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Maximum Power Point Tracking Algorithms for Grid-Connected Photovoltaic Energy Conversion System

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ABSTRACT

The output power of Photovoltaic (PV) arrays is always changing with weather conditions, i.e., solar irradiation and atmospheric temperature. Therefore, a Maximum Power Point Tracking (MPPT) control to extract maximum power from the PV arrays at real time becomes indispensable in PV generation system. In recent years, a large number of techniques have been proposed for tracking the maximum power point (MPP). MPPT is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and radiation conditions and of the load electrical characteristics the PV array output power is used to directly control the dc/dc converter, thus reducing the complexity of the system. The resulting system has high-efficiency. This paper presents in details comparison of most popular MPPT algorithms techniques which are Perturb & Observe algorithm (P&O) and Improved Perturb & Observe algorithm (IP&O). In this paper, an improved perturbation and observation method (IP&O) based on adaptive algorithm is proposed, which is automatically adjusts the reference step size and hysteresis bandwidth for power *cum*parison. The results show that the IP&O increases the total PV output power at an unsettled weather condition compare to traditional perturbation and observation method (P&O).

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1. INTRODUCTION

Renewable sources of energy acquire growing importance due to its enormous consumption and exhaustion of fossil fuel. Also, solar energy is the most readily available source of energy and it is free. Moreover, solar energy is the best among all the renewable energy sources since, it is non-polluting. Energy supplied by the sun in one hour is equal to the amount of energy required by the human in one year. Photo voltaic arrays are used in many applications such as water pumping, street lighting in rural town, battery charging and grid connected PV systems. As known from a Power-Voltage curve of a solar panel, there is an optimum operating point such that the PV delivers the maximum possible power to the load. The optimum operating point changes with solar irradiation and cell temperature. Therefore, maximum power point tracking is essential for PV panel. A variety of maximum power point tracking (MPPT) methods is available [1].

All the energy we use on Earth comes from fission or fusion of atomic nuclei, or from energy stored in the Earth. The problem with both fission and fusion is that they have dangerous radioactivity and side effect. Therefore most of the generation of energy in our modern industrialized society is strongly depending on very limited non-renewable resources, particularly fossil fuel. As the world's energy demands rise and resources become scarce, the search for alternative energy resources has become an important issue for our time. Very much exploitation and research for new power has been done not only in the area of nuclear power generation but also in the area of unlimited energy sources such as wind power generation and solar energy transformation. The most effective and harmless energy source is probably solar energy. For many applications it is so technically straightforward to use. Use of solar energy instead of fuel combustion, particularly for simple application like low and medium temperature water heating, can reduce the load on the environment. Solar energy can be harvested by the use of photovoltaic (PV) array. Perturb and observe (P&O) techniques, although thoroughly investigated in previous research, still suffer from several disadvantages, such as sustained oscillation around the MPP, fast tracking versus oscillation tradeoffs, and user predefined constants In this paper, a modified P&O MPPT technique, applicable for PV systems, is presented. The proposed technique 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. A design example is presented by experimental implementation of the proposed technique. Practical results for the implemented setup at different irradiance levels are illustrated to validate the proposed technique.

2. RESEARCH METHOD

2.1. Mathematical Modeling of PV Array

The PV receives energy from sun and converts the sun light into DC power. The simplified equivalent circuit model is as shown in Figure.1.

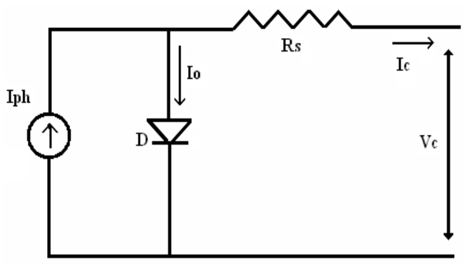


Figure.1. Simplified – equivalent Circuit of Photovoltaic Cell

The PV cell output voltage is a function of mathematical equation of the photocurrent that mainly determined by load current depending on the solar irradiation level during the operation. The equation (1) is,

$$V_{cx} = \frac{AKT_c}{q} \ln\left[\frac{I_{ph} + I_0 - I_c}{I_0}\right] - R_s I_c \quad (1)$$

where the symbols are defined as follows:

- q: electron charge (1.602 × 10-19 C).
- k: Boltzmann constant (1.38 × 10-23 J/^{0}K).
- I_c: cell output current, A.
- I_{ph}: photocurrent, function of irradiation level and junction temperature (5 A).
- I_o: reverse saturation current of diode (0.0002 A).
- R_s: series resistance of cell (0.001 Ω).
- T_c: reference cell operating temperature (25 °C).
- V_c: cell output voltage, V.

Both k and T_C should have the same temperature unit, either Kelvin or Celsius. A method to include these effects in the PV array modeling is given in [4]. These effects are represented in the model by the temperature coefficients C_{TV} and C_{TI} for cell output voltage and cell photocurrent, respectively, as in equation (2) and (3),

$$C_{TV} = 1 + \beta_T (T_a - T_x) \quad (2)$$

$$C_{T1} = 1 + \frac{\gamma_t}{sc}(T_x - T_a) \quad (3)$$

Where, β_T=0.004 and γ_T=0.06 for the cell used and T_a=20°C is the ambient temperature during the cell testing. If the solar irradiation level increases from S_{X1} to S_{X2}, the cell operating temperature and the photocurrent will also increase from T_{X1} to T_{X2} and from I_{Ph1} to Iph2, respectively. C_{SV} and C_{SI}, which are the correction factors for changes in cell output voltage V_C and photocurrent I_{ph} respectively in equation (4) and (5),

$$C_{SV} = 1 + \beta_T \alpha_S (S_x - S_C) \quad (4)$$

$$C_{ST} = 1 + \frac{1}{S_c}(S_X - S_C) \quad (5)$$

where S_C is the benchmark reference solar irradiation level during the cell testing to obtain the modified cell model. The temperature change, ΔT_C occurs due to the change in the solar irradiation level and is obtained using in equation (6),

$$\Delta_{TC} = 1 + \alpha_S (S_X - S_C) \quad (6)$$

The constant α_S represents the slope of the change in the cell operating temperature due to a change in the solar irradiation level [1] and is equal to 0.2 for the solar cells used. Using correction factors C_{TV}, C_{TI}, C_{SV} and C_{SI}, the new values of the cell output voltage V_{CX} and photocurrent I_{PHX} are obtained for the new temperature T_X and solar irradiation S_X as follows in equation (7) and (8),

$$V_{CX} = C_{TV} C_{SV} V_C \quad (7)$$

$$I_{ph} = C_{T1} C_{SI} I_{ph} \quad (8)$$

V_C and I_{PH} are the benchmark reference cell output voltage and reference cell photocurrent, respectively. The resulting I-V and P V curves for various temperature and solar irradiation levels were discussed and shown in [3, 4, and 5]; therefore they are not going to be given here again. The output power from PV is the result from multiplying PV terminal voltage and PV output current are obtained from equation (9) and (10). The power output from PV modules is shown in (2).

$$P_c = V_c \left(I_{ph} - I_a * \exp(\frac{q}{AKT} V_c - 1) \right)$$

$$I_c = I_{ph} - I_0 * \exp\left(\frac{q}{AKT} V_c - 1 \right) \quad (9)$$

2.2. MPPT Algorithm for Photovoltaic System

The tracking algorithm works based on the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point as in Fig.2.The derivative is greater than zero to the left of the peak point and is less than zero to the right.

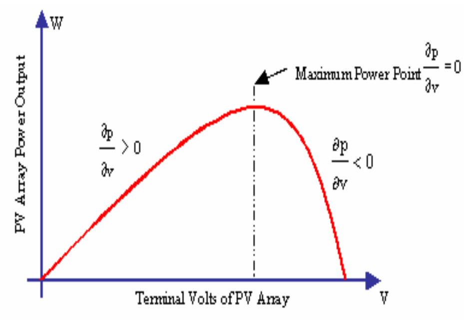


Figure 2. P-V Characteristics of a module

$$\frac{\partial P}{\partial V} = 0 \; for V = V_{mp} \quad (11)$$

$$\frac{\partial P}{\partial V} > 0 \; for V < V_{mp} \quad (12)$$

$$\frac{\partial P}{\partial V} < 0 \; for V > V_{mp} \quad (13)$$

Various MPPT algorithms are available in order to improve the performance of PV system by effectively tracking the MPP. However, most widely used MPPT algorithms are considered here, they are
a) Perturb & Observe algorithm,
b) Improved Perturb & Observe algorithm

3. PERTURB & OBSERVE ALGORITHM

The most commonly used MPPT algorithm is P&O method and is also known as hill-climbing algorithm. The perturbation and observation method (P&O), which moves the operating point toward the maximum power point by periodically increasing or decreasing the array voltage, is often used in many photovoltaic systems. This technique employs simple feedback arrangement and few measured parameters.

The P&O method is implemented in a software program with a self-tuning function, which automatically adjusts the array reference voltage and voltage step size to achieve the maximum power tracking under rapidly changing conditions. The maximum power tracking can be achieved rapidly and accurately by increasing the sampling frequency. The controller features MPPT, battery charge regulation, and eclipse shutdown.

The block diagram of the P&O algorithm is shown in Figure 3. In the perturbation and observation method if the sampling and execution speed of the perturbation and observation method is increased, then the system loss will be reduced. Moreover, this method only needs two sensors, which results in the reduction of hardware requirement and cost. Therefore, the perturbation and observation method was used in this paper to control the output current and voltage of the solar arrays.

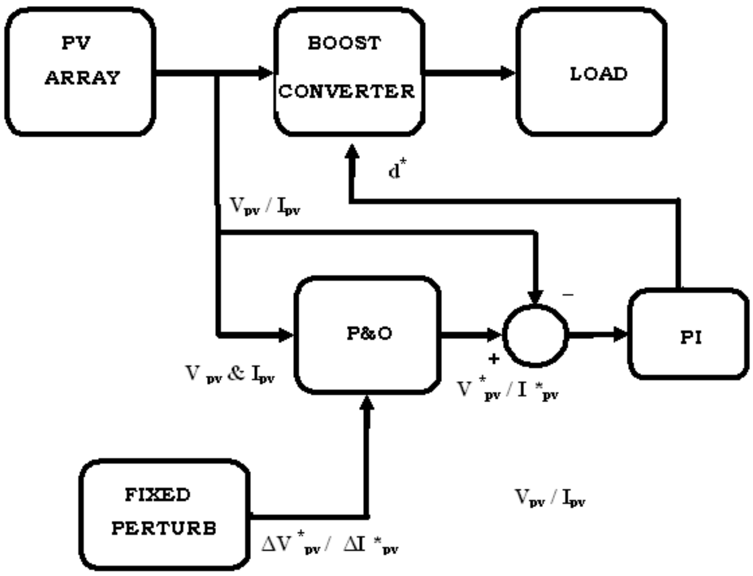


Figure 3. Block diagram of P&O algorithm

Two different control variables are often chosen to achieve the maximum power control.

1) *Voltage Feedback Control:* This method assumes that any variations in the insolation and temperature of the array are insignificant and that the constant reference voltage is an adequate approximation of the true maximum power point. The solar array terminal voltage is used as the control variable for the system. The system keeps the array operating near its maximum power points by regulating the array voltage and matches the array voltage to a fixed reference value. The control method is simple; however, it has the following drawbacks.
   i) It neglects the effect of the insolation and temperature of the solar array.
   ii) It cannot be widely applied in the battery energy storage systems.
   Therefore, the control is only suitable for use under the constant insolation condition, such as a satellite system, because it cannot track the maximum power points of the array when variations in the insolation and temperature occur.
2) *Power Feedback Control:* The actual array power, instead of its estimate from measurements of other quantities, is used as the control variable. Maximum power control can be achieved by forcing the derivative (dP/dV) equal to zero under the power feedback control. A general approach to the power feedback control is to measure and maximize the power at the load terminal. However, it maximizes the power to the load, not the power from the solar array. A converter with MPPT offers high efficiency over a wide range of operating points. The full power may not be delivered to the load completely, due to the power loss for a converter without MPPT. Therefore, the design of a high-performance converter with MPPT is a very important issue. Problems with this approach are undesirable

measurement errors (especially for current) which strongly affect tracker accuracy. The MPPT control using a P&O is very complex in the circuit implementation. A method which regulates the output power by changing the number of batteries [6] requires extra hardware circuits. Neglecting the variations in output voltage, the approach using only an output current measurement simplifies the control circuits by eliminating the need to sense and multiply voltage and current. However, this approach does not track the maximum power points rapidly and accurately.. P&O method control system sometimes deviates from the maximum operating point. The P&O method will oscillate around it in case of constant or slowly varying atmospheric conditions. A drawback of P&O is that the operating point oscillates around the MPP. The present **Perturbation and observation** algorithm demands further fast response which cannot be achieved through the conventional proportional-plus-integral-controller (PI) based system. Hence to enhance the capability of the proposed algorithm, implementation through the improved perturb and observe (IP&O) scheme to keep the system power operating point at its maximum.

4. IMPROVED PERTURB & OBSERVE ALGORITHM

The conventional perturbation and observation (P&O) MPPT algorithm is impossible to quickly acquire the maximum power point (MPP), and the tracking course is very difficulty under veil weather conditions. To overcome the drawback of the conventional P&O algorithm the improved **P&O** method is introduced, based on hysteresis band and auto-tuning perturbation step, there is trade-off between dynamic response and steady state due to the selection of **'dv".** the perturbation step.

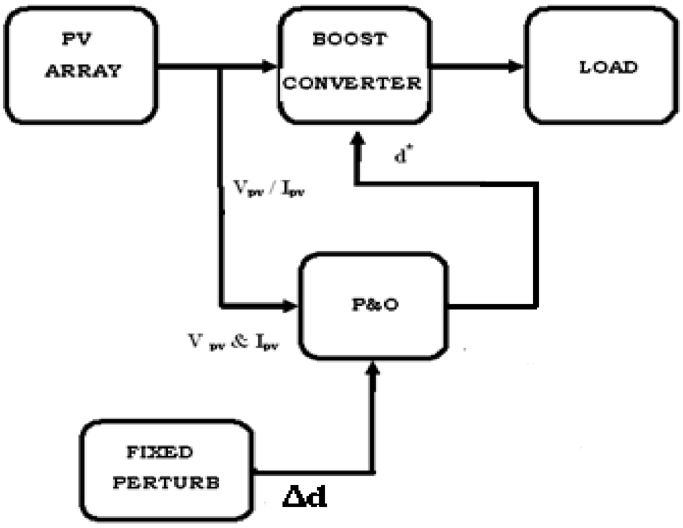


Figure 4. Improved Perturb and Observe MPPT

As previously mentioned, the proposed MPPT system employs peak current control. The switch is turned on by a clock signal and turned off when the actual current reaches the reference current. Therefore, the reference current can be perturbed (increased or decreased) in every switching cycle, meaning that the perturbation cycle or refresh rate is equal to the switching cycle. The size of the perturbation has to be chosen according to the inductor size and the switching (clock) frequency so that the switch always turns off befre the next turn on signal. For a given switching perturbation cycle, the larger the perturbation step the faster the PV current can be driven from an MPP (I_{MPP} 1) to the next (I_{MPP} 2) to a variation on the solar irradiation level. On the other hand, the magnitude of the intrinsic oscillations around the MPP in steady state would be larger, yielding a reduced average PV power conversion in steady state. Since low power converters can operate with frequencies of hundreds of kHz, a satisfactory trade-off between fast transient responses and steady state performance can be obtained with a small perturbation step size.

A calculate the correct direction of the next perturbation with only one instantaneous sample per switching cycle in the actual and previous cycles. Besides, the sampling instants can be arbitrary. This is valid when the instantaneous values of the current are always either below or above I_{MPP}, where ever, in steady state, when the operating point oscillates around the MPP. The direction of the calculated perturbation can vary depending on the sampling instant used.

The remainder of this section investigates the effect of the sampling instant on the power drawn from the PV array. The p $_x$ i curve of a PV array can be represented by 3 segments. In segment 1($0 < i_{pv} < I_{mpp} - \triangle I$), the curve is approximated by a straight line with a small positive slope. In segment 2 ($I_{mpp} - \triangle I < I_{pv} < I_{mpp} + \triangle I$), the curve is represented by a co-sinusoid centered at I_{mpp}. The curve is approximated by a straight line with a large negative slope. Operation in segment 3 should be avoided since the output power decreases very fast with minor increases in the output current.

Improved perturb and Observe based on modified fixed algorithm is automatically adjusts the reference step size and hysteresis bandwidth for power conversion. The improved P&O method (IP&O) is based on auto-tuning perturbation. Improved P&O is trade-off between dynamic response and steady state due to the selection of "dV" the perturbation. The advantage of Improved P&O method is finds the real MPP under any working conditions.

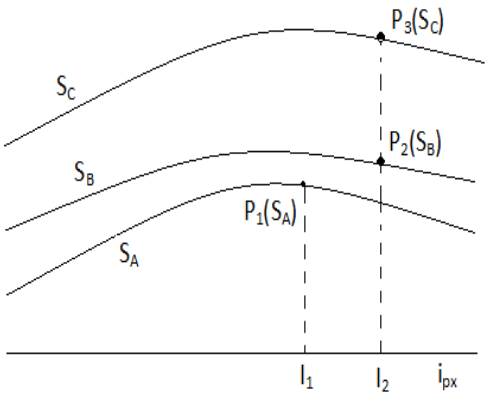


Figure 5. The comparison between samplings for long and short perturbation Cycles under rapidly changing atmospheric conditions.

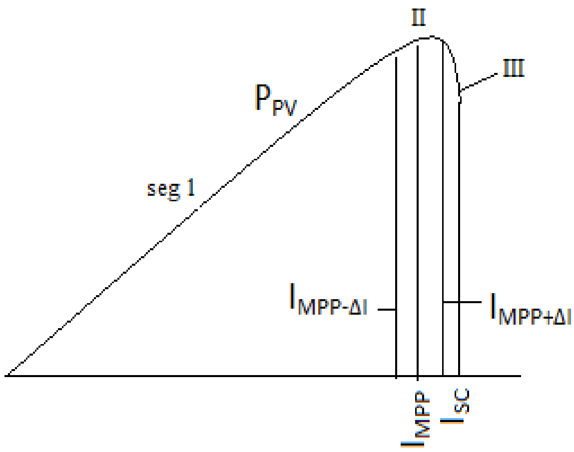
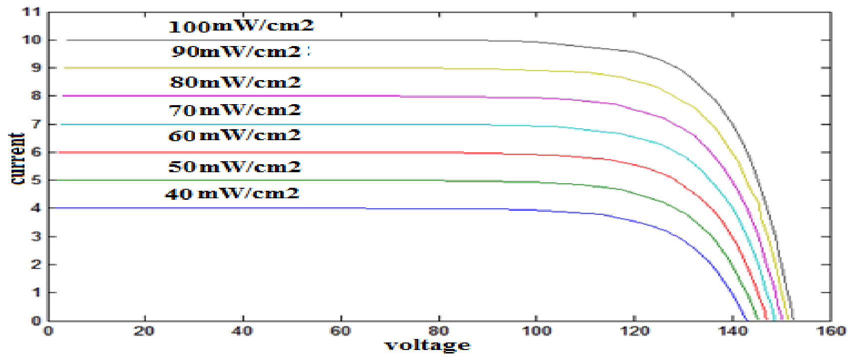


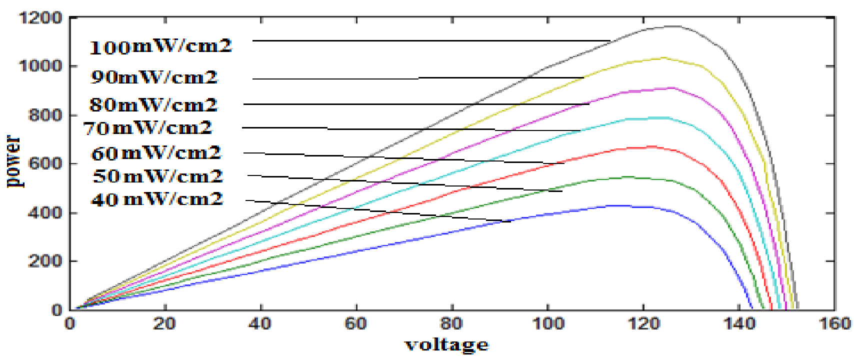
Figure 6. The P-I curve divided in three segments

5. RESULTS AND ANALYSIS

For constant temperature (25˚C) and different intensity (40-100mW/cm2) The PV array current constant up to some voltage level (100V) and then it will be decreased. The PV array current always increases with intensity.

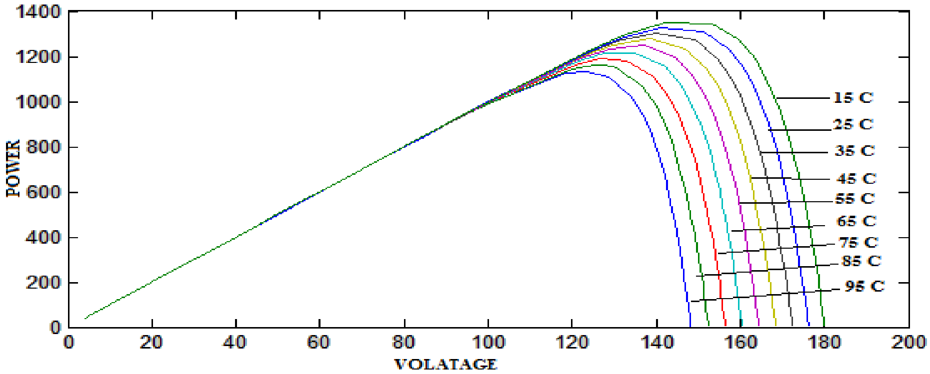


(a)

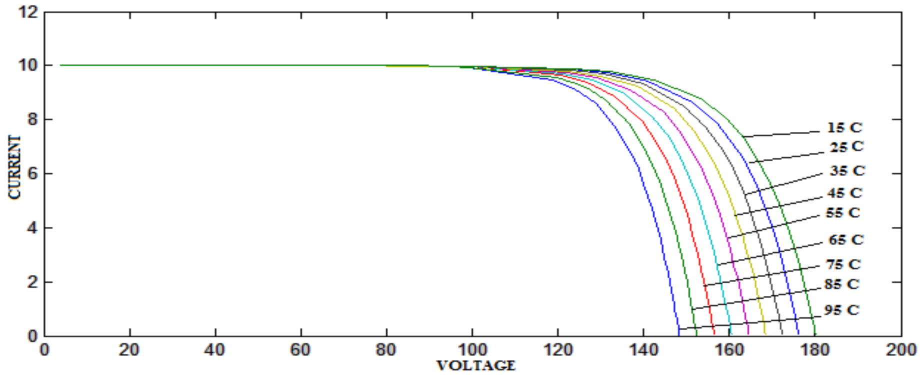


(b)

Figure 7. I-V Characteristics of Solar Array for Various Irradiance; (a) at a constant Temperature of 25°C; (b). for various Irradiance S at a temperature of 25°C



(a)



(b)

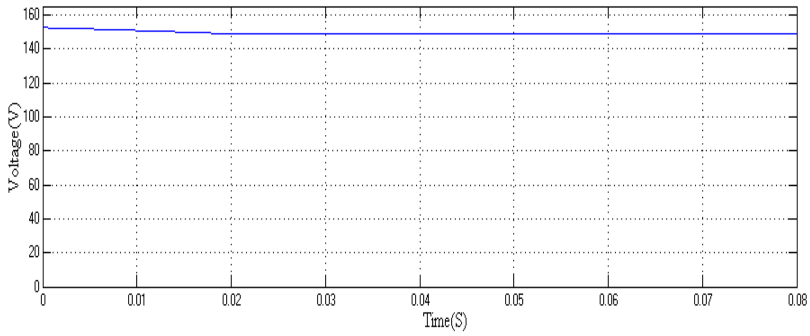
Figure 8. Characteristics of PV array;
(a). P-V characteristics of PV array at various temperature constant irradiation 100mW/cm2
(b). V-I characteristics of PV array at various temperature constant irradiation 100mW/cm2

From Figure 8 (a) P-V characteristics for different temperature and constant irradiance; the generated power is gradually decreased and maximum power available more at low temperature. From Figure 8(b) I-V characteristics for different temperature and constant irradiance. The current is constant up to some voltage and then it will gradually decreses.

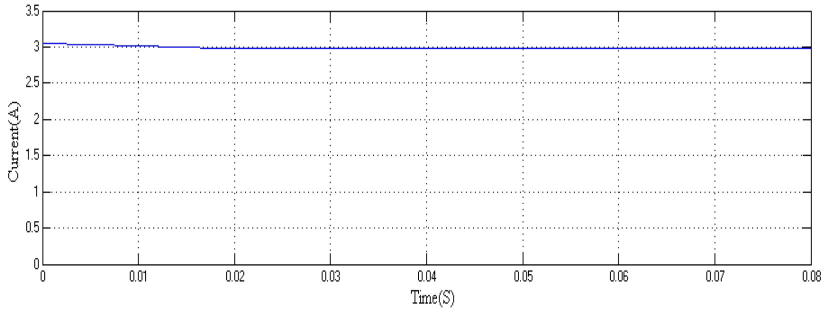
The output voltage, current and power waveforms of the PV array without maximum power point tracking (MPPT) technique is shown in Figure 9(a), 9(b) and 9(c) The voltage, current and power of PV system without MPPT technique is 148.8V, 2.97A and 442.8W respectively.

From Figure 7(a), it shows that the maximum available power is 1162W but the tracked power without MPPT is 442.8W, so an MPPT technique is needed. By using Perturb & Observe MPPT technique the power tracking can be improved from 37% to 90%, the output voltage, current and power of the PV array with Perturb & Observe maximum power point tracking (MPPT) technique is shown in Figure. 10(a), 10(b), 10(c). The voltage, current and power values are 137.8V, 7.577A and 1044W respectively.

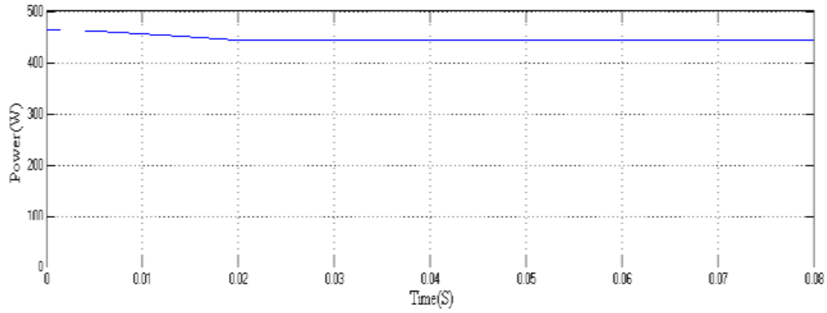
From Figure. 10(c) it shows that the power tracked is 1044W, which is 90% of the maximum available power. This Perturb & Observe method also has some disadvantages like Fail to track MPP when partially shaded or cells are damaged. These can be overcome by using another MPPT technique that is improved perturb and observe (IP&O). By using this IP&O MPPT technique the output results are shown in 11(a), 11(b), 11(c).



(a)

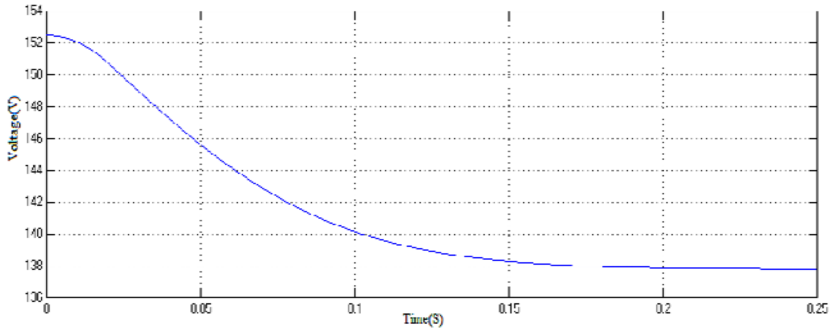


(b)

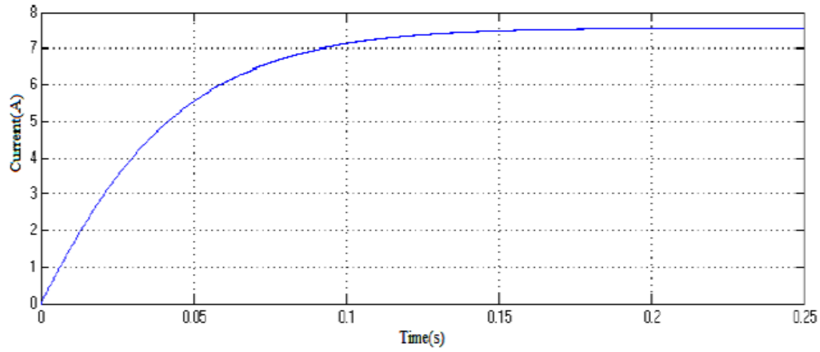


(c)

Figure 9. Outputs without MPPT technique; (a). Output voltage, (b). output current, (c). output power



(a)



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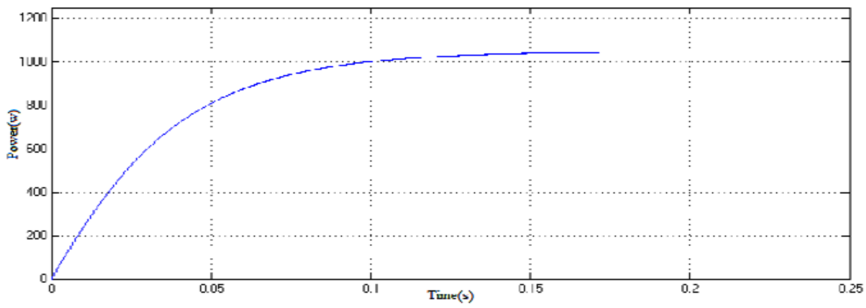
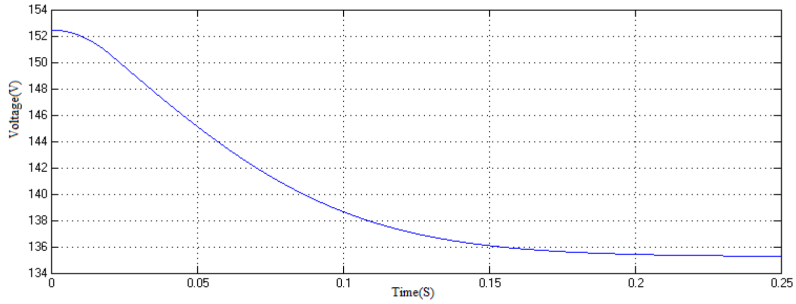
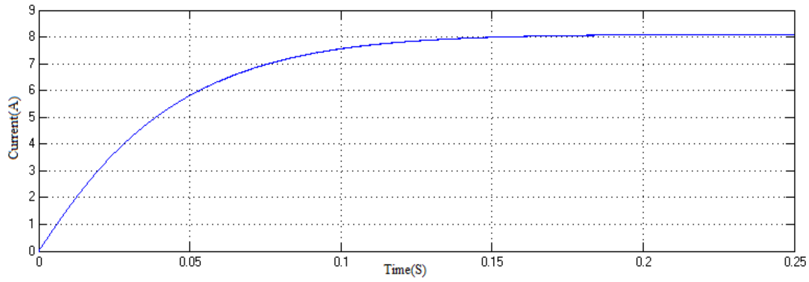


(c)

Figure 10. Outputs with Perturb & Observe MPPT technique; (a) Output voltage, (b) Output current, (c) Output power



(a)



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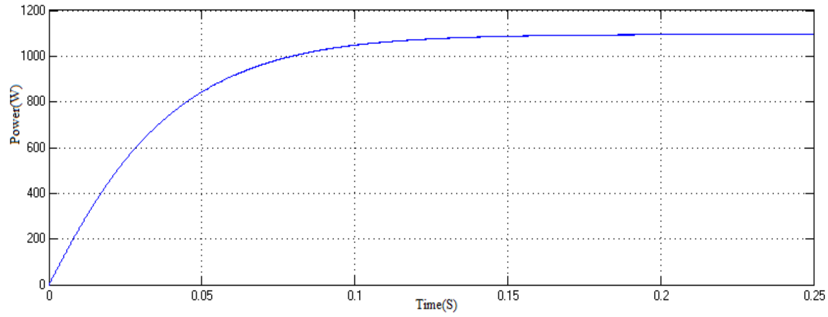


(c)

Figure 11. Outputs with Improved P&O MPPT technique; (a) Output voltage, (b) Output current, (c) Output power

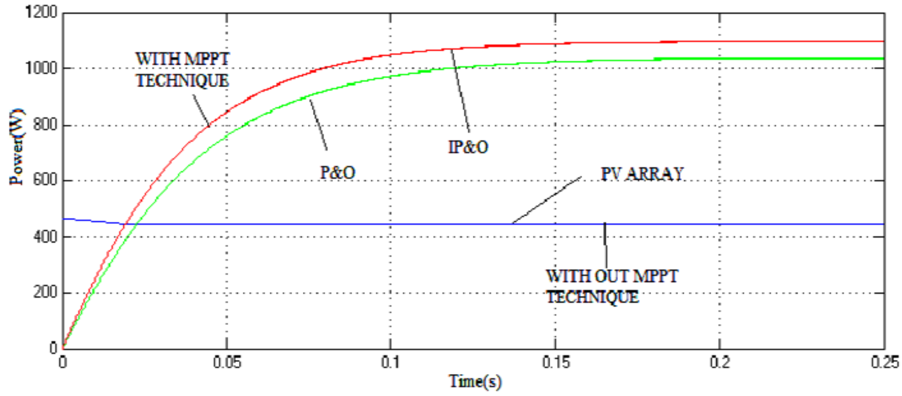
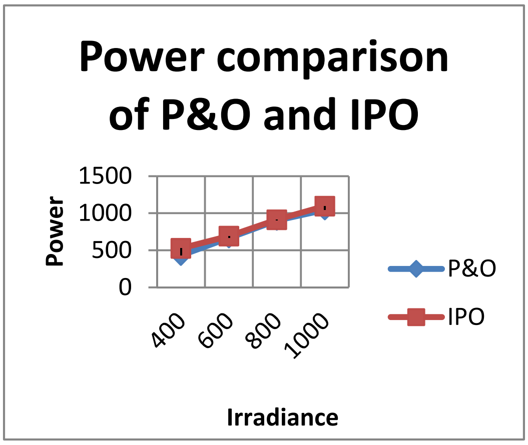


Figure 12. Comparison of output power with and without MPPT techniques

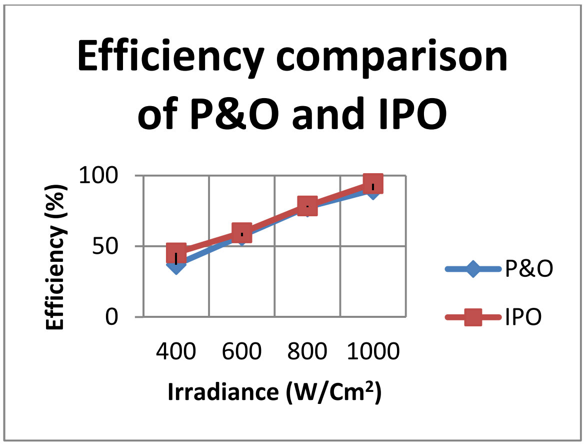
From the Table 1, it can be concluded that the power at different irradiance with constant temperature, it can be found that the IPO method has higher power than PO method. It is verified that the proposed IPO control strategy works well than PO control.

Table 1. Comparison of Power with different irradiance with constant temperature

Irradiance (W/Cm^2)	Power Availability (Watts)	
	P & O	IP & O
400	429.8	527
600	666.8	692.2
800	902.9	912.5
1000	1044	1096



(a)



(b)

Figure 13. Comparisons of P&O vs IPO constant temperature 25°c at various irradiance; (a) Power, (b) Efficiency

From the Table 2, it can be concluded that the IPO method has higher efficiency than PO method. So it is verified that the proposed IPO control strategy works well than PO control

Table 2. Comparison of Efficiency with different irradiance and constant temperature

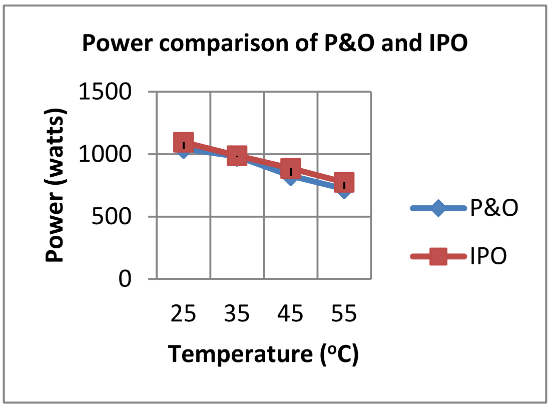
Irradiance (W/Cm^2)	Efficiency (%)	
	P & O	IP & O
400	36.98	45.35
600	57.38	59.56
800	77.72	79.52
1000	89.84	94.32

Simulation is performed to verify the proposed IPO control method. The power at different irradiance with constant temperature is shown in Figure 13 (a) and (b). From the figures it can be concluded that IPO method has tracked more power and efficiency than the PO method.

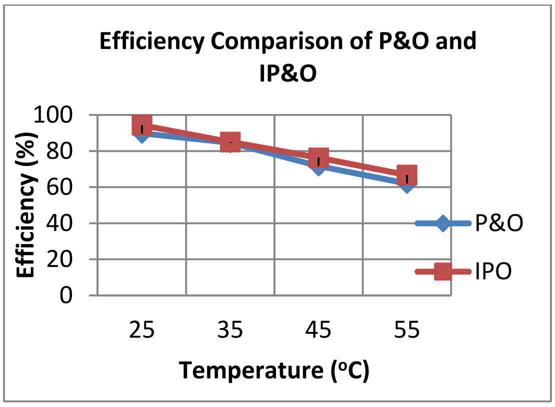
Table 3. Comparison of Power with different temperature and constant irradiance

Temperature (°C)	Power Availability (Watts)	
	P&O	IP&O
25	1044	1096
35	982.4	988.1
45	827	886
55	721.3	775

From the Table 3 it can be concluded that the power is reduced by increasing of temperature. It can be found that IPO method has capability to tracked more power and efficiency than PO at different temperature with constant irradiance. It is verified that the proposed IPO control strategy works well than PO control.



(a)



(b)

Figure 14. Comparisons of P&O vs IPO constant at irradiance various temperature; (a) Power, (b) Efficiency

Table 4. Comparison of Efficiency with different temperature and constant Irradiance

Temperature (°C)	Efficiency (%)	
	P&O	IP&O
25	89.84	94.32
35	84.54	85.03
45	71.70	76.24
55	62.64	66.69

From the Figures 14 (a) and (b), it can be found that IPO method has capability to tracked more power and efficiency than PO at different temperature with constant irradiance. It is verified that the proposed IPO control strategy works well than PO control.

6. CONCLUSION

In order to acquire the maximum power point of PV generate systems it is important to have an efficient MPPT algorithms. A narrative MPPT algorithm was proposed in this paper. An important conclusion is gained in order to track the maximum power point of photovoltaic. The maximum power point tracking is a technique used with PV system to improve its conversion efficiency. To eliminate mismatch between the load line and V-I characteristic, an MPPT control algorithm is necessary. Perturbation and Observation method is relatively simple and easily of implementation could be realized easily with simulation. P&O method has dramatic fast tracking capability, however its performance under different weather conditions is poor due to the nonflexible, and the operating point oscillates around the MPP. In proposed control algorithm, uses the power as the control variable based on the improved perturbation and observation method. A better response for the system under rapid atmospheric condition variations can be obtained by increasing the execution speed. The IP&O method gives high efficiency about 94.32% and performs well with changing radiation and temperature. The IP&O based on modified fixed algorithm is automatically adjusts the reference step size and hysteresis bandwidth for power conversion. No oscillation during tracking and steady state operations. The correctness and validity of MPPT method is verified through simulation under various weather conditions.

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