Due to the variation of solar irradiance, temperature and shading conditions, the power generated by a photovoltaic (PV) module and hence the power delivered to the load changes drastically, which imposes the need for analysis of a complete PV system to get the maximum power under these natural variable conditions. In this paper, a complete off-grid PV module based power generation system has been designed and simulated using MATLAB/Simulink and performance has been scrutinized using the value of standard solar irradiance about 1 kW/m² for Bangladesh. The simulation model includes solar PV module, the converter power stage with MPPT control and charge controlling functions and here performance of each block has been examined conspicuously. Eventually, it has been found that the model is quite competent to simulate both the I-V and P-V characteristics of a PV module and based on the result it has been predicted that the performance of several modules or even PV array connected in series and/or in parallel with the delivery of maximum power can be tested under different solar irradiance and temperature conditions.

Key Words: PV module, Maximum Power, Matlab/Simulink.

II. Modeling of a PV Module Based Power System

A PV cell is a simple PN junction which is fabricated in a layer of semiconductor material. When it is illuminated by sunlight of photons with the energy equal or slightly greater than the band gap energy of semiconductor material, it is absorbed and the valence electrons are knocked out from the atoms in the material, and create electron-hole pairs. These photo generated carries are swept apart by the internal electric fields of this cell and if the cell is connected by external circuit, they contribute to current. 

(a) Modeling of a Solar PV Cell and Module

In order to create a more accurate model of a PV cell, series resistance, parallel resistance, and recombination must be counted in the circuit model which can be represented as in Fig.1.

![Equivalent circuit of a PV cell](image)

From Fig.1, the output current of this cell can be expressed as follows:

\[ I = I_{sc} - I_0 \left( e^{\frac{(V+I*R_p)}{n*k*T}} - 1 \right) - \frac{V+I*R_s}{R_p} \]  

Where \( I_{sc} \) is the short-circuit current, \( I_0 \) is the reverse saturation current of the diode, \( q \) is the electron charge \( (1.602 \times 10^{-19} \text{C}) \), \( k \) is the Boltzmann’s constant \( (1.381 \times 10^{-23} \text{J/K}) \), \( T \) is the junction temperature in Kelvin.

The effect of the shunt resistance is minimal for a small number of modules. Therefore, we can assume \( R_p = \infty \) and simplify the photon-generated current equation (1) into (2)

\[ I = I_{sc} - I_0 \left( e^{\frac{(V+I*R_p)}{n*k*T}} - 1 \right) \]

Equation (2) can be solved by using Newton’s method, which can be described as

\[ X_{n+1} = X_n - f(X_n)/f'(X_n) \]
Where \( f'(X_n) \) is the derivative of the function \( f(X) \), \( X_n \) is a present value, and \( X_{n+1} \) is the next value. Now using equation (3), equation (2) can be written as

\[
f(I) = I_{sc} - I - I_0 \times \frac{e^{q(V+I \times R_s)/(n \times k \times T)} - 1}{-1 - I_0 \times q \times R_s \times e^{q(V+I \times R_s)/(n \times k \times T)/(n \times k \times T)}} = 0 \quad (4)
\]

Then using Newton Raphson’s equation for \( n^{th} \) iteration, we have

\[
I_{n+1} = I_n - \frac{(I_{sc} - I_n - I_0 \times \frac{e^{q(V+I_n \times R_s)/(n \times k \times T)} - 1}{(-1 - I_0 \times q \times R_s \times e^{q(V+I_n \times R_s)/(n \times k \times T)/(n \times k \times T)}} - I_n)}{(-1 - I_0 \times q \times R_s \times e^{q(V+I_n \times R_s)/(n \times k \times T)/(n \times k \times T)}}
\]

(5)

By coding this equation, a PV module block has been generated in Matlab/Simulink.

(b) Modeling of a MPPT

A MPPT strategy is to force the solar cells to operate in an optimal point, giving out maximum power according to the solar radiation condition at that time. The variation of P-V characteristic according to solar radiation variation can be shown as \(^1\) follows

![Fig. 2. P-V characteristic of a solar module at (a) different irradiation levels, (b) different temperatures.](image)

Many MPPT techniques\(^5\)\(^-\)^\(^7\) have been proposed, analyzed and implemented and among them Perturb and Observation (P&O) method (Hill Climbing Method) is being used maximally because of its simplicity and ease of implementation. Basically, in this method the module voltage is perturbed by a small increment, and the resulting change in power is observed as in the algorithm\(^16\) of Fig.3

(c) Modeling of a Buck-Converter

DC-DC converter is power electronics circuits that convert a dc voltage to a different dc voltage level. A DC-DC converter is used to increase the efficiency of the system by matching the voltage supplied to the voltage required by the load. A DC-DC converter can either be step-up (Boost), step-down (Buck), or both increase and decrease (Buck-Boost) the voltage. The DC-DC converter used by this system is a Buck converter\(^17\) as in Fig.4

![Fig. 4. Buck Converter.](image)

Applying Kirchoff’s Voltage Law for Fig.4, we get,

\[
\frac{di_L}{dt} = \frac{1}{L}(V_g D - i_L R_L - V_0)
\]

(6)

Current across the capacitor is,

\[
\frac{dV_c}{dt} = \frac{1}{C}(i_L - i_{out})
\]

(7)

And output voltage is,

\[
V_{out} = V_c + R_L (i_L - i_{out})
\]

(8)

Here, \( D \) is the duty cycle of the buck-converter, \( V_g \) is the Source voltage, \( V_0 \) is voltage across the load, \( i_L \) is Inductor current, \( i_{out} \) is load Current.

Based on equations (6), (7) and (8), the Simulink model of Buck converter has been designed as in the Fig.5.
(d) Modeling of PWM

Traditionally the voltage mode was used in designing the feedback loop. The ramp signal is derived from the oscillator using a simple RC time constant network\(^{18}\). The saw tooth linearly varies with time and using the slope of the saw tooth waveform as shown in Fig. 5, it can be easily deduced that

\[
\frac{dV}{dt} = \frac{V_C}{V_M} (t) \quad \text{for} \quad 0 \leq V_C(t) \leq V_M
\]

(9)

Small signal variation of the duty cycle with the control voltage is obtained by substituting \(V_C(t)\) by ac and dc quantities and taking the partial derivative of duty cycle with respect to control voltage.

\[
\frac{d \alpha(t)}{\alpha C(t)} = \frac{1}{V_M}
\]

(10)

Using equations (9) and (10) the Simulink model has been designed as follows.

(e) Charge Controller

The charge controller consists of two switches, one on either side of battery’s positive terminal. Switch A, on the PV module side, is opened if the battery voltage becomes 14.4 volt (approximately 100% charged) and will remain open until the battery voltage has dropped to 13.4 V. Switch B, on the load side, is opened if the battery voltage drops below 11.5 V (21% charged) and will remain in that state until the voltage has rebounded to 12.5 V\(^{19,20}\).

(f) Modeling of a Battery

The battery with its charge controlling function according to theory of \(^{19,20}\) has been modeled as in the Fig. 10.

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**Fig. 5.** Simulink Model of a Buck-Converter.

**Fig. 6.** PWM voltage mode control.

**Fig. 7.** Simulink model of PWM.

**Fig. 8.** Block diagram of series charge regulation.

To implement the controlling functions of Fig.8, the charge controller model has been designed as

**Fig. 9.** Charge controller implemented by Simulink/ MATLAB function.

**Fig. 10.** Simulink model of Battery block coupled with Charge Controller and Load.
III. Results of Simulation

Finally the PV module with its different components has been designed as follows:

Here the BP SX 150PV module, which contains 72 cells, has been selected to ratify the system under irradiation and temperature variation. Data sheet for the BP SX 150 provides the information of the module as in Table.1.

Table 1. Data sheet for the BP SX 150

<table>
<thead>
<tr>
<th>Electrical Characteristics</th>
<th>BP SX 150PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power (Pmax)</td>
<td>150W</td>
</tr>
<tr>
<td>Voltage at Pmax (Vmp)</td>
<td>34.3V</td>
</tr>
<tr>
<td>Current at Pmax (Imp)</td>
<td>4.35A</td>
</tr>
<tr>
<td>Warranted maximum Pmax</td>
<td>146W</td>
</tr>
<tr>
<td>Short-circuit current (Isc)</td>
<td>4.75A</td>
</tr>
<tr>
<td>Open-circuit voltage (Voc)</td>
<td>43.5V</td>
</tr>
<tr>
<td>Temperature coefficient of Isc</td>
<td>(0.086±0.015)/0°C</td>
</tr>
<tr>
<td>Temperature coefficient of Voc</td>
<td>(-160±20)/0°C</td>
</tr>
<tr>
<td>Temperature coefficient of power</td>
<td>(0.5±0.05)/0°C</td>
</tr>
<tr>
<td>NOCT</td>
<td>47±2°C</td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>600V (U.S. NEC rating)</td>
</tr>
</tbody>
</table>

(a) Output of PV Module

For a sample Temperature T=62°C, Irradiance, G=1 KW/m², Module voltage range from 0 to 39 V, the simulated IV and PV curves are shown in the Fig.12 and Fig.13 respectively.
From figure 12 and figure 13, it is conspicuous that under temperature and irradiation variation, the short circuit current and open circuit voltage of the simulated PV module is about 4.75 A and 40 V respectively, which is nearly about the value of the data sheet of the testing model and it can deliver maximum power of 126.4 W which is very close to the desired data sheet value. MPPT is able to track the operating point of the photovoltaic module at the maximum power point level and the charge controller controls the charge of the battery as it has been shown in the simulation. It can be therefore concluded that a significant amount of additional energy can be extracted from a photovoltaic module by using simple maximum power point trackers and charge controllers and efficiency can be improved for the operation of renewable energy generation systems. The improved efficiency should lead to significant power savings in the long run and at the same time provides information about the types of devices that should be chosen. In conclusion, it can be said that this simulation model will serve as a good tool to test the performance of any PV module/array under the variation of temperature and irradiance condition.

Effect of shading or partial shadows on the operation of the module and different sorts of algorithms for better MPPT could be the future work of this type of problem.

**References**


