An Improved Incremental Conductance Algorithm for Enhancing the MPP of a Solar PV panel under various Atmospheric Conditions

V.Navya[1], V.Nirmala Devi[2]
[1]M Tech student of Dr KVSRIT, KURNOOL, INDIA.
[2]HOD & Associate Professor, Department of EEE, KVSRIT, KURNOOL,INDIA.

ABSTRACT

The control strategy ensures that the solar PV panel is always perpendicular to sunlight and simultaneously operated at its maximum power point (MPP) for continuously harvesting maximum power. The proposed control strategy is the control combination between the solar tracker (ST) and MPP that can greatly improve generated electricity from solar PV systems. Recording the ST system, the paper presents two drive approaches including open-loop and closed-loop drives. Additionally, the paper also proposes an improved incremental conductance algorithm for enhancing the speed of the MPP tracking of a solar PV panel under various atmospheric conditions as well as guaranteeing the operating point always moves toward the MPP using this proposed algorithm. The simulation and experimental results obtained validate the effectiveness of the proposal under various atmospheric conditions.

Keywords— Maximum power point tracker (MPPT), solar tracker (ST), solar PV panel.

I. INTRODUCTION

As solar power increases in popularity, the need for this power to become more efficient is evident. Clean, renewable energy sources are becoming more desirable throughout the world, and solar power provides this. Unfortunately, solar energy is not as efficient as traditional energy sources such as coal, but electronics can be used to create more stable and efficient sources to offset the problems associated with using solar panels. The problem that arises is that many of these electronics are quite expensive, and do not necessarily work well outside of a larger system. These systems are often very complex, and not easily repaired or modified. To fix the problem of price and complexity, a low cost, easy to use electronic system can be created to better provide solar power. Making this system simple to modify, economical, and repairable is a necessity, especially if it is to be deployed in rural or developing areas. By creating a streamlined, hardy device, solar power can be made more readily available and affordable than conventional energy use. The first step in developing the Maximum Power Point Tracker was to decide the type of solar panel and battery it would be connected to.

It is very important with photovoltaic generation to operate the system at high power efficiency by ensuring that, the system is always working at the peak power point regardless of changes in load and weather conditions. In other words, transfer the maximum power to the load by matching the source impedance with the load one. To confirm that, an MPPT system has been implemented which enables the maximum power to be delivered during the operation of the solar array and which tracks the variations in maximum power caused by the changes in the atmospheric conditions.

As the solar panel outputs power, its maximum generated power changes with the atmospheric conditions (solar radiation and temperature) and the electrical characteristic of the load may also vary. Thus, the PV array internal impedance rarely matches the load impedance. It is crucial to operate the photovoltaic generation system at the MPP or near to it to ensure the optimal use of the available solar energy. The main objective of the MPPT is to match these two parameters by adjusting the duty ratio of the power converter. As the location of the MPP on the I-V curve varies in an unpredictable manner it cannot be defined beforehand due to changes of irradiation and PV panel temperature. Accordingly, the use of MPPT algorithm or calculating model is required to locate this point.

There are several methods to track the MPP of the photovoltaic system that have been carefully studied, developed and published over the last decades. There are variations between these techniques in terms of, simplicity, sensor requirements, cost, range of efficiency, convergence speed and hardware implementation. Some MPPT algorithms outperform the others under the same operating conditions.

A. Literature survey

Solar energy is one of the most important renewable energy sources. As opposed to conventional resources such as gasoline, coal, etc..., solar energy is clean, inexhaustible and free. The main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic and street lighting, electric vehicles, military and space applications) [1-2] or grid-connected configurations (hybrid systems, power plants) [3].

Unfortunately, PV generation systems have two major problems: the conversion efficiency of electric power generation is very low (9÷17%), especially under low irradiation conditions, and the amount of electric power generated by solar arrays changes continuously with weather conditions.

Moreover, the solar cell V-I characteristic is nonlinear and varies with irradiation and temperature. In general, there is a unique point on the V-I or V-P curve, called the Maximum Power Point (MPP), at which the entire PV system (array, converter, etc…) operates with maximum efficiency and produces its maximum output power. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Therefore Maximum Power Point Tracking (MPPT) techniques are needed to maintain the PV array's operating point at its MPP.

Many MPPT techniques have been proposed in the literature; examples are the Perturb and Observe (P&O) methods [4-7], the Incremental Conductance (IC) methods [4-8], the Artificial Neural Network method [9], the Fuzzy Logic method [10], etc... These techniques vary between them in many aspects, including simplicity, convergence speed, hardware implementation, sensors required, cost, range of effectiveness and need for parameterization. The P&O and IC techniques, as well as variants thereof, are the most widely used.

The MPP is not known on the V-I or V-P curve, and it can be located by search algorithms such as the perturbation and observation (P&O) algorithms [7]–[12], the incremental conductance (InC) algorithm [13], [14], the constant voltage (CV) algorithm [15], [16], the artificial neural network algorithm [17], [18], the fuzzy logic algorithm [19], [20], and the particle swarm optimization algorithm [21]–[24]. These existing algorithms have several advantages and disadvantages concerned with simplicity, convergence speed, extra-hardware and cost. This thesis proposes an improved InC algorithm for tracking a MPP on the V-I characteristic of the solar PV panel. Based on the ST and MPPT, the solar PV panel is always guaranteed to operate in an adaptive and optimal situation for all conditions.

II. PROBLEM FORMULATION

One of the major concerns in the power sector is the day-to-day increasing power demand but the unavailability of enough resources to meet the power demand using the conventional energy sources. Demand has increased for renewable sources of energy to be utilized along with conventional systems to meet the energy demand. Renewable sources like wind energy and solar energy are the prime energy sources which are being utilized in this regard. The continuous use of fossil fuels has caused the fossil fuel deposit to be reduced and has drastically affected the environment depleting the biosphere and cumulatively adding to global warming.

Solar energy is abundantly available that has made it possible to harvest it and utilize it properly. Solar energy can be a standalone generating unit or can be a grid connected generating unit depending on the availability of a grid nearby. Thus it can be used to power rural areas where the availability of grids is very low. Another advantage of using solar energy is the portable operation whenever wherever necessary.

In order to tackle the present energy crisis one has to develop an efficient manner in which power has to be extracted from the incoming solar radiation. The power conversion mechanisms have been greatly reduced in size in the past few years. The development in power electronics and material science has helped engineers to come up very small but powerful systems to withstand the high power demand. But the disadvantage of these systems is the increased power density. Trend has set in for the use of multi-input converter units that can effectively handle the voltage fluctuations. But due to high production cost and the low efficiency of these systems they can hardly compete in the competitive markets as a prime power generation source.

The constant increase in the development of the solar cells manufacturing technology would definitely make the use of these technologies possible on a wider basis than what the scenario is presently. The use of the newest power control mechanisms called the Maximum Power Point Tracking (MPPT) algorithms has led to the increase in the efficiency of operation of the solar modules and thus is effective in the field of utilization of renewable sources of energy [3], [8].

The objective would be to develop MPPT and successfully implement the MPPT algorithms using the Simulink models. Modeling the photovoltaic and interfacing with the MPPT algorithm to obtain the maximum power point operation would be of prime importance. Detailed simulations to support the same have been carried out in MATLAB, and the results are presented.

III. MAXIMUM POWER POINT (MPP) TRACKING

In this Chapter, two of the most prevalent MPPT algorithms, perturb and observe as well as incremental conductance, were used to control the converter and solar panel so that the panel operated at its MPP. The logic within these algorithms determines the state of the solar panel's power in relation to its voltage and then decides how to modify the control parameters in order to find the MPP. Once the algorithm determines what needs to be done, there are several variables that can be controlled to force the system to the MPP. For maximum power transfer, the load should be matched to the resistance of the PV panel at MPP. Therefore, to operate the PV panels at its MPP, the system should be able to match the load automatically and also change the orientation of the PV panel to track the Sun if possible (Sun tracking is usually left out of most systems due to the high cost of producing the mechanical tracker). A control system that controls the voltage or current to achieve maximum power is needed. This is achieved using a MPPT algorithm to track the maximum power.

A controller that tracks the maximum power point locus of the PV array is known as a MPPT controller. There are several algorithms to track the MPP and a few common maximum power point tracking algorithms have been reviewed. For optimal operation, the load line must match the PV arrays MPP locus and if the particular load is not using the maximum power, a power conditioner should be used in between the array and the load.

Some of the frequently discussed MPPT techniques in the literature are as follows:

1. Fractional short circuit current (I_{sc}), a current based MPPT
2. Fractional open circuit voltage (V_{oc}), a voltage based MPPT
3. Perturb and Observe (P&O) /Hill climbing
4. Incremental Conductance Technique (ICT)
5. Constant Reference Voltage(CRV)

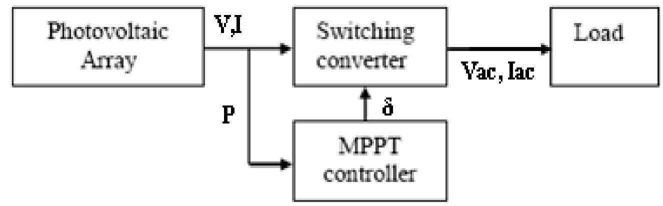

Fig.3. 1: Basic MPPT system

Advantages of the MPPT approach

1. Only one ac current sensor is required to sense ac inverter current output for MPPT purpose in a balanced three-phase system.
2. No dc sensors required, nor multiplier required revealing the power in digital control. This simplifies algorithm and computation.
3. Since no voltage (no power) measurement is required, this avoids additional software filtering for the oscillating PV voltage.
4. For a three-phase system, a sensor of smaller rating is required compared to the conventional method as whole dc power is not measured, instead ac current in one of the phases (which reflects ac power) is sensed, which is small.

A. Perturb and Observe

Perturb and observe is probably the most commonly utilized MPPT method [24]. The basic premise for P&O is to continually perturb or alter the power converter's operating point and then to observe or sense the ensuing effects. In other words, the settings within the converter are changed so that the solar panel's voltage and current are changed. Then, the system senses the panel's voltage and current to see if its power has increased or decreased. Subsequently, the algorithm makes a decision on how to further adjust the converter's settings. Typically, the settings that are modified are either a reference voltage or the duty cycle.

In Fig.3.1, the P&O flowchart is presented in order to understand the finer details of this algorithm. As one can see from Fig.3.1, the algorithm reads in the voltage measurements V[k] and the current measurements I[k] at a specified time interval called the MPPT period. This time interval governs how often the algorithm makes a decision to change the operating point of the system.

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Subsequently, the algorithm calculates the power P[k], the change in power ΔP, and the change in voltage ΔV. The ΔP and ΔV values are found by using the measurements at the present moment V[k] and I[k] as well as the previous measurements V [k-1] and I [k-1]. From there, the algorithm uses basic logic in order to decide what to do. The ΔP and ΔV values are each compared against zero to determine if they have increased or decreased.

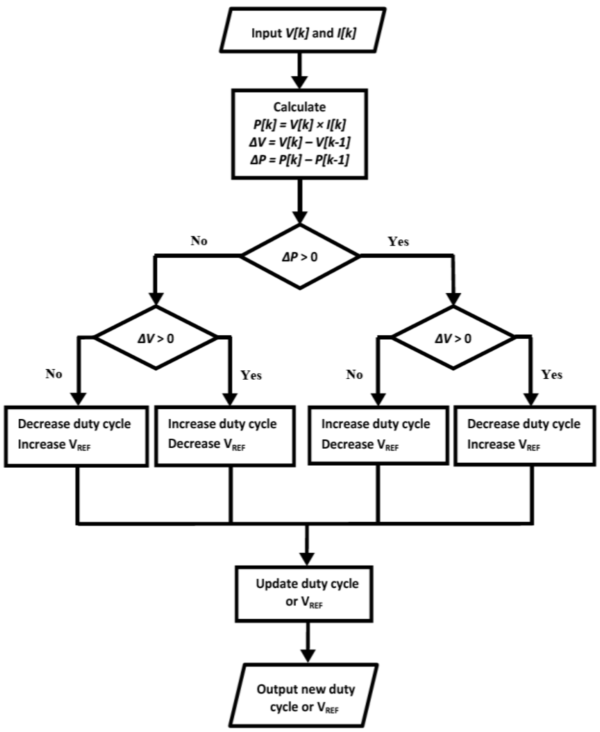

Fig.3.2: Perturb and observe flowchart

P&O and Hill climbing use the same fundamental strategy. The duty ratio is the perturbation in hill climbing, while the voltage of the PV module is the perturbation for the P&O. Changing the value of the duty cycle causes a change to the current and as consequence, perturbs the voltage array. To summarize, if the power goes up after a certain perturbation, then the next perturbation should remain unchanged; however, if the power goes down, then the ensuing perturbation should be in the opposite direction.

Utilizing the P&O algorithm has several benefits. For one, it is a reliable approach to MPPT, which means that it finds the MPP in almost all circumstances. Also, it is relatively simple and easy to implement [25]. Additionally, it does not require a lot of logic or computational calculations when compared to other methods; however, it does require two sensors – one for the voltage and one for the current [25]. On the other hand, there are a few shortcomings of the P&O MPPT method. For one, this MPPT algorithm always oscillates about the maximum power point and is never truly stable at the MPP [22], [25], [26]. This may result in a reduced amount of power that can be generated by the system [22], [26]. Furthermore, P&O may command the wrong perturbation during rapidly changing solar irradiance conditions.

Assume the solar irradiance rapidly increases to 1000 W/m^2 prior to the next MPPT decision. This causes the algorithm to sense that both the power and the voltage have increased, as is shown by the transition from one point to another point. Consequently, the algorithm commands the system to increase the voltage. The P&O algorithm quickly recovers from this situation after one MPPT period provided the solar irradiance does not change again. Nevertheless, these circumstances cause the P&O algorithm to take extra time to find the new MPP, and some energy that could have been harvested is lost.

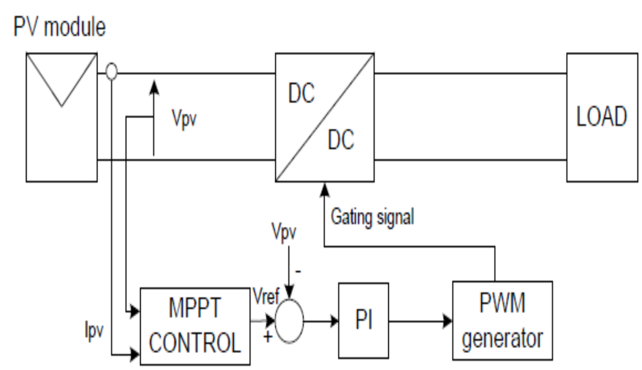

Fig. 3.3: Block diagram of MPPT with P&O

In Fig.3.3, the voltage and current are measured and the MPPT controller determines the voltage reference. The input for the regulator PI is the difference of the V_{ref} and V_{pv}. The voltage regulated generates the PWM for the converter.

In Fig. 3.4, it can be observed that incrementing the PV voltage increases the power of the PV and decrementing the PV voltage decreases the power of the PV when operating on the left of the MPP. On the right of MPP, incrementing the voltage decreases the power and decrementing the voltage increases the power. This process will be implemented in the MPPT controller to extract the maximum power from the PV module

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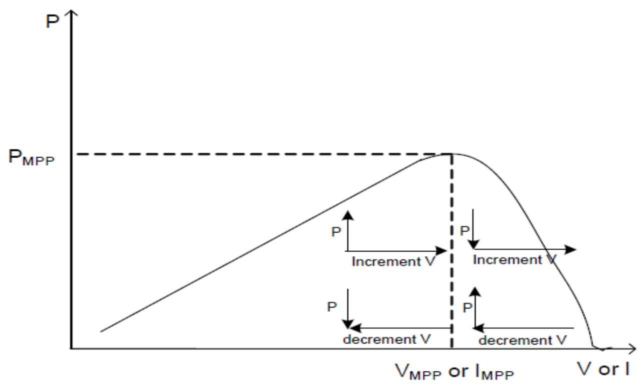

Fig.3.4: Principle of P&O

The system oscillates around the MPP with this method. The process of incrementing and decrementing can fail under rapid change in irradiation. The system diverges away from MPP if the irradiance increases suddenly. To remedies those problems, improved methods of perturb and observe are used: reduced perturbation step size, variable step size, three point's weights comparison methods and optimized sampling rate.

The performance of the Perturb and Observe depends on the sampling interval and the duty-cycle perturbation of the algorithm. Those parameters set "the dynamic response of the MPPT, such as speed, accuracy and stability". The duty cycle step must be chosen properly. Since the Perturb and Observe technique oscillates around the maximum power point, reducing the duty cycle step can minimize the oscillation and the steady state losses. However, the controller is less efficient when the atmospheric conditions change rapidly.

The other parameter to consider is the sampling interval of the algorithm. Higher sampling interval can cause instability. The maximum power can be missed between sampling interval if the perturb and observe algorithm samples the PV voltage and current too quickly. The sampling interval of the algorithm should be set as small as possible without causing oscillation of the system and the divergence away from the MPP. Otherwise, the instability will reduce the efficiency of the PV.

B. Incremental Conductance

The Incremental conductance method eliminates the drawbacks of the Perturb and Observe method. It uses the advantage that the derivate of the power with respect to the voltage at the maximum power point is zero. Furthermore the derivative at the left of the MPP is greater than zero and less than zero to the right of the MPP.

The main idea behind the incremental conductance algorithm is that one is trying to drive *dP/dV* to zero in order to reach the maximum power point. First, one must recognize that the solar panel's power *P* is just its voltage *V* times its current *I*, and its current is a function of its voltage.

The following set of equations describes the incremental conductance algorithm:

$$P = V \times I \tag{3.1}$$

Deriving Equation 3.1 with respect to *V*:

$$\frac{dP}{dV} = \frac{d(V \times I)}{dV}$$

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV}$$

$$\frac{dP}{dV} = I + V\frac{dI}{dV} \tag{3.2}$$

Since it is known that:

$$\frac{dP}{dV} = 0 \tag{3.3}$$

At the MPP, combining Eqn (3.2) and Eqn (3.3) and substituting $\frac{I}{V} = G$, with G being the conductance, the following relationship is established:

$$\frac{dI}{dV} = -\frac{I}{V}$$

$$\frac{dI}{dV} = -G \tag{3.4}$$

If the incremental changes d*V* and d*I* are approximated by comparing the most recent measured and approximated to

$$dV(k) \approx V(k) - V(k-1)$$

$$dV(k) \approx \Delta V$$

And

$$dI(k) \approx I(k) - I(k-1)$$

$$dI(k) \approx \Delta I$$

Finally the algorithm can be summed up in the following set of equations.

$$\frac{dP}{dV} > 0, \rightarrow G > \Delta G \tag{3.5}$$

$$\frac{dP}{dV} = 0, \rightarrow G = \Delta G \quad (3.6)$$

$$\frac{dP}{dV} < 0, \rightarrow G < \Delta G \quad (3.7)$$

The incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationships describes in Eqn (3.5) and Eqn (3.7).

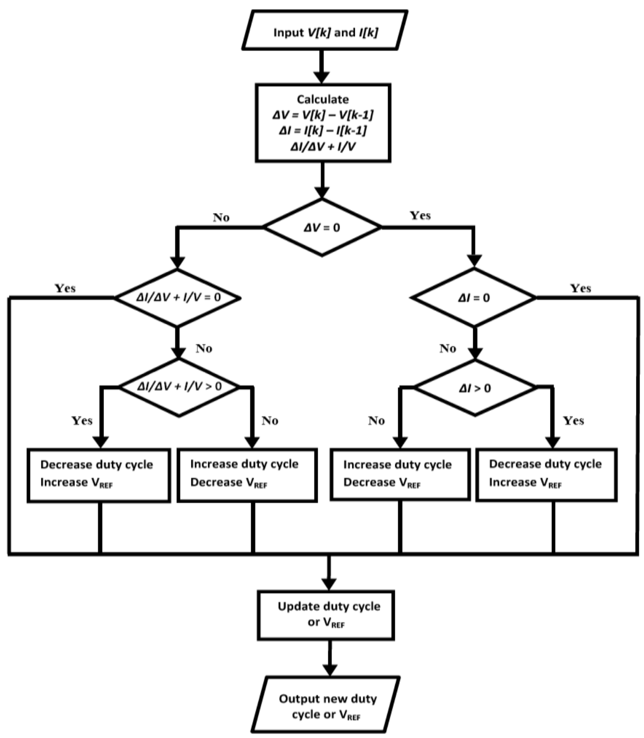

Fig.3.5: flowchart of Incremental conductance

The Fig. 3.5 shows the algorithm of incremental conductance. This algorithm has advantages over perturb and observe. One of them is that it is able to determine when the MPPT has reached the actual MPP and stop searching, whereas perturb and observe oscillates around the actual value of the MPP. Also, incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher accuracy than perturb and observe. One disadvantage of this algorithm is the increased complexity when compared to perturb and observe.

During various studies [14] and [15] after conducting several experiments they concluded that the condition in Eqn (3.4) does not occur very often.

A simple solution was added and implemented by adding a small margin of error (tolerance) to Eqn (3.4) so it is modified to:

$$\left|\frac{dI}{dV} + \frac{I}{V}\right| \leq \varepsilon \quad (3.8)$$

The INC method is based on the principle that the derivative of the PV array power curve is zero at maximum power point (MPP), i.e. the slope of the power curve is zero(dp/dV=0). The slope of power curve is positive on the left of the MPP and negative on the right.

In this method, the PV model operates at maximum power when the Voltage reference V_{ref} is reached. When there is a variation of the irradiation or the temperature, the current ΔI changes and then the MPP.

Once the $I/V + \Delta I/\Delta V$ calculation is within the threshold, the algorithm commands the system to stop changing the voltage and current for one MPPT period. If after that MPPT period the algorithm determines that the ΔV and ΔI are both zero, then the algorithm keeps the system operating at that point. Practically, ΔV or ΔI is never exactly zero for the reasons mentioned earlier. When determining if ΔV or ΔI is equal to zero, it is necessary to utilize another threshold. This threshold is a small value that is sufficiently close to zero but allows for small deviations due to noise and measurement errors.

Additionally, when the ΔV is close to zero, then the $I/V + \Delta I/\Delta V$ calculation may be abnormally large. Typically, this occurs when ΔI is also small but slightly larger in magnitude than ΔV due to noise; however, faulty calculations can take place in other circumstances. For instance, erroneous calculations may take place due to biases in the measurements. The bottom line is that this can cause some problems for the control algorithm; hence, it is necessary to offer a logical alternative in this case. That is why the algorithm first asks if ΔV equals zero. If ΔV is large enough, then the $I/V + \Delta I/\Delta V$ calculation is used to find the MPP. If ΔV is small enough to be considered zero, then the alternate logic path is taken. Then the algorithm checks if ΔI is close enough to zero. If it is, the system does not change its settings. If ΔI exceeds its threshold due to a change in irradiance or random noise, then the system is perturbed according to the $\Delta I > 0$ logic.

Primarily, the alternate logic path exists to account for changing irradiance levels when the ΔV does

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not exceed its threshold. If the irradiance level goes up while the voltage does not change, the current and the power increase; however, on this new power versus voltage curve, the system is now left of the MPP, and the algorithm is programmed to increase the reference voltage (or decrease duty cycle). A similar argument can be made for when the irradiance decreases in order to determine what the IC algorithm decides to do. In this case, it decreases the reference voltage (or increases the duty cycle).

There are certain advantages and disadvantages associated with the incremental conductance algorithm. For instance, IC can lock on to the MPP. In other words, it finds the maximum power point and then stops perturbing the system unless conditions change. This causes the converter's input as well as its output to be steadier and more constant. While the algorithm is more complicated than P&O, it is still moderately simple to understand. Additionally, just like P&O, this algorithm requires one to measure both the voltage and the current. An obvious drawback to the IC algorithm is the increased requirement for computation and logic when compared to P&O. Also, this algorithm can command the wrong perturbation just as the P&O algorithm but for a slightly different reason. When the solar irradiance increases, the I/V + ΔI/ΔV calculation can continually yield a positive answer. This happens if the ΔV and ΔI are repeatedly both positive and the algorithm causes the reference voltage to increase even if it should not. Yet, just like P&O, the algorithm quickly recovers from a situation such as this once the irradiance is relatively stable. On the other hand, when the solar irradiance decreases, the I/V + ΔI/ΔV computation tends to alternate between a positive and negative value, and the algorithm essentially keeps the reference voltage where it was prior to the decrease in irradiance. As a final point, IC can possibly lock onto the wrong setting. If an erroneous I/V + ΔI/ΔV calculation causes the algorithm to command no change in the duty cycle, then the algorithm may detect ΔV and ΔI below their thresholds after the next MPPT period. This causes the algorithm to stay at the current operating point indefinitely even if it is not the MPP. Either a change in irradiance or excessive noise in the current or voltage signal may cause the algorithm to exit this adverse mode of operation.

IV. SIMULATION RESULTS

This Chapter presents detailed simulation results of the proposed solar photovoltaic using improved InC MPPT & will be compared with conventional MPPT. The simulated system is shown in Fig. 4.1. Simulation studies are carried out in the MATLAB/SIMULINK environment.

Simulations are performed using MATLAB/SIMULINK software for tracking MPPs of the solar PV array whose specifications and parameters are in Table 4.1.

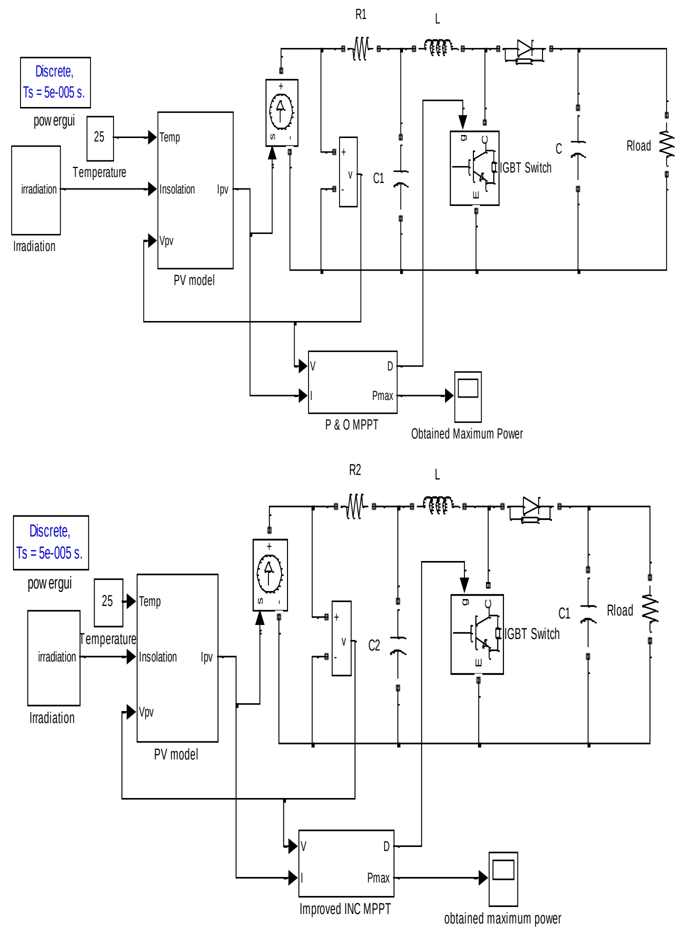

Fig.4.1: Matlab Simulink model for solar PV system

The solar PV panel provides a maximum output power at a MPP with V_{MPP} and I_{MPP}. The MPP is defined at the standard test condition of the irradiation, 1 kW/m^2 and module temperature, 25 °C but this condition does not exist most of the time. The following simulations are implemented to confirm the effectiveness of the improved InC algorithm which is compared with those of the InC and P&O algorithms. Matlab Simulink block diagram is shown in Fig, 4.1.

- *Case 1:* It is assumed that the module temperature is constant, T = 25 °C.
- *Case 2*: It is assumed that both the module temperature and solar irradiation are changed.

Table 4.1: Simulation parameters

S. No.	Description	Values

1.	Maximum power, P_{max}	22 W
2.	Short-circuit current, *Is* c	1.34 A
3.	Open-circuit voltage, *Voc*	21.99 V

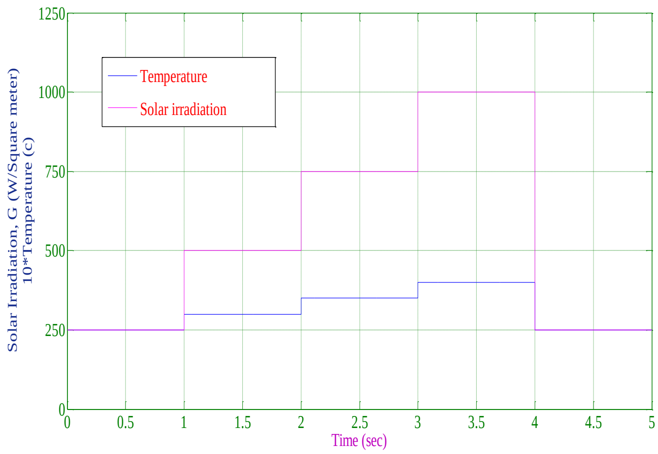

Fig.4.2: The variations of the solar irradiation and temperature

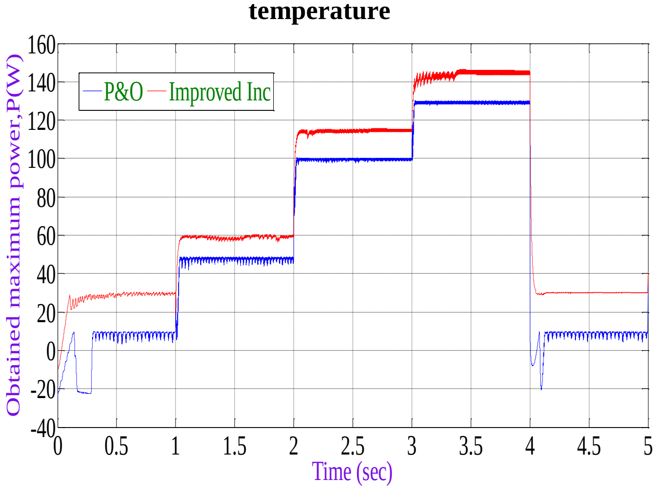

Fig.4.3: OMP with the P&O and improved InC algorithms under the variation of the solar irradiation

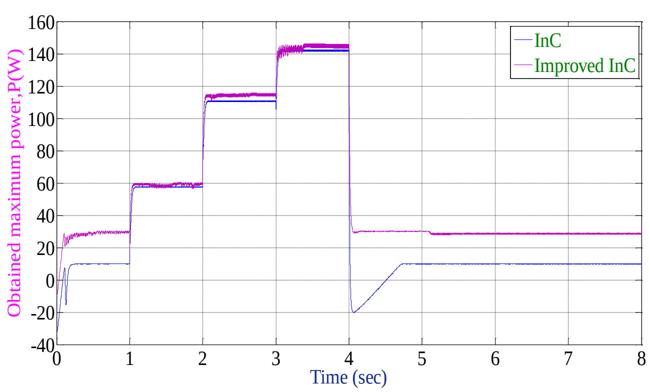

Fig.4.4: OMP with the InC and improved InC algorithms under the variation of the solar irradiation

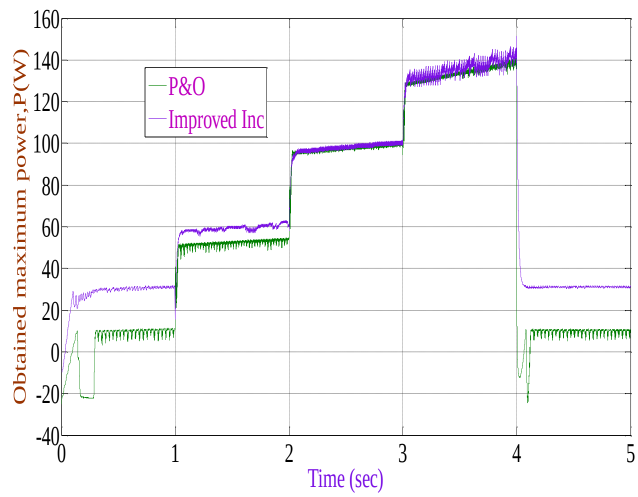

Fig.4.5: OMP with the P&O and improved InC algorithms under both the variations of the solar irradiation and temperature

The obtained output powers are shown as in Fig. 4.5 & 4.6 using the P&O, InC and improved InC algorithms under the variation of both the temperature and solar irradiation. It can be realized that the simulation results of the cases using the improved InC algorithm are always better than the cases using the P&O and InC algorithms, Figs. 4.3–4.4 and Figs.4.5–4.6. The better results are shown through the algorithm convergence and the MPPs' tracking ability, especially with the rapid variation of both the temperature and solar irradiation. This means that the drawbacks of the InC algorithm have been overcome using the proposed InC algorithm.

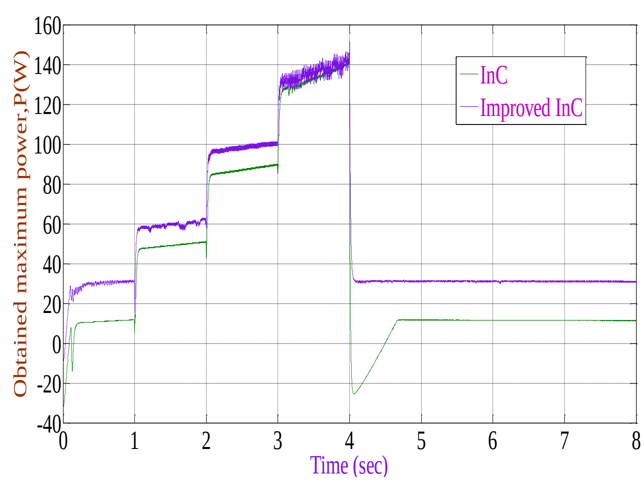

Fig.4.6: OMP with the InC and improved InC algorithms under both the variations of the solar irradiation and temperature

V. CONCLUSION

In this thesis, the adaptive and optimal control strategy plays an important role in the development of solar PV systems. This strategy is based on the combination between the ST and MPPT in order to ensure that the solar PV panel is capable of harnessing the maximum solar energy following the sun's trajectory from dawn until dusk and is always operated at the MPPs with the improved InC algorithm. The proposed InC algorithm improves the conventional InC algorithm with an approximation which reduces the computational burden as well as the application of the CV algorithm to limit the search space and increase the convergence speed of the InC algorithm. This improvement overcomes the existing drawbacks of the InC algorithm. An adaptive and optimal control strategy in the solar PV panel through the comparisons with other strategies is validated through simulation studies.

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