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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):

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

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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.