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Impact of temperature on performance of series and parallel connected mono-crystalline silicon solar cells

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ABSTRACT

This paper presents a study on impact of temperature on the performance of series and parallel connected mono-crystalline silicon (mono-Si) solar cell employing solar simulator. The experiment was carried out at constant light intensity 550 W/m^2 with cell temperature in the range 25–60 °C for single, series and parallel connected mono-Si solar cells. The performance parameters like open circuit voltage, maximum power, fill factor and efficiency are found to decrease with cell temperature while the short circuit current is observed to increase. The experimental results reveal that silicon solar cells connected in series and parallel combinations follow the Kirchhoff's laws and the temperature has a significant effect on the performance parameters of solar cell.

1. Introduction

The solar energy is considered as one of the fundamental energy resources for future world due to its easy availability as well as clean and cheap energy resources. It is one of the renewable, low-carbon resources with both the scalability and the technological maturity to meet fast-growing global demand for electricity. Among solar power technologies, solar photovoltaic (PV) is the most widely used technology which caters about 0.87% demand of the world's electricity. The solar cells are the main component in photovoltaic power systems because these convert the solar radiation directly into electrical energy and the conversion process is based on the photovoltaic effect. Silicon is one of the most important raw materials used in the solar cell production as well as the PV industries are using it as poly-silicon (Jean et al., 2015; Cuce et al., 2013; Parous and de Oliveira, 2013). Silicon solar cell is the part of solar energy and has potential applications especially in the field of photovoltaic technologies for power systems. Mono-crystalline silicon (mono-Si) solar cells have paid more intention due to their rapid development of technology and potential applications to fulfill the energy demands of the society (Amouche et al., 2012; Radziemska, 2006; Cai et al., 2012; Singh and Ravindra, 2012; Chauhan and Srivastava, 2012). The mono-Si solar cell is one of the first developed and mostly used solar cells because it has a number of advantage like low maintenance cost, high reliability, noiseless and eco-friendly (Solanki et al., 2013; Chander et al., 2015). The overall performance of mono-Si solar cell strongly depends on the environmental parameters such as light intensity, tracking angle and cell temperature etc. The efficiency of a solar cell is varied in a range 5%–18% where the lower limit is referred to the amorphous PV cells and the higher limit to the mono-crystalline solar cells. The efficiency is strongly affected by the temperature and according to nominal operative cell temperature, the typical operating temperature for solar cells is about 45 °C ± 2 °C which is also depended on manufacturer specifications. The cell temperature is the key environmental parameter to decide the quality and performance of a solar cell by changing photovoltaic parameters like open circuit voltage, short circuit current, maximum power, fill factor and efficiency (Radziemska, 2003; Vergura et al., 2011; Khan et al., 2010b; Skoplaki and Palyvos, 2009; Chegaar et al., 2013; Dubey et al., 2013). The current–voltage characteristics relation of a solar cell is given as Khan et al. (2010b):

$$I = I_0\left[\exp\left(\frac{q\,(V-IR_s)}{nKT}\right)-1\right]+\left(\frac{V-IR_s}{R_{Sh}}\right)-I_L. \qquad (1)$$

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Nomenclature

I	Current
I_0	Reverse saturation current
q	Electron charge (1.602×10^{-19} Coulomb)
V	Voltage
R_s	Series resistance
n	Ideality factor
K	Boltzmann's constant (1.381×10^{-23} J/K)
T	Temperature
R_{sh}	Shunt resistance
I_L	Light generated current
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
P_{max}	Maximum output power
FF	Fill factor (FF)
η	Efficiency
V_D	Contact potential difference
N_D	Donor concentration
N_A	Acceptor concentration
n_i	Intrinsic concentration
V_{max}	Maximum voltage
I_{max}	Maximum current
P_{in}	Input power
$I(t)$	Light intensity
A	Surface area of solar cell

Here, I_0 is the reverse saturation current, q is electron charge, n is diode intensity factor, K is the Boltzmann constant, T is temperature, R_s is the series resistance, R_{sh} is the shunt resistance and I_L is the light generated current of the solar cell.

The effect of temperature on the forward dark current–voltage characteristics of silicon solar cells and diodes is reported by Radziemska (2006). He found that the forward voltage of solar cell and diode was decreased 2 mV/K and increased 1 mV/K respectively at constant forward current of 100 mA. Cuce et al. (2013) investigated the dependency of photovoltaic cell parameters on illumination intensity and temperature. A study on the effect of spectral variations intensity of the incident solar radiation on the Si solar cells performance is undertaken by Ghitas (2012). He observed that the shift in the solar spectrum towards the infrared has a negative impact on the performance of the module. Ramabadran et al. (2009) carried out the effect of shading on series and parallel connected solar PV modules. The maximum photovoltaic power tracking for the photovoltaic array is reported by Lin et al. (2011) using the fractional-order incremental conductance method. Khan et al. (2013) developed an analytical method to extract diode parameters (series resistance, shunt resistance, diode ideality factor and reverse saturation current density) using a single current–voltage characteristics based on one exponential model of silicon solar cells under high illumination conditions. A depth study on temperature dependence of heterojunction with intrinsic thin layer (HIT) structure is carried out by Taguchi et al. (2008) with varying thickness of undoped amorphous silicon layer. The development status of HIT solar cells at Sanyo electric is also reported by Mishima et al. (2009).

Thorough literature survey reveals that the environmental parameters always play a significant role on the performance of mono-Si solar cells and there is a gap to study these parameters in the series and parallel combinations. Therefore, to bridge this gap, a study on the impact of cell temperature on the performance of series and parallel connected mono-crystalline silicon solar cell is undertaken in this paper. The experiment was carried out with cell temperature in the range 25–60 °C at constant light intensity 550 W/m^2 employing solar cell simulator. The performance parameters like open circuit voltage, short circuit current, maximum power, fill factor and efficiency are calculated. The temperature coefficients of these parameters are also calculated and discussed in detail.

2. Experimental details

In this work, two mono-Si solar cells of (4 × 4) cm^2 area were used and the measurements were performed employing solar cell simulator. These solar cells are connected in series and parallel combinations and the experiment was carried out at constant light intensity 550 W/m^2 with cell temperature in a range 25–60 °C of simulated two quartz halogen lamps (OSRAM 50 W, 230 V each). The light intensity of halogen lamps was measured by solar power meter. A schematic diagram of the series and parallel combinations of mono-Si solar cells is presented in Fig. 1. To cool the solar cell simulator, an exhaust fan was used during the entire period of acquisition. To vary the cell temperature of the mono-Si solar cells, a temperature control unit was also used which comprised a heater and temperature sensor. It controlled and stabilized the required temperature from room temperature to 80 °C. The mono-Si solar cells were used as a power source and the current–voltage as well as power-voltage characteristics were taken.

3. Results and discussion

The current–voltage and power-voltage characteristics for series and parallel connected mono-Si solar cell are presented in Figs. 2–4. The observations were undertaken at constant light intensity 550 W/m^2 for cell temperature 25 °C, 40 °C, 50 °C and 60 °C.

It is clearly visible in Figs. 2–4 that the cell temperature has a significant impact on current–voltage and power-voltage characteristics. In the current–voltage characteristics, the current is almost constant in the lower voltage range and the characteristics estimation follows the order of cell temperature as the successive higher underestimates the lower one. The trend is reversed at about voltage 0.3 V, 0.7 V and 0.43 V for single, series and parallel combinations respectively. Thereafter, the current is observed to decrease rapidly with voltage and reach minimum in the range 8–10 mA and the characteristics corresponding to successive lower cell temperature existed beyond the higher which may be attributed to the increase in rate of charge carrier generation with cell temperature reveals the rapid increment in the reverse saturation current (Arjyadhara et al., 2013). The power-voltage characteristics estimation follows similar trend like the current–voltage characteristics. The output power is found to increase almost linearly at the low voltage range, reached at maximum and rapidly decreased at the higher range. The power-voltage characteristics clearly show a point of maximum output power and the voltage at this point is found to be less than the open circuit voltage. The current at this point is also observed to be less than the short circuit current. The results are in agreement with the earlier reported work of single crystalline silicon solar cells (Chander et al., 2015; Khan et al., 2013; Reich et al., 2009; Purohit et al., 2015). The series and parallel connected mono-Si solar cells follow the Kirchhoff's laws of voltage and current. For series combination, the output voltage is found to be the sum of individual cells and the current is identical for the both while in parallel combination, the voltage is found to be identical and the current is observed to be the sum of individual cells.

The temperature dependence of performance parameters viz. V_{oc}, I_{sc} and FF for single, series and parallel connected mono-Si solar cells with the cell temperature is presented in Fig. 5 and tabulated in Table 1.

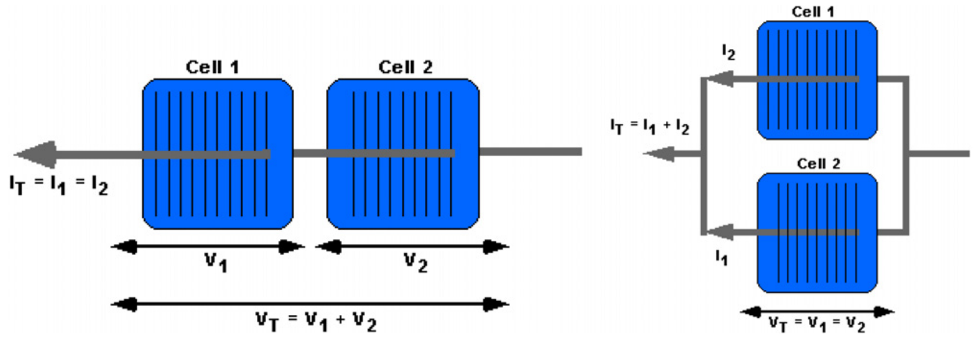

Fig. 1. Schematic diagram of the series and parallel connected mono-Si solar cells.

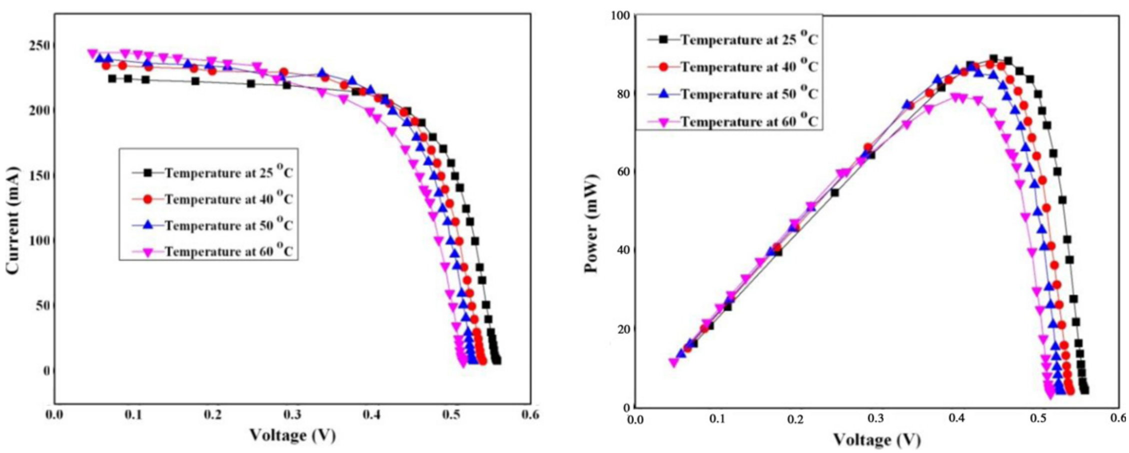

Fig. 2. The I–V and P–V characteristics of mono-Si solar cell with cell temperature.

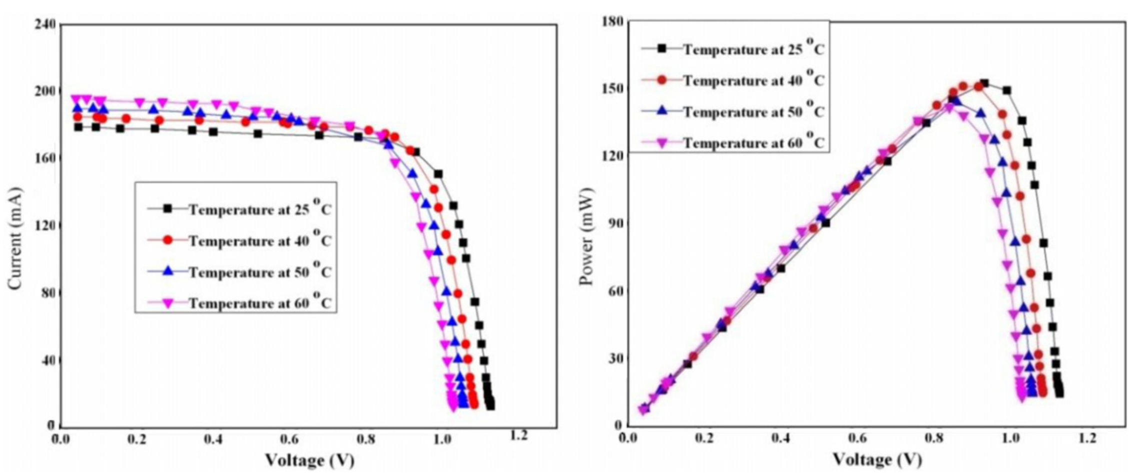

Fig. 3. The I–V and P–V characteristics of mono-Si solar cells for series combination with cell temperature.

Table 1
The open circuit voltage (V_{oc}), short circuit current (I_{sc}) and fill factor (FF) of mono-Si solar cells.

Temperature (°C)	Open circuit voltage V_{oc} (V)			Short circuit current I_{sc} (mA)			Fill factor (FF)		
	Single	Series	Parallel	Single	Series	Parallel	Single	Series	Parallel
25	0.558	1.128	0.565	225	179	385	0.7044	0.7562	0.6996
40	0.54	1.084	0.548	235	185	395	0.6900	0.7448	0.6844
50	0.528	1.056	0.53	240	190	418	0.6644	0.7192	0.6593
60	0.515	1.029	0.519	245	196	440	0.6292	0.7040	0.6219

It is visible in Fig. 5 and Table 1 that the open circuit voltage and fill factor are observed to decrease slightly with cell temperature while the short circuit current is found to increase for single, series and parallel combinations of the mono-Si solar cells. It is also observed that the open circuit voltage is strongly depended on cell temperature while the short circuit current showed only slight variation (Zondag, 2008). The open circuit voltage (V_{oc}) is proportional to the contact potential difference (V_D) which is given

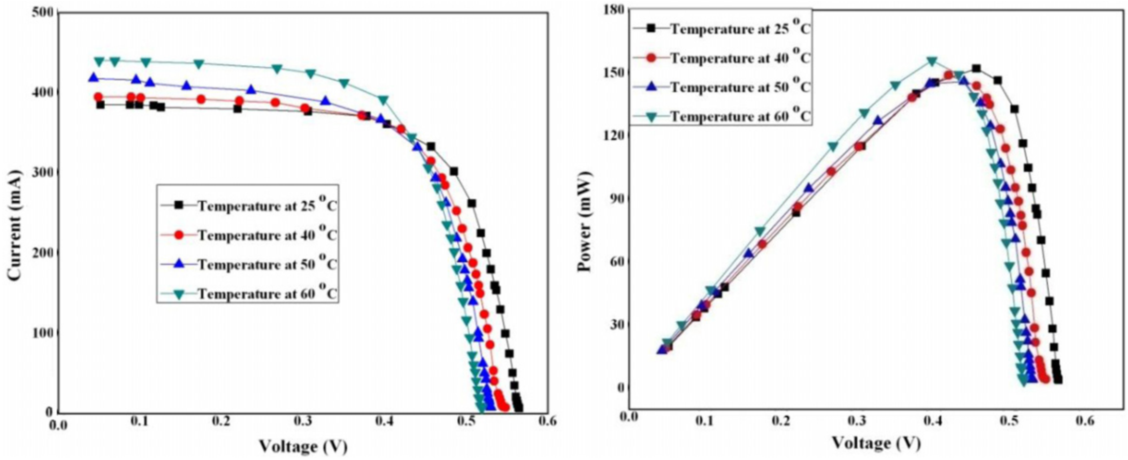

Fig. 4. The *I–V* and *P–V* characteristics of mono-Si solar cells for parallel combination with cell temperature.

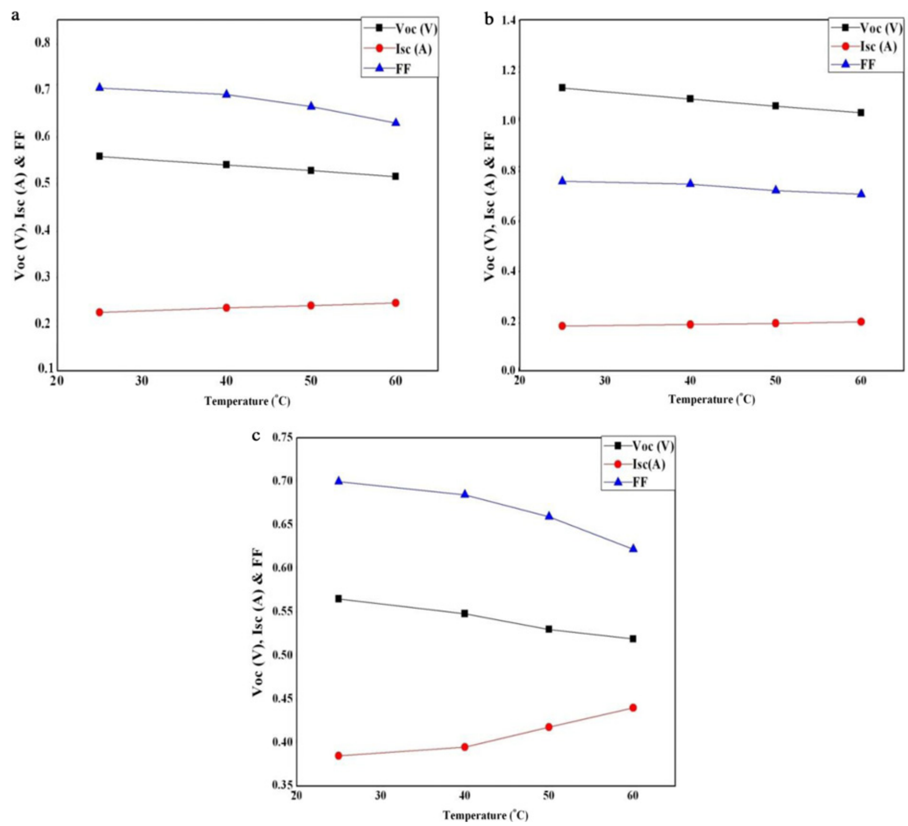

Fig. 5. The variation of open circuit voltage (V_{oc}), short circuit current (I_{sc}) and fill factor (FF) of mono-Si solar cells with cell temperature for (a) Single, (b) Series and (c) Parallel combinations.

by relation concerned (Cai et al., 2012).

$$V_D = \left(\frac{kT}{q}\right) \ln\left(\frac{N_D N_A}{n_i^2}\right). \tag{2}$$

Here, N_D is the donor concentration, N_A is the acceptor concentration and n_i is the intrinsic concentration. As cell temperature increases, n_i increases rapidly and consequently both V_D and V_{oc} decreases. The short-circuit current (I_{sc}) is proportional to the number of generated charge carriers and mobility as well as it depends strongly on the generation rate and the diffusion length. The rate of generation of charge carrier increases with cell temperature which causes an increment in the short circuit current (Chander et al., 2015). A similar behavior is also observed in earlier reported work of other researchers for silicon solar cells (Lammert and Schwarts, 1997; Saran et al., 2013; Arora and Hauser, 1982; Emery and Osterwald, 1987; Tsuno et al., 2005). The temperature coefficients of the open circuit voltage (V_{oc}), short circuit current (I_{sc}) and the fill factor (FF) are also calculated. The temperature coefficient of the open circuit voltage (dV_{oc}/dT) is found −0.0012/°C, −0.0028/°C and −0.0011/°C for single, series and parallel combinations of mono-Si solar cells respectively which revealed that the open circuit voltage is decreased with cell temperature. The temperature coefficient of the short circuit current (dI_{sc}/dT) is found 0.0005/°C, 0.0004/°C and 0.0002/°C for single, series and parallel combinations of mono-Si solar cells respectively which shows that the short circuit current slightly increased with temperature. The results are well supported by earlier reported work of Kamkird et al. (2012).

Table 2
The maximum output power (P_{max}) and efficiency (η) of different combinations of mono-Si solar cells.

Temperature (°C)	Maximum output power P_{max} (mW)			Efficiency (η %)		
	Single	Series	Parallel	Single	Series	Parallel
25	89.00	152.68	152.18	10.049	8.6752	8.6466
40	87.56	149.37	148.15	9.95	8.4872	8.4178
50	86.736	144.31	146.08	9.856	8.1995	8.3000
60	79.40	141.98	142.01	9.023	8.0674	8.0691

The fill factor (FF) was calculated using relation concerned (Azim et al., 2014).

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}}. \quad (3)$$

Here, V_{max} and I_{max} are the voltage and current respectively corresponding to the maximum output power. The fill factor is found to decrease with cell temperature due to change in corresponding open circuit voltage and short circuit current. It is also observed to decrease in parallel combination which may be due to increase in the resistive loss (Khan et al., 2010a). The temperature coefficient of the fill factor (dFF$/dT$) is found -0.0023/°C, -0.0020/°C and -0.0021/°C for single, series and parallel combinations of mono-Si solar cells respectively.

The variation of the maximum output power (P_{max}) and efficiency for different combination of mono-Si solar cell with cell temperature is tabulated in Table 2. The solar cell efficiency was calculated using relation concerned (Khan et al., 2014).

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{max} \times I_{max}}{I(t) \times A} = \frac{FF \times V_{oc} \times I_{sc}}{I(t) \times A}. \quad (4)$$

Here, $I(t)$ is the light intensity and A is the surface area of solar cell.

The maximum output power and cell efficiency are found to be decreased with cell temperature for all combinations of the mono-Si solar cells (Table 2). The temperature coefficient of the maximum output power (dP_{max}/dT) is found in the range $-(0.096 - 0.0734)$/°C, $-(0.221 - 0.506)$/°C and $-(0.207 - 0.407)$/°C for single, series and parallel combinations of mono-Si solar cells respectively. The efficiency of series and parallel combinations is slightly lower than the single mono-Si solar cell due to increment in the corresponding surface area of mono-Si solar cells and maximum output power which revealed their applications in photovoltaic modules.

The temperature coefficient of efficiency ($d\eta/dT$) is found $-(0.006 - 0.094)$/°C, $-(0.0125 - 0.0288)$/°C and $-(0.0117 - 0.0203)$/°C for single, series and parallel connected mono-Si solar cells respectively which revealed that the cell efficiency is decreased with temperature. The efficiency is strongly affected by the temperature in accordance to the nominal operative cell temperature (NOCT) and the typical operating temperature for solar cells is about 45 °C ± 2 °C which also depends on manufacturer specifications. A significant efficiency loss is observed with increasing cell temperature over the NOCT range which revealed the linear power loss with the temperature (Khan et al., 2010b). The results are well supported by the earlier reported work of Khan et al. (2014), Menes-Rodrìguez et al. (2005) and Coello et al. (2004).

4. Conclusion

In this paper, a study on impact of temperature on the performance of series and parallel connected mono-crystalline silicon solar cell is reported. The experiment was carried out employing solar cell simulator at constant light intensity 550 W/m^2 with cell temperature in the range 25–60 °C for single, series and parallel connected mono-crystalline silicon solar cells. The performance parameters were calculated and discussed. The open circuit voltage, maximum power, fill factor and efficiency are observed to decrease with cell temperature while the short circuit current is found to increase slightly which may be attributed to the increase in the rate of charge carrier generation with cell temperature. The experimental results show that mono-Si solar cells connected in series and parallel combinations follow the Kirchhoff's laws and the cell temperature has a significant effect on performance parameters.

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