Simulation of Photovoltaic Cell and MPPT Controllers and their Analysis
ANAND KUMAR S, K L RATNAKAR, B.S YOGANANDA, Dr. B. Rajesh Kamath

Abstract—Although solar photovoltaic technology is one of the matured technologies, its initial high cost and low efficiency have not made it fully attractive as an alternative option for electricity users. Hence it is very critical to utilize the maximum available solar power of the array and to operate the PV array at its highest energy conversion output. For this, the solar PV generating system has to operate at the maximum power output point. Since the maximum power point varies with radiation and temperature, it is difficult to maintain optimum power operation at all radiation levels. Over the years, many MPPT techniques have been advocated, developed and implemented. These methods vary in several aspects such as complexity, required number of sensors, convergence speed, cost, range of effectiveness, ease of hardware implementation etc. Although different methods have been developed by different research groups, very little literature is available, where different MPPT techniques/methods are compared in terms of energy capture, conversion efficiency, response time and reliability. This study compares the performance of different MPPT methods that are currently used in a solar PV system and also advocates a new MPPT technique which offers better performance than the existing ones. The methodology adopted for analysis is as follows: Initially, a MATLAB based solar PV array model is first developed and validated; then, different MPPT techniques are employed on this PV array under varying temperature and insolation conditions to study the effectiveness of the particular MPPT technique under consideration.

I. INTRODUCTION

The growing demand for electrical energy throughout the world has caused a great need to consider renewable energy sources as a technological option for sustainable energy supply. Among the renewable energy sources photovoltaic (PV) energy is now becoming one of the fastest growing renewable energy technologies due to continuous cost reduction and technological progress. PV is the field of technology related to the application of solar cells by converting sunlight directly into electricity.

Due to the nonlinear relationship between the current and the voltage of the PV cell, it can be observed that there is a unique Maximum Power Point (MPP) at a particular environment, and this peak power point keeps changing with solar illumination and ambient temperature. An important consideration in achieving high efficiency in PV power generation system is to match the PV source and load impedance properly for any weather conditions, thus obtaining maximum power generation. Therefore, the system needs a Maximum power point tracking (MPPT) which sets the system working point to the optimum and increases the system’s output power.

The main aim of this work is to use the solar power with MPPT technique. An attempt has been made to design solar panel with MPPT controller and DC - DC converter which switches in between buck and boost topology depending upon the input voltage and the switching signals from the MPPT algorithm. It uses a multi objective control algorithm wherein, the system is classified into various states based on operating conditions of the PV array and the load to generate the Pulse Width Modulation (PWM) pulses. By judging the state and setting the related control goal, the power will be balanced to satisfy the MPPT control.

II. SOLAR CELL

A solar cell (also called a photovoltaic cell) is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of photoelectric cell (in that its electrical characteristics e.g. current, voltage, or resistance vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source, but do require an external load for power consumption.

The operation of a photovoltaic (PV) cell requires 3 basic attributes:
1. The absorption of light, generating either electron-hole pairs.
2. The separation of charge carriers of opposite types.
III. CHARACTERISTICS OF PV CELLS

Electrical characteristics of PV cells

The voltage-current (V-I) characteristic of each solar cell is as shown in the Fig.1. The nonlinearity of the characteristic curve is due to the problem associated to extract maximum possible power from the photovoltaic (PV) cell. The Fig.1 below also shows the power-voltage characteristic curve.

While observing the P-V curve of the photovoltaic cell [2] it can be observed that there is a peak power that corresponds to a particular voltage and current. It is to make that the solar panel must be operating at a point where P-V curve is at the maximum. However, the point at which the solar panel operates keeps on changing due to changing ambient conditions such as temperature levels and insolation.

Effect of Insolation Levels

The insolation is described as the flux of radiant energy extracted from the sun and is closely related to irradiance. The power taken is in per unit area; where the intensity and spectral content varies with the position of sun, cloud cover, moisture content in the air. The amount of sunlight that is being delivered to the specific surface area over a day is being referred as insolation and is measured in kilowatt-hours per square meter per day (kWh/(m²*day)). The sun radiation should be extracted in perpendicular to the photovoltaic module in order to extract maximum amount of energy. The effects of insolation at different temperature on V-I curve of solar panel are shown in Fig. 2.

Effect of Temperature

The performance of a photovoltaic module is greatly affected by the temperature. However, it is not that much important factor as compared to the duration and the sunlight intensity. It should also be noted that the output power of the photovoltaic module decreases with increase in temperature. The temperature affects the efficiency of the photovoltaic module and normally the crystalline silicon photovoltaic module the efficiency is reduced by 0.5
percent for temperature increase by every degree Celsius. The fig .3 shows the output of solar panel with varying temperature. It can be observed that with the increase in temperature there is drop in voltage which is shown in fig.3

Fig 3: Temperature effect on solar panel V-I curves

IV. MAXIMUM POWER POINT TRACKING (MPPT)

Power output of a Solar PV module changes with change in direction of sun, changes in solar insolation level and with varying temperature as shown in the Fig .4

Fig 4: Changes in the characteristics of the Solar PV module due to change in the insolation level.

As seen in the PV (power vs. voltage) curve of the module there is a single maxima of power. That is there exists a maximum power corresponding to a particular voltage and current. We know that the efficiency of the solar PV module is low about 13%. Since the module efficiency is low it is desirable to operate the module at the maximum power point so that the maximum power can be delivered to the load under varying temperature and insolation conditions. Hence improves and maximize the utilization of the solar PV module. A maximum power point tracker (MPPT) is used for extracting the maximum power[7] from the solar PV module and transferring that power to the load. A DC-DC converter (step up/step down) serves the purpose of transferring maximum power from the solar PV module to the load. A DC-DC converter acts as an interface between the load & module shown in Fig .5

Fig.5: Block diagram of a typical MPPT system

Methods of Maximum Power Point Tracking

The maximum power is reached with the help of a dc/dc converter by adjusting its duty Cycle. Now question arises
how to vary the duty cycle and in which direction so that maximum power is reached. An automatic tracking can be performed by utilizing various algorithms.

a. Perturb and observe
b. Incremental Conductance
c. Parasitic Capacitance
d. Voltage Based Maximum Power Tracking
e. Current Based Maximum power Tracking

1. Perturb and observe
In this method the controller adjusts the voltage by a small amount from the array and measures power; if the power increases, further adjustments in that direction are tried until power no longer increases. This is called the perturb and observe method and is most common, although this method can result in oscillations of power output. It is referred to as a hill climbing method, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point. Perturb and observe is the most commonly used MPPT method due to its ease of implementation.

2. Incremental conductance
In the incremental conductance method, the controller measures incremental changes in array current and voltage to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more rapidly than the perturb and observe method (P&O). The incremental conductance method computes the maximum power point by comparison of the incremental conductance to the array conductance. When these two are the same, the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated.

Comparison of methods
Both perturb and observe, and incremental conductance, are examples of "hill climbing" methods that can find the local maximum of the power curve for the operating condition of the array, and so provide a true maximum power point. The comparison [1] is detailed in table below.

<table>
<thead>
<tr>
<th>MPPT</th>
<th>Additional power component</th>
<th>Sensor</th>
<th>Micro controller computation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>absent</td>
<td>low</td>
<td>absent/low</td>
<td>low</td>
</tr>
<tr>
<td>P&amp;Oa</td>
<td>absent</td>
<td>medium</td>
<td>low</td>
<td>low/medium</td>
</tr>
<tr>
<td>ICa</td>
<td>absent</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>ICb</td>
<td>absent</td>
<td>high</td>
<td>medium/high</td>
<td>high</td>
</tr>
</tbody>
</table>

V. MODELING AND SIMULATION
Mathematical Modeling of photovoltaic cell/ module and development of power converter using Matlab/Simulink is presented in this paper in order to simulate the basic operation of MPPT based controller.

DETAILED BLOCK DIAGRAM

Model of a photo voltaic (PV) cell
The solar cell is modeled by a current source and inverted diode connected parallel to it. It also has series and
parallel resistance as shown in Fig 6 below.

![Parallel Resistance Diagram](image)

**Fig. 7: Single diode model of a PV cell**

From the Fig 7, the output voltage (V) and current (I) of a solar cell can be expressed as:

\[
I = I_L - \{\exp(V + I_R s/\alpha) - 1\}
\]

Where, \( I_L \) is light current, \( I_0 \) is saturation current and \( \alpha \) is the thermal voltage timing completion factor of the cell.

\[
I = \{\exp(V + I_R s/\alpha) - 1\}
\]

Where,

- \( I_r_s = I_n (T/T_r)\exp\{E_G/A K (1/T_r - 1/T)\}; \)  
- \( I_p_h = S/100 \)  
- \( K_1 = \text{short circuit current temperature coefficient} \)

**MATLAB – Simulink model of PV cell/module** has been designed based on the above equations, Fig 8a shows six solar cell connected in series to make one solar array, Fig 8 b shows the six solar are connected in series to make solar panel as shown in Fig 8 c

![Solar Panel Model](image)

**Fig. 8 a: Solar cell connected in series**  
**Fig. 8 b: Solar array connected in series**  
**Fig. 8 c: solar panel model in MATLAB-SIMULINK**

The data required for modeling and simulation of solar panel and the maximum power point tracking systems will be used from the available sources in the literature. The parameters required for the photovoltaic cells can be used...
from manufacturer's datasheet. For instance, the Lorentz mono-crystalline data sheet as shown in table 1 will be used for the purpose of photovoltaic cells modeling in MATLAB/SIMULINK.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power</td>
<td>$P_{m}$</td>
<td>95W</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>$V_{oc}$</td>
<td>20.6V</td>
</tr>
<tr>
<td>Voltage at $P_{m}$</td>
<td>$V_{mp}$</td>
<td>17.2V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>$I_{sc}$</td>
<td>6.2A</td>
</tr>
<tr>
<td>Current at $P_{m}$</td>
<td>$I_{mp}$</td>
<td>5.5A</td>
</tr>
<tr>
<td>Temp coefficient for $V_{oc}$</td>
<td>$\beta$</td>
<td>-58.7 mV/°C</td>
</tr>
<tr>
<td>Temp coefficient for $I_{sc}$</td>
<td>$\alpha$</td>
<td>5.3 mA/°C</td>
</tr>
</tbody>
</table>

Table 1: Lorentz mono-crystalline specifications (1kW/m², 25°C)

Flow chart of Incremental conductance method

Comparative study on MPPT techniques shows that the incremental conductance algorithm which is used for simulation performs well under rapidly changing atmosphere conditions and has good accuracy and efficiency. Flow chart of the incremental conductance algorithm is shown in above Fig 1. The MPPT model tracks the MPP of the PV array by comparing incremental conductance with instantaneous conductance. The duty of the algorithm is to search a suitable duty cycle at which the incremental conductance equals to instantaneous conductance so that the PV system always operates at its maximum power point. MPPT block shown in Fig 10 incorporates the Simulink block of incremental conductance algorithm to generate pulses for switching the MOSFET in the buck-boost converter.

Fig 9: Flowchart of the incremental conductance method

Fig 10: Pulse generator using MPPT block
Modeling and Matlab–Simulink model for buck boost converter

Usually the output voltage of the DC-DC buck boost converter is greater than the input voltage of the converter. It is a converter operated basically by changing the switch mode to ON or OFF positions. The circuit diagram of the buck-boost converter is shown in Fig 2 below.

**Fig 11: DC-DC Buck Boost converter circuit diagram**

In Fig 11 the resistance denoted by $r_L$ and $r_C$ are the parasitic resistors of inductor $L$ and capacitor $C$ respectively. The field effect transistor (MOSFET) is usually used as the electronic switch denoted by $Q$ in Fig 12.1. In case of high power levels the power switch used is insulated gate bipolar transistor (IGBT). The property of switch should be offering low resistance when it’s ON and high resistance while it’s OFF.

### The power switch Q is turned on

With power switch $Q$ in ON position; the diode is reversed biased as shown in the Fig 2.1. The voltage across the inductor $L$ can be expressed as:

$$v_L = V_{in} - i_Lr_L$$  \hspace{1cm} (1)

Since $i = L \frac{dv}{dt}$, (1) can be modified to

$$\frac{di}{dt} = \frac{1}{L} (V_{in} - i_Lr_L)$$  \hspace{1cm} (2)

According to Kirchhoff’s current law, the current of the Capacitor $C$ can be expressed as

$$i_C = -iR = -(v_C/(R+r_C))$$  \hspace{1cm} (3)

Equation (3) can be modified as

The output voltage of the converter can be expressed as

a. $\frac{dv_C}{dt} = -v_C/(R+r_C)$  \hspace{1cm} (4)
b. $V_0 = R/(R+r_C) \cdot v_C$  \hspace{1cm} (5)

**Fig 12.1: DC-DC buck boost converter when power switch Q is turned ON**

**Fig 12.2: DC-DC buck boost converter when power switch Q is turned OFF**

With the addition of switching parameter $u$ and rearranging the equation (2), (4), (7) and (9), the derivative of $i_L$ and $v_C$ can be expressed as

$$i_L = i_C = C \cdot d(v_C)/dt + (v_C + C(dv_C/dt)r_C)/(R+r_C)$$  \hspace{1cm} (6)

$$d v_C/dt = \left(\frac{1}{(R/(R+r_C))} - \frac{1}{(R+r_C)}\right) v_C$$  \hspace{1cm} (7)

Equation (6) can be modified to

According to Kirchhoff’s voltage law, the loop of the inductor $L$ and capacitor $C$ can be expressed as

$$i_L = (d(v_C)/dt) + v_C + i_C = 0$$  \hspace{1cm} (8)

Equation (8) can be rearranged to

$$\frac{di_L}{dt} = -1/L \cdot (R/r_C + R/C + R/(R+r_C))^*i_L + R/(R+r_C)^*v_C$$  \hspace{1cm} (9)

The converter output voltage is expressed as

$$V_0 = R/(R+r_C) \cdot v_C$$  \hspace{1cm} (10)

With the addition of switching parameter $u$ and rearranging the equation (2), (4), (7) and (9), the derivative of $i_L$ and $v_C$ can be expressed as
While the DC-DC buck boost converter operates in steady state, the net change of inductor current over one period should be zero as shown below;

\[
(\Delta I)_{\text{on}} + (\Delta I)_{\text{off}} = 0
\]  

(12)

\[
V_o DT/L + (\frac{-V_0}{(1-D)T})L = 0
\]  

(13)

The output voltage can be derived from (13) and expressed as

\[
V_o = D/(1-D)*V_{in}
\]  

(14)

With \(D = t_{\text{on}}/(t_{\text{on}} + t_{\text{off}})\) = \(T/0 < D < 1\); where D is the duty ratio

The Vin and Vo in equation (14) denotes the input and output voltage of the converter respectively. In order to operate the DC-DC buck boost converter in continuous mode, the minimum capacitance and inductance required in order to generate continuous current is expressed as below;

\[
L_{\text{min}} = \frac{(1-D)^2R}{2f}
\]  

(15)

\[
C_{\text{min}} = \frac{D}{(\Delta V_o/V_o)}
\]  

(16)

With \(\Delta V_o\): output voltage ripple

**VI. MATLAB SIMULINK MODEL RESULTS**

Fig 13: output of solar panel current, voltage and power

Fig 13 shows the current, voltage and power respectively, it is observed that current value of 6 Amps starts linearly decreasing at 0.3 sec were the voltage starts increasing to 20 volts and the V-I and V-P characteristics are obtained are Shown in Fig 14 and Fig 15.

Fig .14: V-I graph of solar pane

Fig 15: V-P graph of solar panel
In Fig 17 shows that MPPT algorithm tries to track the maximum power after 0.4 seconds so that the duty ratio of the converter is changing to track maximum power point as the illumination changes and the maximum power is obtained for a particular value of irradiation.

Fig 18 shows the switching pulses given to the MOSFET of Buck-Boost converter where these switching pulses are generated by the MPPT model based on the current and Voltage values of solar panel.

The above Fig 18 shows the output across the buck-boost converter where the voltage is boosted to 95V.

VII. CONCLUSION

The modeling of photovoltaic arrays and simulations of its behavior is carried out from the data sheet as mentioned in Lorentz mono-crystalline specifications. The photovoltaic cells can be arranged in series or parallel depending upon the voltage and current to be increased.

The present work includes mathematical modeling of photovoltaic module and development of power converter using MATLAB/SIMULINK to simulate the basic operation of MPPT based DC-DC buck-boost converter. The
algorithm chosen is incremental conductance method and simulation studies performed and compared with various MPPT algorithms. The incremental conductance method has ensured maximum power point tracking is obtained by varying the duty ratio of switching pulses given to the MOSFET of buck-boost converter.

VIII. FUTURE WORK

Present simulation model can be implemented in hardware design with battery charging circuit and inverter so that it can be used for home application and also it can used for other solar power applications. The model simulation can be extended to use in a hybrid system where the microcontroller performs simultaneously the MPPT control of more than one renewable energy source.

REFERENCES


AUTHOR BIOGRAPHY

Anand Kumar S received B.E. degree in Electrical & Electronics Engineering from VTU Belgaum in 2010. He is currently studying in 4th SEM M.Tech (Computer Application in Industrial Drives) in SSIT Tumkur. Attended National Symposium and National conference in different institutions. His area of interest is power system and renewable energy sources.

K.L. Ratnakar had the privilege to get both B.Tech., and M.Tech., degrees from Jawaharlal Nehru Technological University, College of Engineering, Kakinada and stood first in M.Tech., with 85.25%. He has vast teaching experience of 30 years at undergraduate and postgraduate levels. He has presented around 20 technical papers in the national and International conferences, including one at Brisbane, Australia. He has authored a text book on “Electrical Power Transmission and Distribution” for Engineering students. His main area of interest is Power Systems and High Voltage Engineering. He has a life membership of Indian Society for Technical Education (ISTE) and The Institution of Engineers (India). Presently he is working in Sri Siddhartha Institute of Technology from December 1985.

Assistant Prof. B S Yogananda received the B.E. degree in Electrical & Electronics engineering from VTU, Belgaum in 2004 and M.Tech degree Computer Applications in Industrial Drives from VTU Belgaum in 2007. He is currently pursuing the PhD degree in in power quality and reliability. His area of interest in power quality and reliability. He is currently working as Assistant professor in Dept. of electrical and electronics SSIT, Tumkur.
Dr B Rajesh Kamath completed his B.E & M.E from national institute of engineering Mysore. Did his Phd from Dr.M.G.R University, Chennai. He has presented many papers in national and International conferences and published papers in reputed journals. His area of interest are in partial discharge measurement, Breakdown voltages in air and different gas mixtures.