CHAPTER 5

HYBRID CONTROL METHOD FOR MAXIMUM POWER POINT TRACKING (MPPT) OF SOLAR PV POWER GENERATING SYSTEM
5.1. Introduction

The actual maximum power points vary with conditions such as the surface temperature and the quantity of solar radiation (Mutoh, N et al. 2002). The efficient control of MPPT is required for an optimized efficiency of solar PV system. MPPT can be efficiently controlled using a control algorithm for the switch of the DC-DC converter in MPPT circuitry. In all the applications, it is desired that the optimized power should flow from solar PV to the load (Coelho, R.F et al. 2010). For this condition it is required to establish the operating point at maximum power point (MPP). MPPT works as an embedded system (combination of hardware and software) in which DC-DC converter works as hardware part and control algorithm acts as software part of MPPT system. This combination of software (control algorithm) and hardware (DC-DC converter) defines the efficiency of solar PV system (Coelho, R.F. et al. 2012). Many MPPTs have been designed and developed with new MPPT approaches using various control algorithms.

We present simulation results of hybrid algorithm for an improved MPPT which shows the faster convergence speed and therefore improved efficiency of the whole SPV system for power generation. We have used the boost converter in the present work.

5.2. Solar Photovoltaic (PV) Power Generating System

A typical solar PV power generating system has the following components; Solar PV module (or array for larger power), charge controller, battery, inverter (for ac loads). To maximize the efficiency of this system, MPPT is used between the solar PV module and load. To extract maximum power from the solar PV module, it is required to track the maximum power points
(MPPs) on the characteristics curves of solar PV module. Therefore to obtain the realistic characteristic curve, the solar PV module is to be characterized (modeled) using its characteristic equation. The characterization of solar PV module is described in the next section.

Figure 5.1. Solar PV Power Generating System
5.2.1. **Solar PV Module Characterization**

5.2.1.1. **Electrical equivalent of solar PV Module**

To model a solar PV cell (or module), the electrical equivalent circuit of solar PV cell is needed which is shown as in Figure 5.2. It is clear from the figure that solar cell is equivalent to a current source with a diode in parallel and two resistors ($R_{SH}$ in parallel and $R_S$ in series) are connected.

![Figure 5.2. Electrical Equivalent of Solar PV Cell](image)

5.2.1.2. **Characteristic equation of Solar PV cell**

From the equivalent circuit, it is evident that the current produced by the solar cell is equal to that produced by the current source, subtracted that which flows through the diode, subtracted that which flows through the shunt resistor (using Kirchhoff’s current law)

Where
\[ I = I_L - I_D - I_{SH} \]  \hspace{1cm} (5.1)

- \( I \) = output current (amperes)
- \( I_L \) = photo generated current (amperes)
- \( I_D \) = diode current (amperes)
- \( I_{SH} \) = shunt current (amperes).

The current through these elements is governed by the voltage across them:

\[ V_j = V + IR_s \]  \hspace{1cm} (5.2)

where

- \( V_j \) = voltage across both diode and resistor \( R_{SH} \) (volts)
- \( V \) = voltage across the output terminals (volts)
- \( I \) = output current (amperes)
- \( R_s \) = series resistance (\( \Omega \)).

By the Shockley diode equation, the current diverted through the diode is:

\[ I_D = I_0 \left[ \exp \left( \frac{qV_i}{nkT} \right) - 1 \right] \]  \hspace{1cm} (5.3)

where

- \( I_0 \) = reverse saturation current (amperes)
- \( n \) = diode ideality factor (1 for an ideal diode)
- \( q \) = electronic charge
- \( k \) = Boltzmann’s constant
- \( T \) = absolute temperature
- At \( 25^\circ C \), \( kT/q \approx 0.259 \) volts.
By Ohm’s law, the current diverted through the shunt resistor is:

\[ I_{SH} = \frac{V_j}{R_{SH}} \]  

(5.4)

where,

\[ R_{SH} = \text{shunt resistance (Ω)} \]

By substituting the equations (5.2), (5.3) and (5.4) in equation (5.1) gives the characteristic equation of a solar cell, which relates solar cell parameters (as in figure 5.2) to the output current and voltage:

\[
I = I_L - I_o \left[ \exp \left( \frac{q(V + IR_S)}{nkT} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}}
\]  

(5.5)

5.2.1.3. Characteristic curves of solar PV module

The performance of a Solar PV system depends upon the operating conditions. The maximum power extracted from solar PV system mainly depends upon the insolation and PV cell (module) temperature (ambient temperature) (Garcia, O. et al. 2013). The current-voltage and power-voltage characteristic curves for the solar PV module are simulated in MATLAB using the characteristic equation as described in the previous section. The effect of two important parameters, series resistance (R_s) and shunt resistance (R_{SH}) of electrical equivalent circuit of solar PV module is shown in Figure 5.4(a) and 5.4(b) respectively.

The variation of the I-V curve with respect to the series resistance (R_s) is represented in Figure 5.4(a). In this figure, for the minimum value (in comparison to other values of R_s) of R_s=1Ω-
cm², the I-V curve is sharpest and the saturation period of current (at 3.5 A) with respect to voltage (at 0.6 V) is more and upto 0.5 V. In the case of Rₛ=2 Ω-cm², the saturation period of same current (3.5 A) is decreased and it is upto 0.35 V. When the value of Rₛ=20 Ω-cm², then the I-V curve is changed abruptly and the curve is no more saturated. Now the starting value of current is 2.9 A and the starting value of voltage is 0.6 V.

The changes in the shape of I-V curve with the change in shunt resistance (Rₛₕ) are depicted in Figure 5.4(b). At Rₛₕ=1000 Ω-cm², the current (at 3.5 A) is saturated upto 0.48 V. When the value of Rₛₕ is reduced to 100 Ω-cm², the current is no more saturated (but almost constant) upto higher value of 0.52 V. In case, the Rₛₕ=20 Ω-cm², a sudden change in the shape of I-V curve is observed. At this instant, the current (starts at 3.3 A) decreases almost proportionally with respect to voltage upto the value of 0.57 V.

The simulated I-V and P-V curves are represented in Figure 5.3(a) and 5.3(b) respectively. The maximum power point (MPP) is at (V=21V, I=3.8A) in I-V curve and MPP is at (V=21V, P=60W) in P-V curve of solar PV module.

![Figure 5.3. (a) Simulated I-V characteristic curve of solar PV module](image1.png)

![Figure 5.3. (b) Simulated P-V characteristic curve of solar PV module](image2.png)
Figure 5.4. (a) Effect of series resistance on the I-V characteristics of solar cell

Figure 5.4. (b) Effect of shunt resistance on the I-V characteristics of solar cell

The simulated results for the I-V and P-V curve (with respect to temperature) are shown in Figure 5.5(a) and 5.5(b) respectively. In Figure 5.5(a), it is observed that as the temperature (ambient) is decreasing (from 50°C to 20°C in the interval of 10°C), the saturation interval of current is increased.

Figure 5.5(b) shows the variation of P-V curve with the change in temperature (from 50°C to 40°C, 40°C to 30°C and 30°C to 20°C), the power level is increased.
5.3. Boost Converter

A boost converter is chosen for implementing the MPPT circuitry. A boost converter [Garcia, O. et al. 2013] provides the higher voltage at output than the input voltage supplied. As per the law of energy conservation, the output current is lower than the input current.

During the On-state, the switch SW is closed, the input voltage ($V_{PV}$) is fed to the inductor. During this period the diode is reverse biased and the voltage across the inductor is $V_L = V_{PV}$.

![Figure 5.6. A typical solar PV system with MPPT (DC-DC converter and control algorithm)](image-url)
During the Off-state, the switch SW is open, therefore the inductor current flows through the load as the diode is forward biased in this condition. Now the voltage across inductor is

\[ V_L = V_{pv} - V_o \]  

(5.6)

By using the two values of voltage across the inductor during \( T_{ON} \) and \( T_{OFF} \), the relationship between input and output voltage of boost converter can be expressed as:

\[ V_o = \frac{V_{pv}}{1 - d} \]  

(5.7)

Where \( d \) is the duty cycle of the switch of the boost converter and can be defined as \( T_{ON}/T \).
5.4. **Maximum Power Point Tracking (MPPT) Control Algorithms**

There are following conditions for the most efficient operation of MPPTs.

1. In winter or in cloudy days: When there is higher demand of electric power for various needs.
2. In the low state charge of battery: When the battery withstands with a low charging status, the MPPT feeds the more current to battery.
3. In cold weather: When the ambient temperature is lower, the solar cells (modules) provide an efficient output to the load and hence MPPT works better.

Various MPPT control algorithms have been designed and developed by many researchers. The performance parameters for some popular control algorithm for MPPT are summarized in Table 5.1.
TABLE 5.1: Parameters of Various MPPT Algorithms

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Algorithm Type</th>
<th>Dependency on PV array</th>
<th>Tracking efficiency</th>
<th>Implementation level</th>
<th>Sensing parameters/ Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Incremental conductance (INC) method (D. P. Hohm and M. E. Ropp 2003; Trishan Esram and Patrick L. Chapman, 2007)</td>
<td>Not dependent</td>
<td>Good</td>
<td>Medium</td>
<td>Voltage &amp; Current</td>
</tr>
<tr>
<td>2.</td>
<td>Perturb and Observe (P&amp;O) Method (D. P. Hohm and M. E. Ropp 2003; Marcelo Gradella Villalva et al., 2009; Trishan Esram and Patrick L. Chapman, 2007)</td>
<td>Dependent</td>
<td>Good but with unstable operating points</td>
<td>Simple</td>
<td>Voltage &amp; Current</td>
</tr>
<tr>
<td></td>
<td>Method Description</td>
<td>Dependent</td>
<td>Accuracy</td>
<td>Complexity</td>
<td>Required Measurements</td>
</tr>
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<td>---</td>
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<tr>
<td>4.</td>
<td>Temperature method (Trishan Esram and Patrick L. Chapman, 2007)</td>
<td>Dependent</td>
<td>Excellent</td>
<td>Medium</td>
<td>Voltage and temperature</td>
</tr>
<tr>
<td>5.</td>
<td>Linear current control method (Marcelo Gradella Villalva et al., 2009; Moacyr A. G. de Brito, 2007)</td>
<td>Dependent</td>
<td>Not good</td>
<td>Medium</td>
<td>Irradiance/digital type</td>
</tr>
</tbody>
</table>

Apart from the above described control algorithm, the proposed hybrid control algorithm (combining constant voltage and P&O method) is also described for efficiently track the MPP throughout the day with varying insolation condition.
5.5. Proposed Hybrid Control Method for MPPT

The proposed hybrid control method combines the classical perturb and Observe (P&O) method and Constant Voltage (CV) method. This algorithm provides an easier implementation of P&O method in dynamic environmental conditions. In steady state weather conditions, the constant voltage method will be able to approximately track the MPP. P&O method operates in such a way that the output voltage is perturbed with the change in insolation and hence the maximum power is extracted from solar PV system. The CV method works on the fact that ratio of open circuit voltage and maximum power voltage is constant (i.e. $V_{MP}/V_{OC} = \text{constant}$) and ranging from 0.75 to 0.98. In this proposed hybrid algorithm, the converter is provided with the voltage closer to MPP which is a predetermined fraction of $V_{OC}$. Therefore in this manner, the MPPT tracks the MPPs faster after the logic switches over to the P&O algorithm. The disadvantage of this algorithm is that it requires the prior information about the $V_{OC}$ for implementation of CV method, before P&O method, in steady state conditions.

Here, the “Hybrid” word is used for a combined MPPT control method by using P&O method and CV method. In static (steady) weather conditions, the CV method is found to be well suited in order to track the MPPs as it works on the basis of prior information about the $V_{MP}$ and $V_{OC}$. On the other hand, in changing environmental conditions (varying solar insolation), the classical P&O (with simpler implementation) may be used as a MPPT control algorithm in order to track the MPPs.

However, the efficiency may not be fully optimized using these two classical MPPT control method, yet the performance (in terms of stability) of the overall system would be improved (by faster regulation of solar PV system parameters) with a reduced implementation complexity.
Figure 5.8. Hybrid control method for MPPT
5.6. Results and Discussion

The solar PV system with MPPT has been simulated in MATLAB/SIMULINK software. The simulated results for MPPT with control algorithm (based upon P&O and constant voltage method) are also been presented here. The results show that MPPT provides the fast convergence speed and hence higher tracking efficiency using the hybrid P&O method (with constant voltage). The simulation results of MPPT control algorithm with involved ripples are also presented.

This rapid stabilization indicates that the proposed control method is effective, efficient and able to track the MPPs in very shorter time and capable to reduce the wastage of power in solar PV system significantly.

The simulation results from 5.9.to 5.15 have been obtained in MATLAB/Simulink platform. These simulation results are based upon the proposed hybrid control method (as shown in figure 5.8) which show the stabilized regulation of solar PV system parameters within a shorter time period.

The result of the output power from solar PV module (or array) is shown in Figure 5.9. In this figure, power increases from 0 W to 1.05 W (approx.) in 2 seconds. The PV power gets constant after 2 seconds onwards. This shows the faster speed of stabilization of power with the proposed MPP tracking method.
In Figure 5.10, the variation of PV voltage (from MPPT) is shown. Here, the voltage first decreases from 0 V to -0.25 V and then increases from -0.25 to 0.65 V. After some minor oscillations the voltage stabilizes at 0.78 V (approx.) and gets constant at this value after 0.25 sec. (approx.) from initial point.
Figure 5.11 represents the variation of current which behaves almost same as voltage in the Figure 5.10. The current starts to increase from 0 A to 0.65 A in 0.12 sec. (approx.) and after some small oscillations, it stabilizes at 0.75 A in 0.25 sec. After this moment onwards, the current gets constant which also shows that the current stabilizes very rapidly which points out that the overall power of the system will be stabilized faster.

The variation of power from MPPT of solar PV system is shown in Figure 5.12. Here, the power increases from 0 mW to 600 mW in 1.5 sec. After this value, the power gets constant which shows the fast tracking of proposed MPPT method and reduced wastage of power in tracking the MPP and stabilizing the power in a very shorter time of 1.5 sec.
Figure 5.12. MPPT Power with proposed control method

Figure 5.13 depicts the variation of voltage from MPPT (with proposed hybrid control method). The voltage increases form 0 V to 725 mV (approx.) in 0.15 sec. which is very shorter time. At 0.20 sec. (approx.) the MPPT voltage gets constant after some oscillations. This result shows that the proposed control MPPT method works very efficiently with reduced time for stabilizing the MPPT voltage.

Figure 5.13. MPPT voltage with proposed control method

The variation of MPPT power with reduced frequency or increases time period is represented in Figure 5.14. Here, the power increases from 0 mW to 600 mW in 1.75 sec. Here the
variation of MPPT power is very smooth and rapid which shows the good performance of the proposed MPPT method.

The variation of PV voltage (with proposed MPPT method) is shown in Figure 5.15. The PV voltage significantly increases from 300 mV to 725 mV (approx.) in 0.05 sec. (which is very shorter time), then it reduces from this value to 0 V at 0.075 sec. Then it again increases from 0 V to 725 mV at 0.15 sec. After some minor oscillations, this value of voltage (725 mV) stabilizes at 0.25 sec. from the initial point.
Actually, the solar insolation may be in steady state condition and dynamic condition throughout the day of particular month. Therefore, hybrid control method of MPPT has been designed by considering the steady and changing weather condition. On the other hand, the previous designed MPPT algorithm (as described chapter 4) was designed for one condition (i.e. for a primarily estimated pattern of solar insolation)

For an effective and efficient operation of solar PV system, it is required to have a stabilized load voltage and load current (and hence stabilized output power). From the above presented results and corresponding discussion, it is clear that the solar PV system parameters (voltage, current and power) are regulated in shorter duration. Mainly, a new attempt has been made to couple the two simpler and previously developed MPPT control methods in order to improve the regulation (stabilization) of the solar PV system parameters. This consequently improves the operating performance of solar PV system in both steady and varying solar insolation conditions.

5.7. Conclusion

The efficiency of solar PV system is the key factor for effective utilization of these systems for power generation. We investigate a Hybrid Control (HC) method based MPPT for a typical solar PV power generating system in this chapter. For an efficient operation of MPPT for extraction of maximum possible power from solar PV module, an efficient control algorithm is the basic requirement which functions to control the DC-DC converter circuitry. Various MPPT algorithms are summarized with various performance parameters for their selection for a particular application. We simulate and implement the present Hybrid Control MPPT algorithm in MATLAB/SIMULINK environment. This algorithm combines the advantages of P&O method and constant voltage method for an improved operation of MPPT. The simulation results show that the HC algorithm provides a fast convergence of constant power
to obtain the MPP. Hence the power extracted from the solar PV module is maximized efficiently in order to increase the efficiency of the overall PV system.