Chapter 2

Investigation of the Effect of Various Operational Parameters on PV Cell/Panel Performance

2.1 Performance of SPV

There are several factors that affect the performance of PV panel, as has been mentioned briefly in the introduction. The focus of this chapter is to investigate the effect of temperature on Solar PV cell and panel. On average about 20% of the incident solar energy is converted into electrical energy while the rest 80% gets accumulated as heat energy, causing rise in the temperature of Solar PV cell or panel. This phenomenon in turn reduces the efficiency.

This chapter is divided in two sections. In the first section, mathematical modeling of solar PV cell is performed to find the effect of temperature as well as the PV cell performance at different temperature with the help of simulation using MATLAB / SIMULINK software. In second section, effect of temperature on 100 watt PV panel by simulation is shown. The simulation model uses information about the electrical characteristics of PV such as max current, max voltage, open circuit voltage, short circuit current etc.

2.2 Modeling of Solar Photovoltaic Cell

An ideal solar cell can be considered as a current source wherein the current produced by the solar cell is proportional to the solar irradiation intensity falling on it. Since the practical behavior of a cell is slightly different from ideal due to the optical and the electrical losses, thus in order to develop an electrical equivalent circuit model for solar cell, appropriate components should be added with ideal current source. An electrical circuit representing a solar cell is shown in figure 2.1 and 2.2. The optical
loss is represented by the current source itself, where the generated current $I_{PV}$ is proportional to the light input.

The ohmic losses in the cell occur due to the series and shunt resistance denoted by $R_s$ and $R_{Sh}$ respectively. As the name suggests, the series resistance is the resistance offered by the solar cell in the path of current flow; therefore, $R_s$ is shown in the current path. The shunt resistance is referred as the leakage in the path of the current in a solar cell and therefore it is represented in parallel with the current source. The electrical characteristics of solar photovoltaic (PV) cell can be represented as the relationship between cell output voltage and current, and cell voltage and power. In spite of these, many other quantities are also needed to understand the cell characteristic better, such as open circuit voltage ($V_{OC}$), short circuit current ($I_{SC}$), cell voltage, current and power corresponding to maximum power point $V_{MPP}$, $I_{MPP}$ and $P_{MPP}$ respectively [1-2].

Our understanding of the PV system is based on the experimental data gathered from the PV system about the effects of environmental or manmade factors on the output power. An efficient way would be to study the model of a solar PV panel as it is easier to control the parameters such as sun irradiance and temperature and study their effects in a controlled environment. The model discussed in literature varies inaccuracy and complexity. The single diode model shown in figure 2.2 is most popular physical model used to represent the characteristic of solar PV cell or solar PV panel, as it is less sophisticated and thus the computations involved are also easier to handle. The double diode model (shown in figure 2.1), on one hand has more accuracy than single diode model but on the other hand it is more complex, and thus it is cumbersome to explain the characteristic of PV cell. So for the purpose of this chapter single diode model is appropriate and that is what will be discussed hereafter.

The mathematical model of solar PV cell used to describe the characteristic of PV cell or PV panel is shown in figure 2.2.
**Figure-2.1:** Equivalent circuit of a P- N junction solar PV cell (Two diode model)

**Figure-2.2:** Equivalent circuit of solar PV cell (Single diode model)

In the pictorial description of the diagram above, $I$ is Output current or load current of PV cell/ Module, $I_{pv}$ is Photocurrent generated by solar cell, $I_d$ is Diode forward current, $I_{sh}$ is the shunt current flowing through resistance $R_{sh}$, $R_s$ is series resistance corresponds to distributed ohmic resistance in the semiconductor and the resistance of the metallic contact. It is desirable that ($R_s$) is as low as possible, in particular ($R_s = 0$) in an ideal condition and $R_{sh}$ accounts for the leakage current due to impurity in semiconductor. It should be high as possible and in an ideal condition ( $R_{sh} = \infty$ ) [3]. The mathematical model of figure 2.2, degenerates under ideal condition to the model described in figure 2.3 below.
Solar PV cell may be considered as current source with diode connected in parallel. The output current mainly depends on photocurrent $I_{pv}$, which is positively correlated with sun irradiance. More precisely, it depends on three different currents ($I_{PV}$, $I_D$, $I_{Sh}$) and these currents are proportional to irradiance, temperature and resistances. The expression for output current ($I$) of solar PV cell from equivalent circuit can be written as,

$$I = I_{PV} - I_D - I_{Sh} \tag{2.1}$$

Here,

The Diode current $I_D$ can be determine by Shockley diode current equation

$$I_D = I_0 \left[ \exp \left( \frac{V_D}{nV_T} \right) - 1 \right] \tag{2.2}$$

Here, $I_0$ is diode reverse saturation current, $V_o$ is applied forward voltage on diode, $n$ is Ideality factor, $V_T$ is thermal voltage. The thermal voltage has the following relation with temperature.

$$V_T = \frac{KT}{q} = 26 \text{ mV at } 25^\circ\text{C} \tag{2.3}$$

$K = 1.381 \times 10^{-23} \text{ J/K}$ is Boltzmann constant, $T$ is temperature of PV cell, $q = 1.602 \times 10^{-19} \text{ C}$ is charge on an electron. The shunt current can be expressed as follows.

$$I_{Sh} = \frac{V + IR_S}{R_{Sh}} \tag{2.4}$$
Substituting for various variable in the equation 2.1 we get

\[ I = I_{PV} - I_0 \left[ \exp \left( \frac{V_o}{nV_t} \right) - 1 \right] - \frac{V + IR_S}{R_{sh}} \]  

2.5

With \( R_{sh} = \infty \), put in the above equation 2.5 we get the I-V equation of equivalent circuit of an ideal cell is given as:

\[ I = I_{PV} - I_0 \left[ \exp \left( \frac{V_o}{nV_t} \right) - 1 \right] \]  

2.6

The I-V equation of equivalent circuit of a two diode model of solar PV cell shown in figure 2.1 can be written in the following form:

\[ I = I_{PV} - I_{O1} \left[ \exp \left( \frac{V_o}{nV_t} \right) - 1 \right] - I_{O2} \left[ \exp \left( \frac{V_o}{nV_t} \right) - 1 \right] - \frac{V + IR_S}{R_{sh}} \]  

2.7

Solar PV cell Characteristics

Solar cells are characterized and compared with respect to following four parameters:

- Short circuit current(\( I_{SC} \))
- Open circuit voltage (\( V_{OC} \))
- Fill factor (FF) and
- Efficiency (\( \eta \))

These parameters can be represented using figure 2.4. The characteristic curve of solar PV cell/panel also shown in figure 2.4, represent the variation of current and voltage with varying load. The output current is shown at y axis and output voltage is at x axis.
2.3 PV Cell Parameters

2.3.1 Short Circuit Current $I_{SC}$

Short circuit current is the maximum current produced by a solar cell when its terminals are shorted. When a photon is absorbed in a solar cell, it generates an electron-hole pair, which is separated by the junction and then transported to the external circuit. For the maximum short circuit current, we have to assume that each photon will contribute to one electron flow to the load. A photon is required to possess energy higher than the band gap energy of the material in order to be absorbed. This implies that the short circuit current will depend on the band gap of the material. Therefore, the short circuit current will increase with decrease in band gap energy.

2.3.2 Open Circuit Voltage ($V_{OC}$)

Open circuit voltage $V_{OC}$ is the maximum voltage that can be obtained from solar cell when its terminals are left open. The $V_{OC}$ is corresponding to the amount of forward bias of a P-N junction due to light-generated current. If a photon of energy higher than the band gap energy is absorbed, it excites an electron from the valence band to the conduction band, raising its potential energy by an amount equal to $E_g$ (Energy band gap). The upper limit to $V_{OC}$ is decided by the band gap energy of the material. The larger the band gap of the material, the higher is the $V_{OC}$ of the solar
cell. The band gap of Si is 1.1 eV therefore, maximum possible $V_{oc}$ is 1.1 V. The recombination current is represented by $I_o$ in the expression for $V_{oc}$, which is written as:

$$V_{oc} = \frac{kT}{q} \ln \left( \frac{I_l}{I_o} + 1 \right)$$

Thus, for higher $V_{oc}$, the $I_o$ should be lower. The lowest value of $I_o$ is obtained when the recombination rate is equal to the thermal equilibrium recombination rate.

2.3.3 Fill Factor (FF)

The fill factor (FF) is defined as the squareness of the I-V curve and mainly related to the resistive losses in a solar cell. In ideal case, its value can be 100% corresponding to square I-V curve. However, it is not feasible to have square I-V curve. There are always some losses which reduce the value of FF. The best values of FF that can be obtained for a solar cell can empirically be written as a function of $V_{oc}$.

$$FF = \frac{v_{oc}-1n (v_{oc}+0.72)}{v_{oc}+1}$$

Above equation shows that the solar cell with higher $V_{oc}$ has higher FF. Good solar cells typically will have FF values of more than 0.80 or close to this.

2.3.4 Efficiency ($\eta$)

We have already discussed that the short circuit current of solar cell decreases with increases in band gap, while the open circuit voltage of a solar cell increases with increase in band gap. So, there is an optimum band gap for which efficiency of a solar cell would be maximum. The maximum solar cell efficiency of about 31% is obtained for the optimum band gap of about 1.45eV.

It is defined as the ratio of the power output to power input. The power output is the maximum power point $P_m$ of a solar cell, and input power is the power of solar radiation $P_{rad}$. According to the international standard for characterization of solar cells, $P_{rad}$ is equal to 100 mW/ cm$^2$ or 1000 W/m$^2$.

$$\eta = \frac{P_m}{P_{rad}} \text{ or } \eta = \frac{V_{oc}I_{sc}FF}{P_{rad}}$$
2.4 Losses in Solar Cell

A loss in a solar cell refers to loss of photon energy which, due to some reason, is not able to deliver an electron out of a solar cell. This loss could be due to the fundamental reason or it could be due to the technological reason. There are several ways in which photon energy loss could occur, such as:

Loss due to low energy photon, loss due to excess energy of photon, voltage loss, fill factor loss, loss of reflection, loss due to incomplete absorption, loss due to metal coverage and loss due to recombination etc [4].

Figure-2.5: Categorization of loss mechanisms in solar PV cell arising from technological limitation
2.4.1 Effect of Series and Shunt Resistance on Efficiency

The parasitic resistances (series and shunt resistance) mainly affect the Fill Factor (FF) of solar cells, which in turn affects the efficiency of the solar cell. The series resistance is the sum of resistance due to all the components that come in the path of current. This includes the base, emitter, semiconductor-metal contact resistance and resistance of metal contact. It is desirable to have the value of series resistance as low as possible. The shunt resistance is due to the leakage across the P-N junction. It could be due to a shunt around the periphery of the cell or due to the crystal defect or precipitates of impurities in the junction region. It is desirable to have the value of shunt resistance as high as possible. The effect of both of these resistances is to reduce the fill factor of solar cells [5].

The effect of series resistance and shunt resistance on the FF is shown in figure 2.6. The effect observed by the change in the squareness of the curves.

![Figure-2.6](image)

**Figure-2.6:** The effect of (a) series resistance and (b) shunt resistance on the FF of the solar PV cell

2.4.2 Effect of Solar Radiation on Efficiency

The short circuit current is proportional to the intensity of radiation. The expression for $V_{oc}$ can be simplified as:
\[ V_{OC} = \frac{kT}{q} \ln \left( \frac{I_0}{I_{L}} + 1 \right) \approx \frac{kT}{q} \ln \left( \frac{I_0}{I_{L}} \right) \quad 2.11 \]

Using the above approximation, the equation for the cell efficiency can be written as:

\[ \eta = \frac{I_{SC} V_{OC} FF}{P_{in}} = \frac{nI_{L} \frac{kT}{q} \ln \left( \frac{I_0}{I_{L}} \right) FF}{P_{in}} \quad 2.12 \]

Where \( P_{in} \) is the intensity of solar radiation and \( n \) is the factor accounting for radiation intensity (wherein \( n=1 \) for one sun, \( n=0.5 \) for half sun or half radiation intensity etc.). From above equation it can be seen clearly if radiation intensity decreases, the efficiency of a solar cell decreases. This will happen because of the decrease in \( V_{OC} \) with the decrease in \( I_{L} \).

### 2.4.3 Effect of Temperature on Efficiency

The temperature dependency of solar cell efficiency comes from the dependency of \( V_{OC} \) on temperature, which in turn depends on the reverse saturation current \( I_{O} \) that can vary significantly with temperature. The expression for \( I_{O} \) is

\[ I_{O} = \frac{qD_n n_i^2}{L_n N_A} + \frac{qD_p n_i^2}{L_p N_D} \quad 2.13 \]

The variation in \( I_{O} \) because of temperature is mainly due to \( n_i \) (intrinsic carrier concentration). Other parameters in above equation are assumed to be constant with temperature. The \( n_i \) as a function of temperature is expressed as follows

\[ n_i^2 = k_1 e^{-E_g/kT} \]

where \( K_1 \) is constant, from above equations we get

\[ I_{O} = k_2 e^{-E_g/kT} \]

where \( K_2 \) is another constant, the dependency of \( V_{OC} \) on temperature is given by the following equation:

\[ V_{OC} = \frac{kT}{q} \ln \left( \frac{I_{L}}{K_2} \right) + \frac{E_g}{q} \quad 2.14 \]
Differentiating above equation with T and replacing $K_2$ in terms of $V_{OC}$, we will get the rate of change of $V_{OC}$ as a function of temperature.

$$\frac{d(V_{OC})}{dT} = \frac{1}{T} \left( V_{OC} - \frac{E_g}{q} \right)$$  \hspace{1cm} 2.15

Since $E_g/q$ term will always be higher than the open circuit voltage $V_{OC}$ term in above equation, the change in $V_{OC}$ due to the increases in temperature will always be negative, i.e. the $V_{OC}$ decreases as the temperature of the cell increases. For higher $V_{OC}$ solar cell, the drop in $V_{OC}$ will be lower with temperature rise [6].

### 2.4.4 Efficient Solar Cell Design

A solar cell must perform the following three functions as efficiently as possible:

- Absorption of light
- Separation of generated charge carriers and
- Transport of separated charge carriers to external load without resistive losses.

Solar cell of a given material must be designed to maximize the light to electricity conversion efficiency. The cell efficiency is written as:

$$\eta = \frac{I_{SC} V_{OC} FF}{P_{in}}$$  \hspace{1cm} 2.16

This requires optimization of solar cell parameters $I_{SC}, V_{OC}$ and FF such that higher values of each of these are obtained to get high cell efficiency.

### 2.5 Simulation of Effect of Temperature on PV Cell

The output voltage of solar panel decreases with the increase in panel temperature and as a consequence output power also decreases. More precisely, the temperature coefficient is negative for $V_{OC}, P_{MAX}$ and FF, and it is positive for the $I_{SC}$. It is observed that efficiency of the PV panel decreases by about 0.40% - 0.50% for each degree rise in temperature.
The effect of temperature on performance of PV cell is shown in figure 2.7 and 2.8. It can be deduced from the comparison of the data in the figure, that the cell voltage reduces with increases in temperature, hence the output power decreases as explained earlier. The I-V and P-V curve for different temperatures (25°C, 50°C, 70°C) and at constant irradiance 1000W/m² for Si solar PV cell are shown below.

Figure-2.7: I- V graph for a PV cell at different temperature (25,50,70 °C) and constant irradiance
Figure-2.8: P-V graph at different temperature (25, 50, 70 °C) and constant irradiance

The above I-V and P-V graph shows that voltage reduces from 0.61V to 0.52V when temperature rises from 25°C to 70°C while the increase in current is nominal. The P-V graph shows that output maximum power at 25°C is about 2.5W and decreases by 0.5 W when cell temperature increases up to 70°C.

2.6 Effect of Temperature on 100W/12V PV Module by Simulation using Matlab/ Simulink

The simulation in Matlab/ Simulink is performed to investigate the effect of temperature on 100W Solar PV module. The output I-V and P-V characteristic obtained by performing simulation at different temperature (25°C, 50°C and 70°C) and constant irradiance of 1000W/m² is depicted in the figure 2.9 and 2.10. The outputs at different values of temperature are illustrated in the same graph for the ease of comparison. The specification of PV panel is mentioned at STC (standard test condition) in table 2.1.
Table- 2.1: Specification of solar PV module [7]

<table>
<thead>
<tr>
<th>Model</th>
<th>WS – 100/ 12V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal maximum power ($P_m$)</td>
<td>100 W</td>
</tr>
<tr>
<td>Open circuit voltage $V_{OC}$</td>
<td>22.2 V</td>
</tr>
<tr>
<td>Short circuit current $I_{SC}$</td>
<td>6.07 A</td>
</tr>
<tr>
<td>Voltage at maximum Power ($V_{MP}$)</td>
<td>17.4 V</td>
</tr>
<tr>
<td>Current at maximum power ($I_{MP}$)</td>
<td>5.73 A</td>
</tr>
<tr>
<td>No. Of cells per module</td>
<td>36 cells (9×4)</td>
</tr>
<tr>
<td>Module efficiency (%)</td>
<td>12.93 %</td>
</tr>
</tbody>
</table>

Figure-2.9: I- V graph for a PV panel at different temperature (25,50,75°C) and constant irradiance
Figure 2.10: P-V graph for a PV panel at different temperature (25, 50, 75°C) and constant irradiance

The simulation results show that, as the temperature increases, it would cause the output voltage $V_{OC}$ and $V_{MPP}$ to decrease gradually by 1.5 V for every 20°C rise in temperature. Since increases in current can be seen to be negligible, therefore maximum power changes, it is 100 W at 25°C and 82 W at 70°C. The results of the simulation are similar to as it has been described earlier. The characteristic of PV panel at different temperatures are similar to PV cell.

2.7 Experimental Data Measured for 100W/12V Solar PV Module

PV panel Output performance at outdoor condition

The effect of temperature on the output electrical power is observed by measuring the temperature of solar PV panel corresponding to output power. The specification of SPV module used in experiment is mentioned in table 2.1. To measure the temperature of SPV module, LM 35 DZ temperature sensor IC is used. The main advantage of IC LM 35 is that it is linear i.e. 10mV/°C which means for
every degree rise in temperature the output of IC LM 35 will rise by 10 mV. It has been observed practically that with rise in temperature a small increment in output current can be detected, but the output voltage of PV module reduces significantly. The final effect is, decrease in output power with the rise in temperature. These result obtained via experimentations agree with those obtained via simulation. The data obtained has been shown below graphically.

The output power highly depends on solar irradiance falling on solar PV panel. The solar irradiance varies throughout the day. The graph in figure 2.11 shows the variation in solar irradiance in W/m² during the daytime on the particular date. It can be read off the graph that the peak irradiance of 970 W/m² is recorded during 11:30 am to 1:00 pm and least irradiance of 480 W/m² is recorded at the time of morning and evening.

The graph in figure 2.12 shows variation in temperature corresponding to variation in irradiance. The peak ambient and SPV panel temperature is 47°C and 68°C respectively, and is achieved when solar irradiance is maximum (970 W/m²).

Figure-2.11: Time vs irradiance curve for experimently measured
Figure-2.12: Variation in ambient temperature and SPV panel temperature with irradiance

Figure-2.13: Variation in current with temperature of SPV panel
At the starting point of the experiment that is in the morning, SPV and ambient temperature is nearly same. Later in the day as irradiance increases the ambient temperature rises gradually from 27°C to 47°C, and SPV panel temperature varies from 29°C to 68°C. The difference between peak of ambient and SPV panel temperature is about 26°C. This can be understood as a result of absorption of a fraction of incident solar energy by the SPV panel.

Figure 2.13 shows the variation of current with temperature of SPV panel, where temperature of SPV Panel is plotted at x-axis and current is plotted on y-axis. It can be seen that the output current is achieves a peak value of 4.2 A when the temperature of SPV panel is at its highest i.e. 60°C – 68°C. Recall that simulation results from the previous paragraph imply that temperature of SPV panel is maximum when Solar irradiance is at maximum value. In light of this fact previous observation can be rewritten as follows: maximum value of current is achieved for maximum solar irradiance. The effect of temperature on current is negligible as seen earlier.

Figure 2.14 shows the effect of temperature on SPV panel V_{oc}. It was observed during the experiment that the output voltage decreases with increase in
temperature. The maximum voltage 21.4V is recorded in morning when temperature is lowest 27°C and decreases gradually and attains its minimum value of 19.0 V in afternoon when the temperature of SPV panel is 65°C. The difference between maximum and minimum voltage is about 2.4V. Although there is an increase in irradiance in the afternoon, decrement is being recorded in the output voltage. This shows that low temperature is required for higher efficiency of SPV panel.

2.8 Discussion

The results from simulation and experiment performed in this work suggests that the efficiency of the PV panel decreases by about 0.40% - 0.50% for each degree rise in temperature. The simulation results and observation validates the hypothesis that the output power decreases as the temperature increases. With increment in temperature, the open circuit voltage (V_{OC}) reduces appreciably but output current increases by small amount, hence the output power reduces. To minimize the effect of temperature, cost effective cooling arrangements are required.