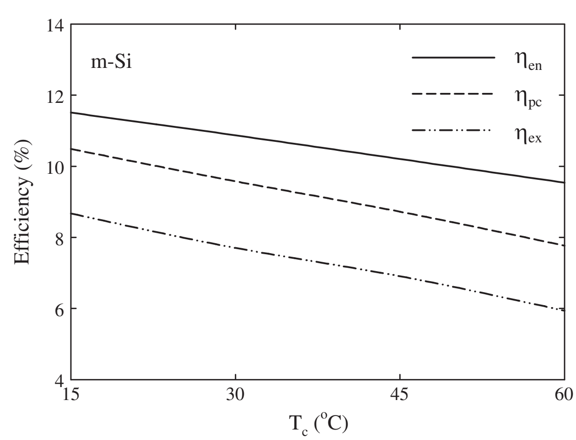

Fig. 15. Temperature dependency of efficiencies for m-Si PV module.

corresponds an increase in output current. The results also indicated that shunt resistance of PV modules decreases linearly with increasing T_c. This decrease can be explained in terms of a combination of tunnelling and trapping–detrapping of the carriers through the defect states in the space-charge region of the device. These defect states either act as recombination centres or traps depending upon the relative capture cross sections of the electrons and holes for the defect. As reported by Cuce et al. [1], energy

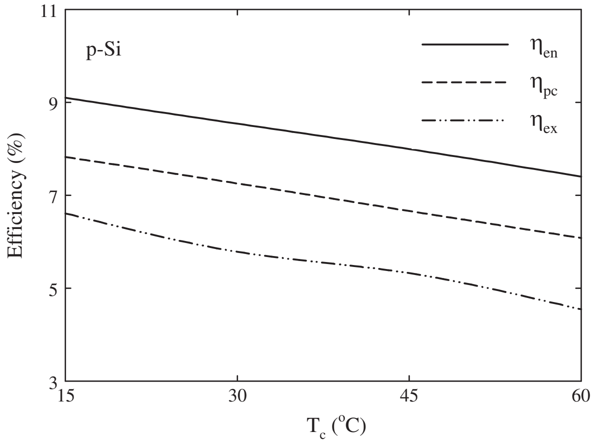

Fig. 16. Temperature dependency of efficiencies for p-Si PV module.

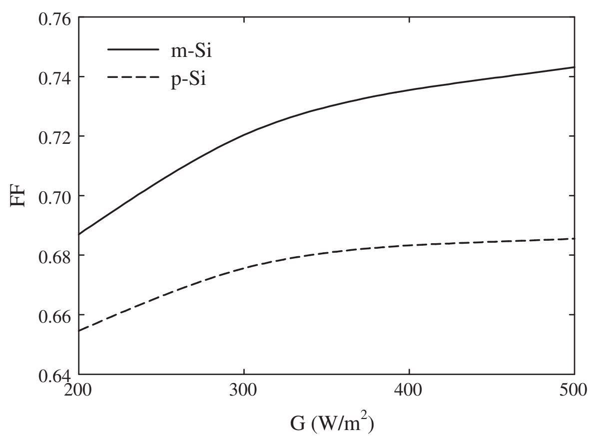

Fig. 17. Illumination intensity dependency of FF value for PV modules.

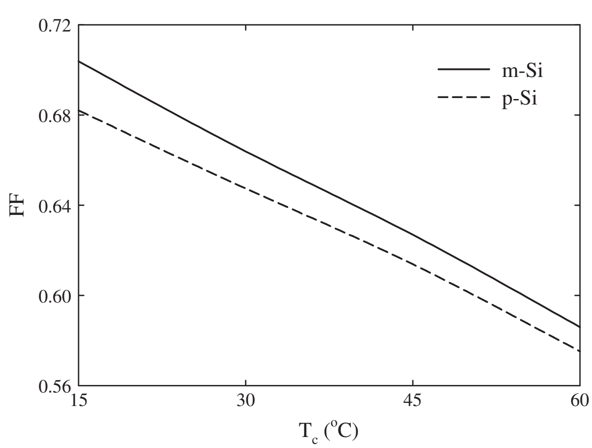

Fig. 18. Temperature dependency of FF value for PV modules.

content and efficiency of the PV modules notably reduce especially in low-intensity levels as a result of the decrease of R_{sh}. Therefore PV cell temperature should be kept as low as possible for a better performance and power output.

4.3. Thermodynamic performance assessment

Thermodynamic performance assessment of the PV modules has been done for each operating condition and the results have been illustrated in Figs. 13–16. For the thermodynamic analysis; equations by Joshi et al. [43], Sahin et al. [44], Cuce and Bali [5] have been used. As shown in Figs. 13 and 14, energy, exergy and power conversion efficiencies of the PV modules increase exponentially with solar intensity level. The trend has been found to be very compatible with the results presented by Srivastava and Sudhakar [42]. On the contrary to the illumination intensity dependency, those efficiencies decrease linearly with increasing cell temperature as illustrated in Figs. 15 and 16. Fill factor values have also been calculated for the PV modules and a similar trend has been observed. *FF* values of the PV modules increase exponentially with G while they drastically decrease with T_c as shown in Figs. 17 and 18, respectively.

5. Conclusion

Accurate knowledge of photovoltaic cell parameters from the measured *I–V* characteristics is quite significant for the quality control and the performance assessment of PV systems. In this study, light intensity and temperature dependency of performance parameters of PV modules have been experimentally investigated. First time, a term namely solar intensity coefficient has been defined and its value has been determined for current parameters. The results indicated that R_{sh} is rather sensitive to the variations in T_c. For higher solar intensity levels, G^* is not affected from the variations in light intensity. Ideality factor decreases linearly with increasing T_c. Fill factor increases exponentially with solar intensity while it decreases linearly with T_c. In terms of performance characteristics such as energy efficiency, power conversion efficiency, exergy efficiency and fill factor, m-Si PV module has been found to be more efficient than p-Si PV module. Through the results obtained, it can be concluded that the key item to improve the performance of PV systems is minimizing the cell temperature as maximizing the light intensity falling on the PV module's surface. Concentrating systems such as Fresnel lenses and booster mirrors can be used to enhance photocurrent, short circuit current and maximum current values of PV modules. On the other hand, to avoid the substantial drop in open circuit voltage and maximum voltage, cell temperature should be kept as low as possible. Cooling of PVs is a quite challenging issue since it should be implemented with a cost-effective process. Therefore most researchers prefer and recommend passive cooling methods. However, alternative cooling techniques should be investigated to reduce the cost per peak power obtained from PVs. It is crucial for the feasibility, reliability and sustainability of this environmentally friendly technology. As a recommendation, exergy efficiency should be taken into account for the feasibility analyses related to the photovoltaic power plants since it includes the irreversibilities in the energy conversion process.

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