CHAPTER 3

ADVANCED PERTURBATION AND OBSERVATION (P&O) BASED MAXIMUM POWER POINT TRACKING (MPPT) OF A SOLAR PHOTO-VOLTAIC SYSTEM
3.1. Introduction

Perturb and Observe algorithm have been mostly used in many MPPT design due to its easier implementation [B. Amrouche et al. (2007), L. Piegari and R. Rizzo (2010)]. As discussed by Mohammed A. Elgendy et al. (2012), P&O method is a simple algorithm that does not require previous knowledge of the PV generator characteristics or the measurement of solar intensity and cell temperature and is easy to implement with analogue and digital circuits.

In P&O method, the voltage is perturbed and final output power is measured for various perturbation stages. Further, the recorded values (of voltage and power) are compared with previous perturbation steps and varied accordingly in order to superimpose the operating point at Maximum Power Point (MPP). But the main hindrance in using this method is that it exhibits the oscillations around the MPP on the characteristic curve of solar PV module. Due to these oscillations, some output power is wasted in reaching to the MPP. The main limitation of this method is the wastage of power (energy) in searching and then reaching to MPP and hence the tracking speed is low and tracking time is high which should be inverted for an efficient and sustainable operation of solar PV system. However the development of newer and improved versions of P&O method has been of interest of researcher ever. Therefore many Maximum Power Point Tracking (MPPT) algorithms have been reported.

Femia et al. (2004) reported that, in presence of rapidly changing atmospheric conditions, the Perturb and Observe (P&O) maximum power point tracking (MPPT) algorithm can be confused due to the fact that it is not able to distinguish the variations of the photovoltaic array output power caused by the duty cycle modulation from those ones caused by the irradiance variation. They have shown that the negative effects associated to such a drawback can be greatly reduced if the magnitude of the duty cycle perturbations is customized to the dynamic
behavior of the specific dc-dc converter adopted to realize the P&O MPPT. Liu and Lopes (2004) suggested an improved P&O method that can mitigate the main drawbacks commonly related to the P&O method. This is achieved with peak current control, small perturbation values and sampling of instantaneous values, instead of averaged, to speed up the system response and reduce the oscillations around the Maximum Power Point (MPP). Femia et al. (2004) also reported that the efficiency of the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) control technique can be improved by optimizing its sampling interval according to the converter's dynamics.

Femia et al. (2009) reported an improved P&O MPPT technique by using a compensation network for cancelling out the PV voltage oscillations. Elgendy et al. (2012) investigated the reference voltage perturbation and direct duty ratio perturbation technique on the basis of system stability, performance characteristics, and energy utilization for standalone PV pumping systems. Liu et al. (2009) reported a new combined perturb and observe (P&O) method is described an improved P&O maximum power point tracking method which is based on the actual diode factor (n) and dark current (Io), and the tracking speed is rapid to compare with the conventional P&O method. Ju-Hui et al. (2011) analyzed that the conventional MPPT control is unable to perform when output is rapidly changing by shadow influence. To solve this problem, the new control algorithm of the multi level Perturb and observe (MLPO) in which the step value changes by output change is presented. Abdelsalam et al. (2011) presented a modified P&O MPPT technique which achieves: first, adaptive tracking; second, no steady-state oscillations around the MPP; and lastly, no need for predefined system-dependent constants, hence provides a generic design core. Piegari and Rizzo (2010) reported an adaptive P&O method for rapidly changing weather conditions which proposed the faster dynamics and improved stability of MPP as compared to the traditional P&O. Amrouche et al. (2007) discusses the drawbacks of conventional P&O such as slow response speed, oscillation around the MPP in steady state, and even tracking in wrong way under rapidly changing atmospheric conditions. In this chapter, it is shown that the negative effects associated to such a drawback can be greatly reduced if the Artificial Intelligence (AI) concepts are used to
improve P&O algorithm. The perturbation step is continuously approximated by using artificial neural network (ANN).

3.2. Solar PV System Description

3.2.1. PV System with MPPT

A typical Photovoltaic (PV) system consists of a PV module and some electrical load. This may also have a Power conditioning unit (PCU) which may comprise of a Inverter (to convert dc into ac), charge controller (to prevent reverse flow of current during dark) and most importantly from the efficiency point of view the Maximum Power Point Tracker (MPPT).

![Block diagram of PV system with MPPT](image)

Figure 3.1. Block diagram of PV system with MPPT
Basically the main problem in tracking the maximum power points (MPPs) using the Perturb and Observe (P&O) method on the characteristic curves solar PV module or cell is that the operating point fluctuates around the MPP as solar insolation varies. The oscillations of operating point (around MPP) have been reduced using the advanced Perturb and Observe as the perturbation steps have been increased and operating point gets stabilized. Consequently the efficiency of the solar PV system has been increased and the performance of overall system is improved.

### 3.2.2. Simulated PV Characteristic Curves

The characteristic curves are represented as Current-voltage (I-V) curve and Power-voltage (P-V) curve which are nonlinear in nature and shown as in Figure 3.2.
The characteristic curves of PV module have been simulated in MATLAB and MPP is also indicated on these curves.

### 3.3. Boost Converter

A boost converter is usually chosen due to its better performance and also simplicity in simulation. The boost converter provides the higher output than input as per the following formula:

\[
V_{\text{out}} = \frac{V_{\text{in}}}{1-D}
\]  

(3.1)

Where \( D \) is the duty cycle of the boost converter. The \( D \) is being controlled by PWM output of the proposed algorithm.

The duty cycle of the boost converter is controlled in accordance with the varying solar insolation by using a controller algorithm. In this chapter the advanced P&O method is being used to accurately track the MPP with minimum possible oscillations of operating point around maximum power point (MPP). The PWM output of the proposed algorithm is found to be able to track the MPP with higher stability of operating point and hence higher efficiency of the PV system.
An ideal boost converter is lossless in terms of energy, so the input and output power are equal. In practice, there will be losses in the switch and passive elements, but efficiencies better than 90% are still possible through careful selection of system components and operating parameters such as the switch frequency.

3.4. P&O Algorithm

The P&O algorithm is a cost effective and with less complexity for MPPT control. In P&O method, the present value of the PV output power is calculated and compared with the past value which gives the difference the power i.e. $P_{\text{Present}} - P_{\text{Past}}$ ($\Delta P$). If $\Delta P$ is greater than zero than the same operation continues for further perturbation otherwise it moves in the reverse direction. The flow chart shows the various steps of the P&O algorithm.

The main drawback of P&O algorithm is that the operating point of PV panel oscillates around maximum power point (MPP) i.e. unstable MPP. To minimize the oscillations of the operating point or to enhance the stability, it is required to increase the tracking speed of the MPPT by
using improved algorithm. Due to the unstable maximum power point (MPP) and thereby higher oscillations of operating point around MPP, the power is wasted before reaching to the MPP. Therefore the efficiency of the solar module for generating power gets reduced and therefore using the advanced P&O algorithm is used by introducing the more number of perturbation and observation steps to reach to MPP without wasting power in oscillation of operating point around MPP. The flowchart for classical P&O algorithm has been represented in Figure 3.4.

Figure 3.4 Conventional P&O Algorithm flowchart
3.5. Advanced P&O Algorithm

We propose an advanced and even more improved version of P&O algorithm for MPPT. In this method, the number of stages of perturb and observe (P&O) are increased by (k-1) to (k-2) & (k-3). By doing so, the tracking speed of the MPPT controller may be increased. We can understand this mechanism as in the case of a characteristic curve of a device like diode or thyristor, if the readings (number of point on the graph) are more, the characteristic curve would be more accurate.

In this approach, the present values of voltage and current (and hence the power) is calculated at some instant of time and compared with the corresponding past values of voltage and current. Then the values of voltage are changed corresponding to the compared values of voltage according to the proposed algorithm.

In this algorithm,

- first of all, the \( n^{\text{th}} \) values of voltage \( V(n) \) and current \( I(n) \) are measured
- then nth value of power \( P(n) \) is measured by taking the product of \( V(n) \) and \( I(n) \).
- further three past consecutive values of difference of power [i.e. \( P(n-1)-P(n-2); P(n-2)-P(n-3); P(n-3)-P(n-4) \)] are calculated as in the earlier case.
- now, the corresponding differences in the values of voltage [\( V(n-1)-V(n-2); V(n-2)-V(n-3); V(n-3)-V(n-4) \)] are calculated.
- then the proposed algorithm further depicts as explained follows:
  - if the past value of power is greater than the present value and also the past value of voltage is greater than the present value (both cases are Yes/No) then the voltage is decreased by a value of \( dV \) otherwise in the case when, the past value of power is not greater than the present value and also the past value of voltage is not greater than the present value (either case is Yes/No) then the voltage is increased by a value of \( dV \).
The main difference between the conventional P&O algorithm and proposed advanced P&O algorithm is that the proposed algorithm perturbs and observes for more number of cycles (hence higher perturbation frequency) which provides more accurate and highly precise control of voltage. This precise control of voltage from solar PV module determines the most probable MPP on the characteristic curve of the solar PV module. This, in turn, ensures the higher efficiency and optimal operation of the overall solar PV system.

Consequently the performance of the P&O algorithm may be improved in terms of better stability of Maximum Power Point (MPP) and hence the higher efficiency of the solar photovoltaic (SPV) system used for electricity generation. Figure 3.5 shows the flow chart for the presented algorithm. The results for variation of various parameters of DC-DC converter (boost converter in this case) are also presented.

Therefore, the proposed algorithm has not been implemented in the boost converter here. It is approached here that with a higher number of perturbation and observation stages would improve the performance of the MPPT which is to be employed in a solar PV system. It is expected on the fact that a large set of data for any two dimensional curve would have been able to improve the preciseness and accuracy of the curve.
Figure 3.5 Advanced P&O algorithm flowchart
3.6. Results and Discussion

We present simulation results of the variation of the various voltages and currents of boost converter including waveforms for voltage (u1), output voltage (u2), switch (IGBT) voltage (uS), inductor current (I_L), capacitor current (I_C) and gate pulses in this section. The results have been carried out in Gecko-CIRCUITS (power electronic simulation software).

Gecko-Circuits is power electronic simulation software in which different DC-DC converter and other power electronic converters can be simulated. This software is basically designed and developed by ETH, Zurich, Switzerland. This software works with a pick and drop environment of various components to design a specified power converter. This software provides an easier circuit implementation and faster simulation response speed.

The circuit of boost converter, designed by us in Gecko-Circuits, is described in the following points:

Basically boost converter is a DC-DC converter which gives a higher output DC voltage from a lower input DC voltage. The main role of boost converter is to provide the necessary voltage to solar PV system in order to reach MPP. The operation of the power electronic switch, used in boost converter, is controlled by a MPPT algorithm. In this chapter, we mainly present the variation of voltage and current (i.e. output voltage, capacitor current, inductor current) possessed by the circuit components of designed boost converter. The results presented here are only intended to show the generalized behavior of boost converter for an initial understanding of the variations of electrical parameters (voltage and current) of a boost converter.

In the present study (Figure 3.6), an inductor (300e^6 H), a power semiconductor switch (IGBT), a diode (D1), a capacitor (C=10e^-6) and a load resistance of 10
ohms have been used. When switch is ON or short circuited (using gate triggering by providing the pulses at gate terminal of IGBT), the energy \( E_L = \frac{1}{2} L i^2 \) is stored in inductor. During the OFF condition (open circuit) of the switch, the stored energy is fed to load along with the input DC voltage \( V_{dc} \) as added inductor voltage \( V_L \).

Now the total voltage appears across the load will be equals to \( V_{dc} + V_L \) which is more than dc input voltage.

The presented boost converter provides the circuit configuration with various components used (i.e. solar cell, inductor, IGBT as a switch, diode, capacitor and load). Therefore, the different parameters used in this circuit are not chosen as a matter of choice but to study the basic operation of a boost converter (i.e. variation of voltages and currents). Therefore, it is evident that the simulation results does not show the solar cell regulation with proposed algorithm but it only shows the behavior of voltage and current of boost converter. However, when this boost converter, implemented in a solar PV system with a MPPT algorithm, the input voltage \( U_1 \) would be functioning as solar cell voltage. Therefore, in that case the voltage of solar cell (or PV array for larger output) must be regulated.

![Figure 3.6 Simulated Boost Converter Circuit](image)
Figure 3.7 Simulation Results for Boost converter circuit [Figure 3.7 (a) represents the regulation of output voltage (u2 waveform in pink colour) of boost converter]
Figure 3.8 Simulation Results for Boost converter circuit (zoom in)
The input voltage \(u_1\) and output voltage \(u_2\) of simulated boost converter are plotted in Figure 3.7 (a). The input voltage \(u_1\) is constant throughout the time with the value of 12.5 V. The output voltage \(u_2\) starts to increase from 0 V and stabilizes (with some oscillations) at 35 V after 700 e\(^{-6}\) secs. Figure 3.7 (b) shows two parameters i.e. input voltage \(u_1\) and switch voltage \(u_S\). The input \(u_1\) is constant as in figure 3.7 (a). The switch is parallel to the output load therefore the envelope of switch voltage is same as that of output voltage \(u_2\) but here the oscillations are very high from peak (35 V) to ground (0 V). The variation of inductor current \(I_L\) is shown in Figure 3.7 (c) which depicts that the inductor current fastly increases and stabilizes at 10 A after 500 e\(^{-6}\) from initial point. Figure 3.7 (d) shows the changes in capacitor current \(I_C\) which indicates that the current changes (oscillates) from the peak value of 7.5 A (approx.) to -3.5 A (approx.). Sequence of gate pulses are shown in Figure 3.7 (e).

The variation of various voltages and currents is shown in a detailed manner in Figure 3.8 by decreasing the frequency of waveforms. It is evident from this figure the variation of voltages and currents associated with input \((V_1)\), output \((V_2)\), switch \((V_S)\), inductor \((I_L)\) and capacitor \((I_C)\). In Figure 3.8 (a), the signal for output voltage \(V_2\) is shown (in blue colour) as the fast charging and discharging case of inductor connected in series with the input DC voltage source. The input DC input voltage \(V_1\) is shown (in red colour) as constant. Figure 3.8 (b) shows the two signals i.e. one is for input voltage \(V_1\) and another for switch voltage \(V_S\). When the switch is ON (closed), the voltage across the switch is zero, as the switch is OFF (opened), the voltage across the switch gets appear (increasing) for a period of OFF condition of the switch. The voltage across the switch is shown in grey colour and the input voltage is constant and shown in red colour. The variation in inductor current \(I_L\) is depicted in Figure 3.8 (e). Inductor current exponentially increases as the inductor charges when the switch is ON (close). This current exponentially decreases when switch is OFF (open) as shown in the figure. Inductor current is shown in green colour. Figure 3.8 (d) represents the variation of capacitor current \(I_C\) . This current increases slowly from initial point to the instant up to the switch is ON. After this instant,
this current goes high within a very short period of time. When the switch is OFF, $I_c$ starts to decrease slowly (but not as much as earlier) until the switch is in OFF condition. It again goes low (as earlier high) within a very short period of time. The capacitor current ($I_c$) is represented in pink colour.

3.7. Conclusion

Actually, the variations of boost converter parameters are shown in this chapter for the initial study of DC-DC converter as a part of a MPPT system. A modified P&O algorithm (with increased perturbation steps) is also proposed in this chapter. We have simulated a boost converter and presented the obtained results in this chapter. The better performance of the boost converter is identified. The output voltage of boost converter is stabilized with faster regulation. The inductor current and capacitor current also gets regulated faster for ensuring a stabilized operation of the boost converter for implementation of an improved MPPT. We have designed the present algorithm with increased number of perturbation steps in order to decrease the oscillations around MPP. This increases the preciseness of the MPP, reduces the wastage of power in finding the exact MPP, lower tracking time and hence optimized efficiency. As the study carried out in this chapter was a starting research of PhD work, so algorithm was not implemented (in this chapter) but proposed only a modified P&O algorithm with basic understanding of boost converter parameters for further implementation. Therefore, the obtained results are shown in order to learn the behavior of boost converter parameters for subsequent implementation of MPPT algorithms in preceding chapters.