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# تحسين أداء نقاط تتبع القوى في أنظمة الخلايا الكهروضوئية بواسطة خوارزمية التشويش والمتابعة المعدلة

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## الخلاصـة

الطاقة الشمسية ومصادر الطاقة المتجددة تحتل موقعاً هاماً في توليد الطاقة. وفي نفس الوقت، إنها صديقة للبيئة ولا تسبب الضجيج ولا تحتاج إلى وقود ولكنها تحتاج الى استثمارات مكلفة وكفاءة إنتاجها للطاقة ضعيف نسبيا. وبالتالي، الدراسات الحالية تقوم على تحسين الأنظمة التي تعمل على الطاقة الشمسية التي اكتسبت الكثير من الأهمية، والتطورات في مجال نظم تحويل الطاقة الحالية مكنت النظم الكهروضوئية من إكتساب المزيد من الزخم. وتستخدم نقاط تتبع القوى للحصول على أقصى قدر من الأداء من النظم الكهروضوئية. وفي هذه الدراسة، التشويش ومراقبة خوارزمية والتي هي الأكثر استخداما في نقاط تتبع القوى قد تم تحليلها، وهو النهج الصحيح نحو القضاء على مشاكل التذبذب، وتحسين سرعة الحصول على مزيد من الطاقة، وترجع القيمة الحالية التي تم الحصول عليها من التشويش ومراقبة الخوارزمية في ظل تغير وثبات الإشعاع الشمسي على النظم الكهروضوئية. وأخيرا، تمت محاكاة التشويش ومراقبة الخوارزمية المقترحة ومناقشة النتائج.

# Improving the performance of MPPT in PV systems by modified Perturb-and-Observe algorithm

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## ABSTRACT

Solar energy is a renewable energy source and occupies an important position in power generation. While it is environment-friendly, silent and non-fuelled, its high investment costs and low efficiency in terms of energy conversion bring about various disadvantages. Therefore, studies on the improvement of systems operated via photovoltaic energy gained importance and the researches and developments within the field of current power conversion systems enabled the photovoltaic systems to gain momentum. Maximum power point tracking (MPPT) must be used to obtain maximum performance from the solar energy system. In this study, Perturb and Observe (P&O) algorithm -the most commonly used algorithm in MPPT systems- was analyzed, an approach towards eliminating oscillation problems, improving speed to obtain more power value, were maintained and reference current value was obtained from P&O algorithm under changing and constant PV panel radiation conditions. Finally, the proposed P&O algorithm was simulated and the results are discussed.

**Key words:** DC/DC boost converter; MPPT; P&O algorithm; solar cell

## INTRODUCTION

Due to an ever-increasing human population and energy consumption, global capacities of conventional fossil energy resources have been decreasing for more than 2 decades (World E.C., 2013). This has encouraged the use of renewable energy resources like solar. Photovoltaic (PV) energy conversion systems have a large scale usage due to its high availability, and presence anywhere there is sunlight. In recent years, studies about PVs have focused on minimizing the costs and maximizing the conversion efficiency. In order to maximize the efficiency of PV energy conversion systems, solar panels and arrays should be operated at maximum power points. At maximum power point, solar arrays generate the electric energy at maximum efficiency and with minimum power loss. Solar cells have variable current and voltage characteristics. Maximum power point depends on solar irradiations and ambient temperature. So a maximum power tracking control should be made rapidly in different temperature and solar insolation conditions. Maximum power point trackers (MPPT) are developed to capture maximum power level in changing atmospheric conditions (Hussein *et al.*, 1995). In order to maximize the conversion efficiency and captured energy from arrays, the PV system should be operated at its maximum power point (Hohm & Roop, 2000). In Figure 1, typical I-V and P-V characteristics of a solar cell are illustrated. In Figure 2, I-V and P-V characteristics of four panels used in this study (case1, case2, case3) are also illustrated. It can be seen from the figures that solar insolation increased the current and power from solar panels under STC (Standard Test Conditions: 1000 W/m$^2$, 25 °C).

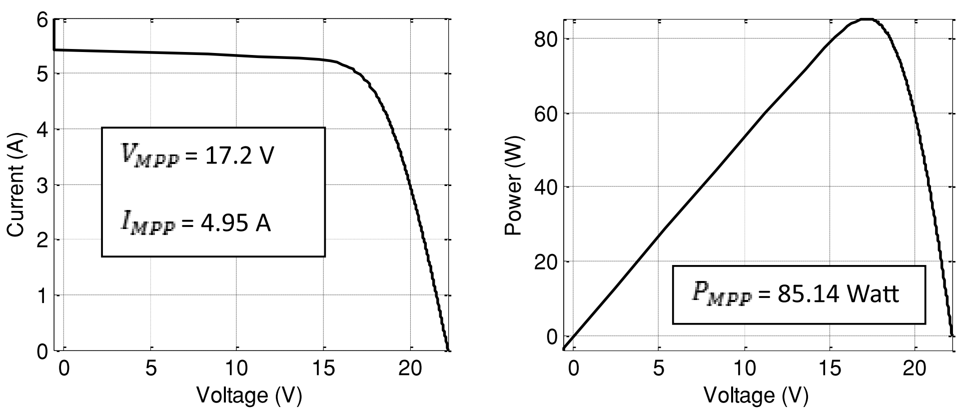


**Fig. 1.** Typical characteristics of solar cell for one PV panel (SHE85-SQ85)
(a) I-V Curve (b) P-V Curve

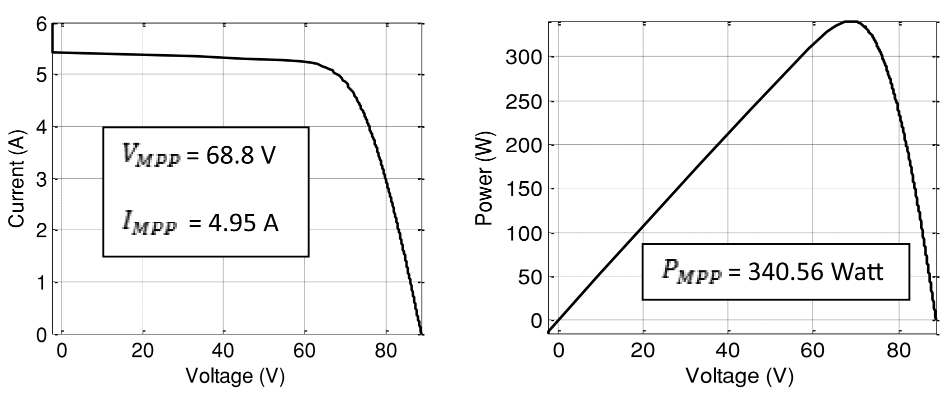


**Fig. 2.** Characteristics of series connected four PV panels
(a) I-V Curve (b) P-V Curve

Although PV systems continue to occupy an important position in electrical power technology, they have disadvantages such as high cost and low energy conversion efficiency. The output voltage and current of PV panels have a non-linear characteristic and it depends on light intensity, operating temperature and load current. Along with the improvement in the PV panel production technology, electrical output power control is also one of the most important approaches in eliminating these disadvantages. To achieve this, PV energy source and load impedance must be adapted to every weather condition and maximum power must be generated. Temperature and solar radiation in PV systems are converted to electrical energy thanks to electron interaction by semi-conductor holes. Output voltage in proportion to radiation amount on solar modules is obtained here. It is possible to design a PV system on the computer through equivalent circuit models of solar batteries, the most important element in these systems.

The greatest disadvantage in PV systems is the continuity problem in the generation of electricity. Researchers encounter this problem both in wind and solar energy conversion systems. Maximum energy in PV systems can only be produced when maximum power point is attained from the panels under any operating condition at any time depending on changing temperature and radiation amount. In this respect, a converter based on power electronics is required in order to track variable voltage and current between panel and load. It is also important to track this intermediary element where DC-DC converter circuits are used. The trigger frequency and range of switching element in the converter have an important role to obtain variable voltage.

The operating point of a photovoltaic generator that is connected to a load is determined by the intersection point of its characteristic curves. In general, this point is not the same as the generator's maximum power point. This difference means losses in the system performance. DC-DC converters together with maximum power tracking systems are used to avoid losses (Enrique *et al.*, 2007). The correct converter type is a significant issue for MPPT design. For example, most commonly on grid PV systems, a boost converter is implemented. This is because the voltage level produced by PV cells is very low and requires boosting in order to be integrated with other systems or the grid (Shehadeh *et al*., 2013). Boost converters need more inductance than the other converter types (Bucks) to achieve the same ripple of inductor current. In these converters, the rms current through inductor is much less than that of buck converters. However, Buck converters need larger and more expensive input capacitors than the Boost type converters to smooth the discontinuous input current from the PV array. Polarity of output voltage Buck-Boost type varies. Therefore, different converter types have been studied and proposed in literature. In addition to well-known buck, boost and buck-boost types, second generation converters such as SEPIC (Veerachary, 2005; Chiang *et al.,* 2009) and CUK (Raiwan & Nayar, 2007; Safari & Mekhilef, 2011) are used in this field as well as isolated Flyback and Forward (Vermulst *et al.,*

2012) type converters used when higher voltage conversion is required. Furthermore, previous studies suggested various controlling methods for MPPT design. Fuzzy logic (Altas & Sharaf, 2008), digital signal processing (DSP) controllers (Hua *et al.,* 1998**)**, field programmable gate array (FGPA) controllers (Koutroulis *et al.*, 2009; Mellit *et al.*, 2011), parallel processing topology (Badawy *et al.,* 2014) are some of the most important methods and controllers. The traditional MPPT techniques are able to track one of those maxima, but they cannot guarantee the extraction of the maximum power the PV array would be able to deliver. To overcome this problem, many techniques have been presented in the literature: the use of one converter for the entire array (centralized MPPT), one converter for each part of the array (distributed MPPT) or reconfiguring the PV array (Rodriguez *et al*., 2013). In conventional PV, energy conversion systems consist of solar panel, DC-DC converter and battery (or DC load) as shown in Figure 3.

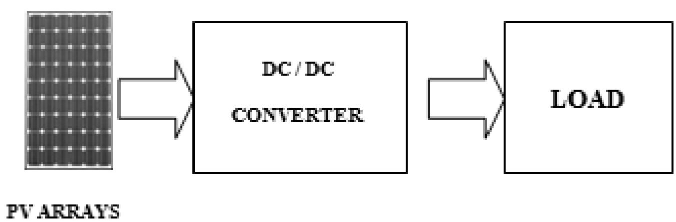


**Fig. 3.** Conventional PV energy conversion system

In the literature, both converter design and MPPT algorithms have been studied and presented so far. To reach maximum power point faster, several algorithms such as Perturbation and Observation (P&O) (Salas *et al.* 2004; Esram & Chapman, 2007), incremental conductance (Safari & Mekhilef, 2011), look-up table (Salas *et al.,* 2004; Esram & Chapman, 2007), current control loop (Wanzeller *et al.,* 2004) were proposed and applied.

The most relevant goals of PV energy include cost reduction of the power-converter stage, increased efficiency of both panels and converters, and considerable improvement in converter reliability and in order to collect the maximum available power, the operating point needs to be tracked continuously using a MPPT algorithm. The main goals of PV energy could be counted as minimizing the costs, increasing the efficiency and stability of the solar panels and converters. To be able to reach the maximum point, it is essential that MPPT algorithm is constantly used. This study focuses on an optimization of P&O algorithm. The chief advantage of this method is that it does not necessitate high "complexity implementation" and that it requires less calculation parameters. The disadvantage being that it generates oscillation when it reaches the maximum power point. At the same time, in the conditions of quickly changing atmospheric situations and in those of others when there is low irradiance it has the tendency to fail in tracking MPP (Mastromauro *et al.,* 2012). Hence, some calculation procedures of conventional P&O algorithm were modified and the oscillations were corrected completely.

## MATERIALS

As the sunlight hits on PV cells, photo-voltage and photocurrent acts like a forward diode on a large surface. The current expression emerging because of the sunlight hitting on the cell is given in equation 1.

$$I = I_{PH} - I_S . \left\{ \exp\left[ \frac{q}{A \cdot k \cdot T} \left( V + I \cdot R_L \right) \right] - 1 \right\} - \frac{\left( V + I \cdot R_S \right)}{R_{SH}} \quad (1)$$

In this expression, photo-current, saturation current, load resistance, series equivalent circuit resistance, parallel equivalent circuit resistance, terminal voltage, load current, diode ideality factor, Boltzman's constant and temperature of PV panel are denoted by $I_{PH}$, $I_S$, $R_L$, Rs, $R_{SH}$, V, I, A, k, and T respectively. The equivalent circuit diagram for a solar cell is displayed in Figure 4.

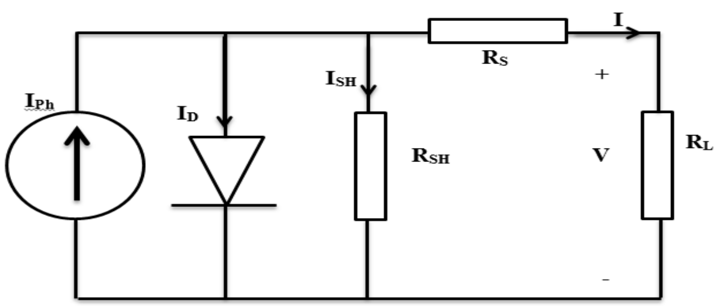


**Fig. 4.** Equivalent circuit diagram for solar cells

Solar cells have a current source that are connected with a parallel diode and resistance, to which is connected a serial resistance. PV panels are built through series or parallel connection of these solar cells. The relation between the voltage of solar battery cells and current switched on the load reveals the I-V and P-V characteristics of the cell. These two characteristics give important clues as to which conditions are required in order for the power obtained from the panel to reach its maximum level. Obtaining maximum power and reaching highest efficiency level in these panels is an important research topic. Solar panels act like a current source for a while, from a certain point onward, they act like a voltage source. Current value that can be obtained from a solar panel is fixed even in case of a short circuit. This value is given along with the label of the panel. It is necessary to obtain maximum power from PV panels in any insolation condition. Maximum power point for PV systems varies depending on atmospheric conditions, which are ambient temperature and insolation amount. In general, PV solar panels reach their maximum power point at around 25°C.

## Boost DC-DC Converter

Boost converter, as its name implies, is a structure that boosts the voltage. Its simplified circuit diagram is shown in Figure 5. In PV systems, input voltage defined as $V_S$ is the voltage in the panel, while output voltage; defined as $V_O$, is the battery or load voltage.

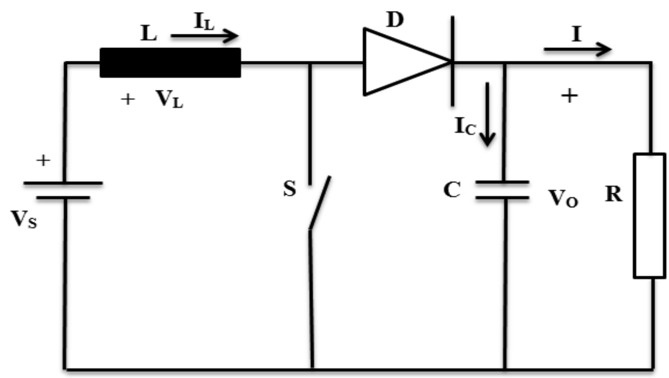


**Fig. 5.** Circuit diagram for boost DC/DC converter

S is MOSFET or IGBT for switching. D is duty cycle which describes duty time ($t_{on}$) of switching MOSFET or IGBT. D is given by equation (2).

$$D = \frac{t_{on}}{t_{on}+t_{off}} = \frac{t_{on}}{T} \quad (2)$$

The conversion is performed as follows:

While switching element (S) turn on, PV structure injects additional energy to inductance through driving current over inductance (L). Then, switching element is cut off and reverse current force in the inductance charges the capacity element over the diode. The relationship between output voltage and input voltage is as follows:

$$V_s = \frac{1}{1-D} V_o \quad (3)$$

$$\frac{I}{I_{pv}} = 1\text{-}D \quad (4)$$

Boost structures are often preferred in stand-alone systems and when panel voltage is lower than battery voltage.

## ESSENTIALS OF PERTURB AND OBSERVE ALGORITHM

P&O algorithm is the most commonly used approach in practice due to its applicability. It enables us to come to a decision through analyzing the change in output power following a variable current increasing or decreasing in PV system. This algorithm is also called Hill Climbing. P-V curve in PV panel is used in this algorithm. The amount of changing (ΔP) in PV panel power is measured following a step increase. If ΔP value is positive, operating current is increased again, which causes PV panel operating point to reach its maximum power point. In other words, output current is observed constantly and it is determined either by decreasing or increasing reference with control variable. This way, it is intended to bring the power to the maximum level. This algorithm and specific changing values are given in Table 1.

**Table 1.** Summary of P&O Algorithm (Wanzeller et al,. 2004)

| **Perturbation** | **Change in Power** | **Next Perturbation** |
|---|---|---|
| Positive | Positive | Positive |
| Positive | Negative | Negative |
| Negative | Positive | Negative |
| Negative | Negative | Positive |

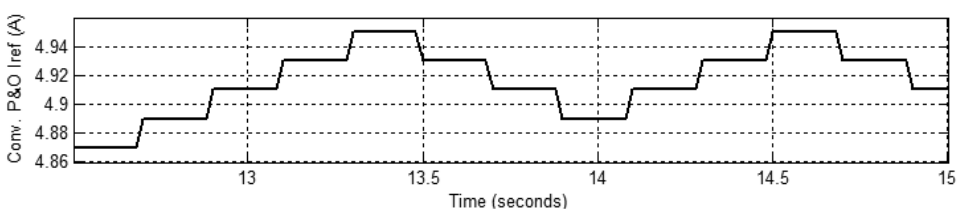


**Fig.6.** PV operating points imposed by the P&O algorithm reference current characteristic

As seen above in Figure 6, the operating points of the PV field are imposed step-by-step by the conventional P&O algorithm. When the system approaches the MPP, the perturbing nature of the P&O MPPT algorithms involves oscillations across the MPP whose characteristics depend on the value of the parameters x: the variable is perturbed, Δx : amplitude of the perturbation imposed x, Tp is the time interval between two perturbations, the general equation describing the P&O algorithm is :

$$x_{((k+1)Tp)} = x_{(kTp)} \pm \Delta x \qquad (5)$$ (Femia *et al.*, 2013)

P&O algorithm is preferred due to its simple structure and useful MPPT algorithm as far as PV energy conversion is concerned where changes in sunlight radiation are constant or slowly changing. This issue can be solved to decrease the perturbation step; but the tracking response will be slower. In rapidly changing weather conditions, P&O algorithm can occasionally make the system operating point far from the MPP (Jung *et al*., 2005). Flowchart of the method is given in Figure 7.

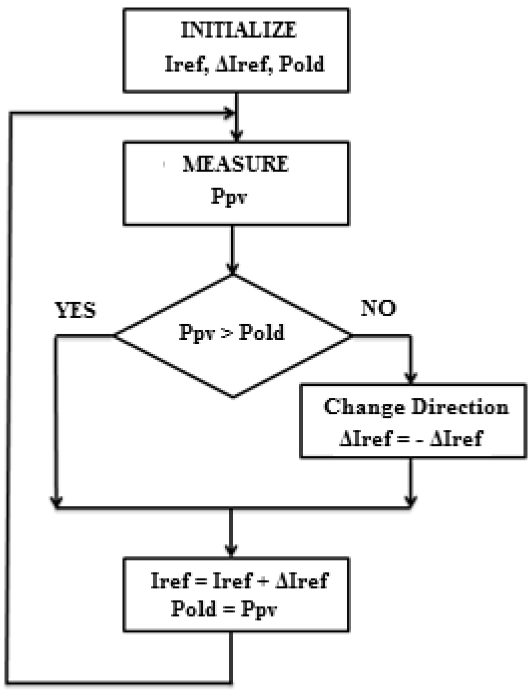


**Fig. 7.** Basic flowchart implementing the conventional P&O algorithm

In this method, output power of PV panel is increased by a fixed step size C, which equals $\Delta I_{ref}$ and it was used to determine whether the current was to change or not.

It is based on the principle that an increase in the power increases current in the same direction while a decrease leads to a direction change, thus causing a decrease in reference current. Adding or subtracting a fixed step size C leads to oscillation around maximum power point. These oscillations may be reduced by improving P&O algorithm. In the following sections, the modified algorithm is presented.

## PROPOSED P&O ALGORITHM WITH MODIFICATION

In the proposed method, instead of a fixed step size C, there was adopted ΔP ($\Delta P = P_{pv} - P_{old}$) in order to attain maximum power point. In other words, power change generates ΔP and it provides a faster way for identifying maximum power point. The meaning of ΔP = 0; no iteration was performed with regards to current changing and oscillation was minimized. The proposed algorithm is shown in Figure 8.

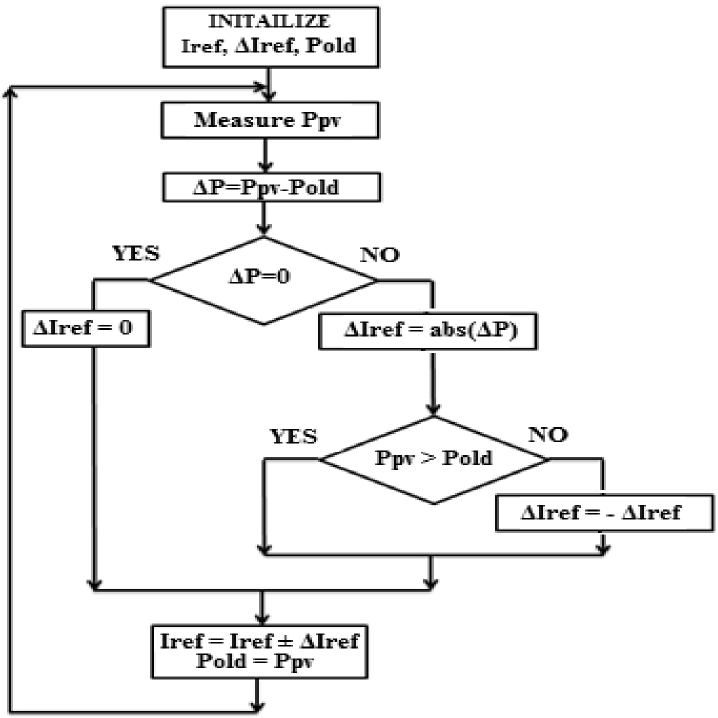


**Fig. 8.** Flow Chart for proposed P&O algorithm

The proposed algorithm was designed in order to prevent oscillation emerging during attempts to identify maximum power point of the P&O algorithm and to faster identify this point following significant power changes. When panel and DC converter reference current is increased or decreased in accordance with this power change, it is found in the simulation results that oscillation is reduced and reference current at maximum power point is identified sooner than it is in the conventional P&O algorithm. In case of no power change, $\Delta P = 0$, and no iteration is performed. In this case, oscillation around maximum power point is eliminated.

When power change increases, iteration coefficient increases. Otherwise, iteration fixed step size decreases. The direction of algorithm is defined by $\Delta I_{ref} = - \Delta I_{ref}$, At left side of MPP, if current increases, power increases and if current decreases, power decreases too. Conversely, at right side of MPP, when current increases, power will decrease and when current decreases, power will increase too. Therefore, when reference current is changed, if there is an increasing in power, changing on same way should be kept on (C which equals absolute value ΔP should be added). If there is a decreasing in power, changing should be continued in an inverse way (C should be subtracted). In Figure 9, the MPPT block structure where simulation is performed is shown. MPPT is a power tracking system that enables to obtain maximum power from PV panels. In MPPT block, DC/DC converter is controlled by P&O algorithm through producing reference current. As a result, the maximum power level from PV panel is reached.

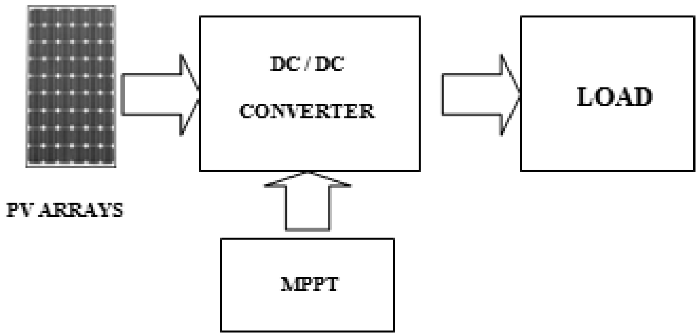


**Fig. 9.** Principal diagram of studied system with MPPT block

In this structure, in parallel with the atmospheric changes, the changing reference current controls DC/DC converter to reach maximum power point. In this study, the solar array terminal power is determined by product block. Inputs of the block are PV panel output voltage and reference current, the MPPT operation relies on the reference current. The proposed system has four PV panels and each module has a maximum power output of 85 W. The control code was written in MATLAB and was tested and run using MATLAB Function block.

## TEST RESULTS

In the following simulations, four cases are considered to compare the two algorithms. In the first case, outputs of PV panels are considered, when insolation increases. In the second one, same parameters are also tested for decreased insolation. In the third case, the insolation was kept constant whereas in the fourth case, the output of PV panels were examined in both increasing and decreasing insolation.

### Case 1: Increasing insolation

Results obtained from the MATLAB Model are presented in case1. Starting solar irradiation is 980W/m$^2$. Irradiation is increased to 996 W/m$^2$ linearly until 16th second.

In this case, a linear increase was observed in the system which is exposed to a irradiation rate of 980W/m$^2$ for 16 seconds and the radiation increased to 996 W/m$^2$. In view of this change, that can be considered as slow, classical method and response of identical systems operated by the modified method were compared. Current, voltage and power responses are shown in Figure 10-13.

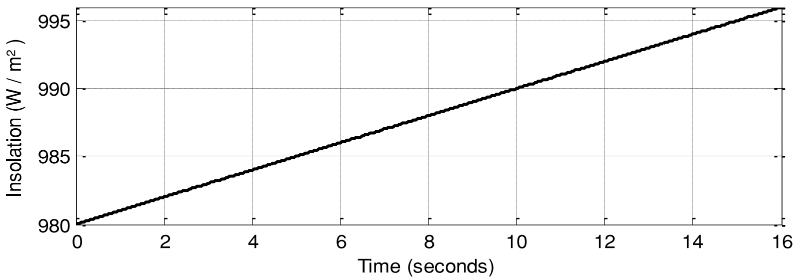


**Fig. 10.** Solar insolation changing for case 1

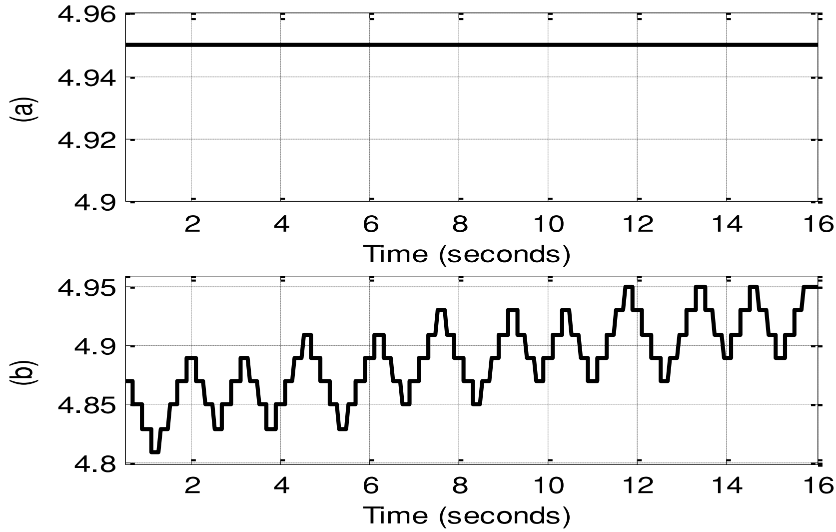


**Fig. 11.** Reference current in (a) modified (b) conventional algorithms for case 1

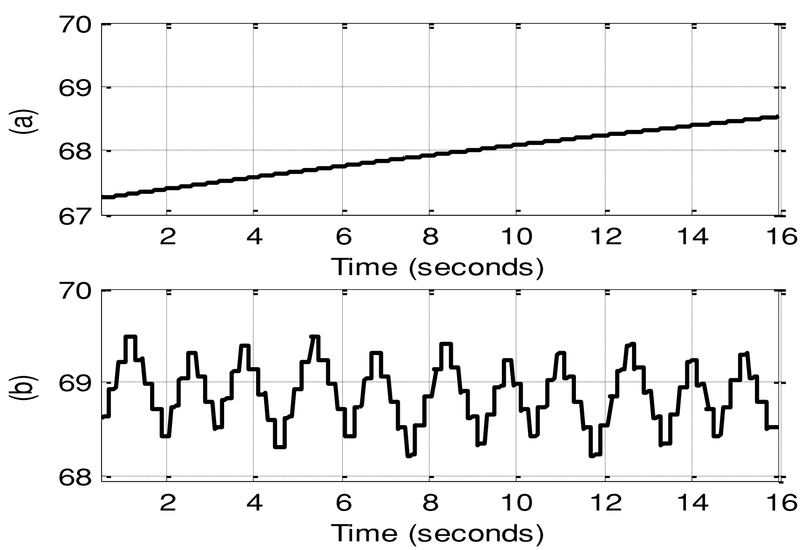


**Fig. 12.** Panel voltage in (a) modified (b) conventional algorithms for case 1

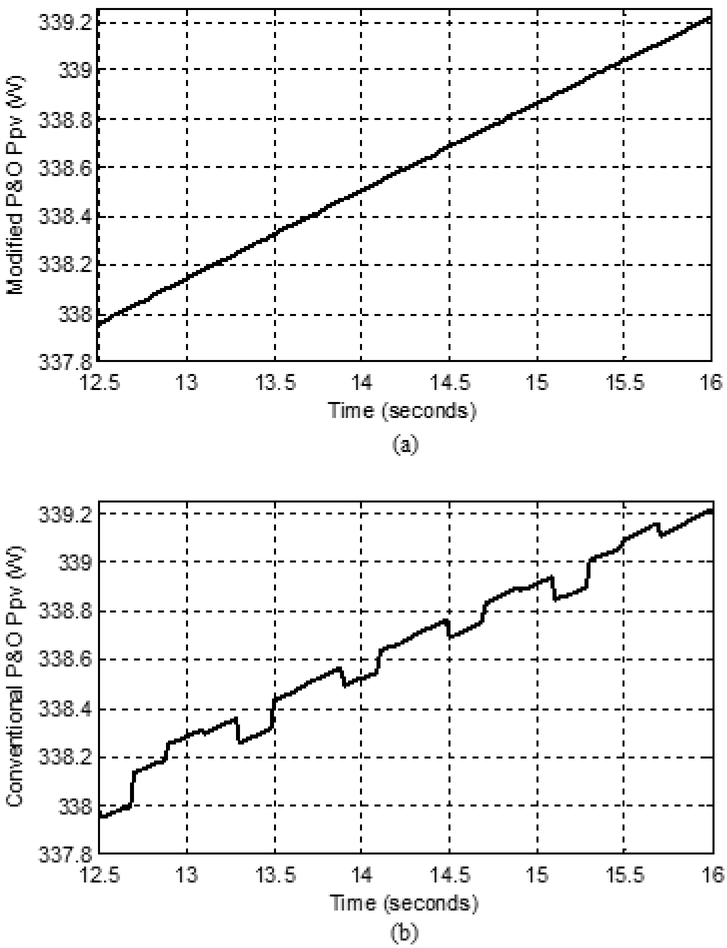


**Fig. 13**. Magnitude panel output power in (a) modified (b) conventional algorithms for case 1

It can be clearly seen from Figures 11-13 that the modified P&O algorithm removes oscillations around the MPP under various insolation levels.

## Case 2: Decreasing insolation

Results obtained from MATLAB Model are presented in case 2. Solar irradiation is 1000 W/m$^2$ at starting point and it is decreased to 984 W/m$^2$ linearly until 16th second.

In this case, a linear decrease was applied in the system from 1000 to 984 W/m$^2$. In view of this change, which can be considered as slow, conventional algorithm and response of identical systems operated by the modified method were compared as in case 1. Current, voltage and power responses are compared in Figures 14-17.

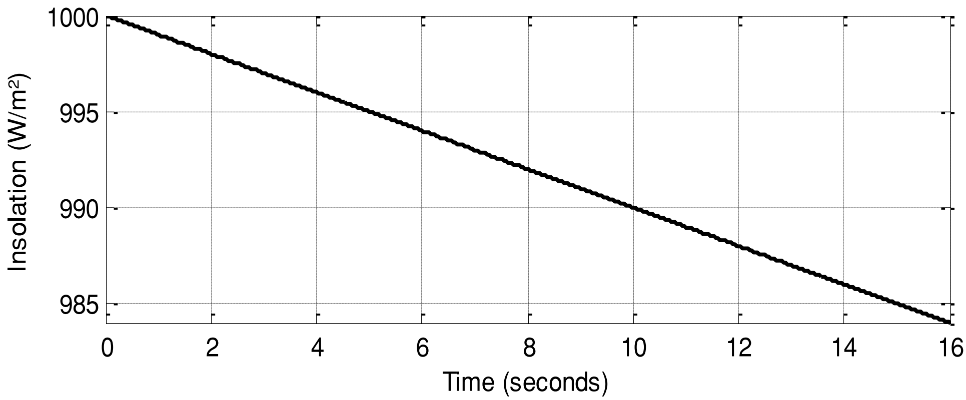


**Fig. 14.** Solar insolation changing for case 2

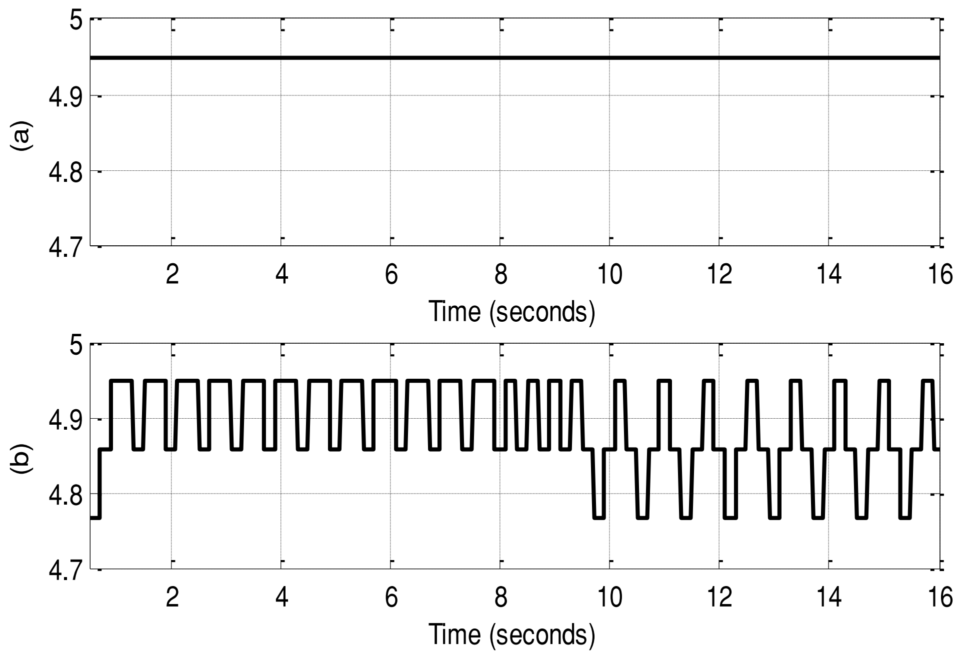


**Fig. 15**. Reference current in (a) modified (b) conventional algorithms for case 2

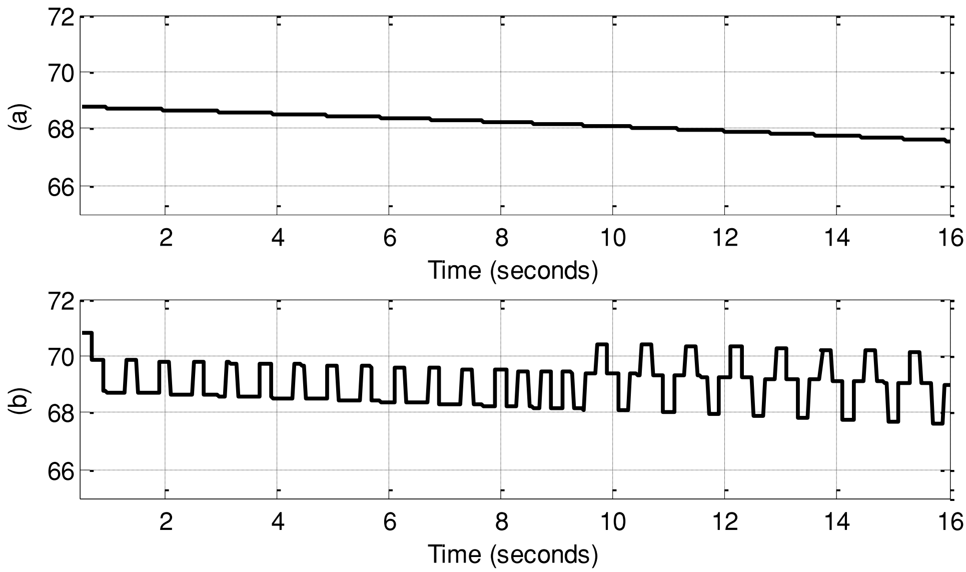


**Fig. 16.** Panel voltage in (a) modified (b) conventional algorithms for case 2

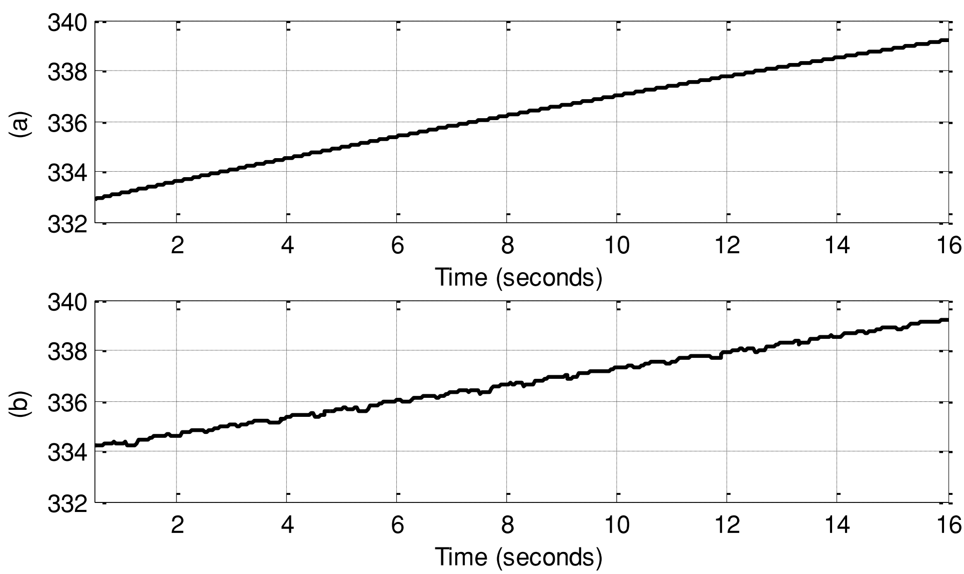


**Fig. 17.** Panel output power in (a) modified (b) conventional algorithms for case 2

It can be seen from the results of the two cases that both algorithms reach assumed values at the end of this process. However, in the conventional algorithm, oscillations occur and maximum power point is attained slightly later. Particularly, as shown in Figures 12 and 16, voltage oscillations are to continue for a specific period of time. These oscillations affect total efficiency of the system negatively, too. Losses may be encountered due to changing parameters as a result of oscillations. As these results also suggest, oscillations persist in conventional methods. These oscillations pose disadvantages because they affect total efficiency of the panel and extend MPPT identification time.

## Case 3: Constant insolation

Results obtained from MATLAB Model are presented in case 3. Solar irradiation is at a constant value of 1000 W/m$^2$ for 400 ms.

In this case, a constant insolation was applied in the system at 1000 W/m$^2$. In view of this value, the conventional algorithm and response of identical systems operated by modified method were compared. The power responses are compared in Figure 18.

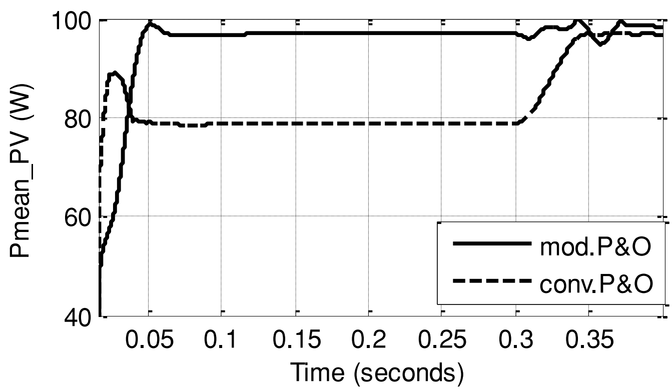


**Fig. 18.** Panel output power in modified and conventional P&O algorithms for case 3

While in this figure, the maximum power reached by modified algorithm at 0.05 second is around 100W, the value reached by the conventional algorithm is about 80 W. At around 0.4 second it appears that both of the power values get close to each other. Here it is seen that the modified algorithm reaches the maximum power value in a shorter time and that it demonstrates a better performance.

## Case 4: Increasing and decreasing insolation

In this case, to make differences clearer between conventional and modified methods: more PV panels (kW) were used and insolation level was increased-decreased in a much shorter time period. Solar irradiation is 950 W/m$^2$ at starting point, it is increased and decreased to 1250 W/m$^2$ levels. Photovoltaic array used in this study has electrical parameters given in Table 2. The power responses are compared in Figure 19 and Table 3.

**Table 2.** Electrical characteristics of PV panel (Sunpower SPR-305) in the simulations

| **Module specifications under STC** | **Parameters** |
|---|---|
| Open-circuit voltage (Voc) | 64.2 V |
| Short-circuit current (Isc) | 5.96 A |
| Voltage at Pmax (Vmp) | 54.7 V |
| Current at Pmax (Imp) | 5.58 A |
| Number of series-connected modules per string | 5 |
| Number of parallel string | 66 |

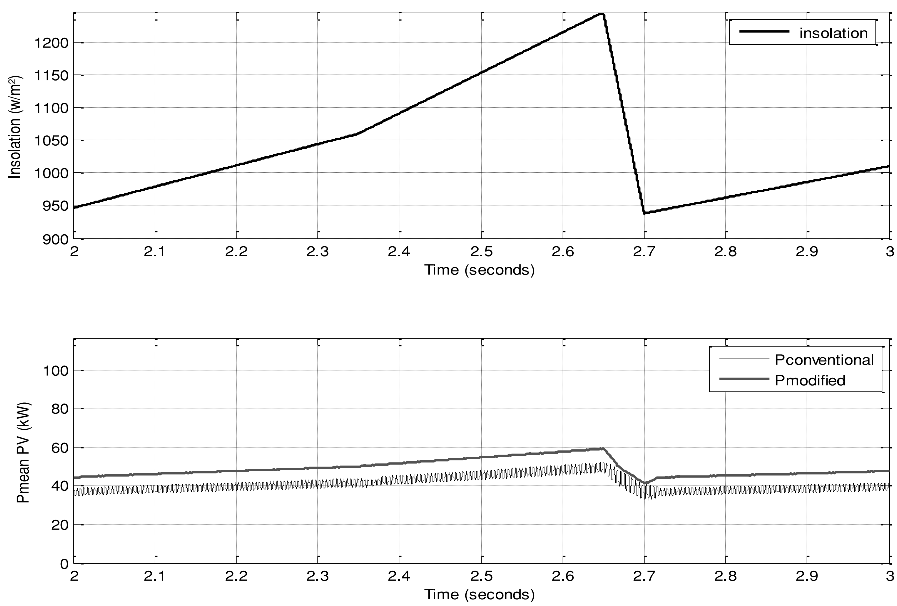


**Fig. 19.** Panel output power in modified and conventional algorithms for case 4.

**Table 3.** Output powers under various solar irradiance

| **W/m²** | **Second** | **Pmod(kW)** | **Pcon(kW)** | **Δ** |
|---|---|---|---|---|
| 949 | 2.0 | 44 | 38 | 8 |
| 975 | 2.1 | 46 | 40 | 6 |
| 1010 | 2.2 | 47 | 42 | 5 |
| 1040 | 2.3 | 49 | 43 | 6 |
| 1080 | 2.4 | 52 | 45 | 7 |
| 940 | 2.7 | 42 | 37 | 5 |
| 970 | 2.8 | 45 | 38 | 7 |
| 980 | 2.9 | 46.5 | 38.5 | 8 |
| 1020 | 3.0 | 47 | 39 | 8 |

In Figure 19, it is demonstrated that in highly changing solar irradiance conditions and in shorter time intervals, the modified algorithm produces a higher value of power and without oscillation.

According to Table 3 $\Delta_{mean} = 6.66\ kW$ and when the differences between output powers are considered, the rate in the lowest irradiation case is 5 kW, while in the highest case there is a difference of 8 kW.

It can be seen from the results obtained from four cases that both algorithms reach different values at the end of this process. Additionally, in conventional algorithm, oscillations occur and maximum power point is attained slightly later with less power value. Particularly, as shown in Figures 11–13 and 15-19 voltage, current, power oscillations are to continue for a specific period of time. These oscillations affect total efficiency of the system negatively, too. Losses may be encountered due to changing parameters because of oscillations.

As the results suggest, the modified P&O algorithm has a good advantage with regards to removing the oscillation and improving performance in the conventional P&O algorithm. Oscillation around MPP is a big difficulty of the conventional algorithm and this proposed method solves this problem under the above conditions.

## DISCUSSION

Even though, PV systems have low efficiency values, the systems are preferred more. System efficiency involves many equipments and parameters in the system. Efficiency of a single solar cell may differ from that of the panels comprised of these cells. Problems during installation negatively affect panel efficiency. There are also other factors such as panel angle, shadows of neighboring high buildings or cloudy weather. Which cause total or partial shadowing and thus decrease total efficiency. Additionally, software and hardware problems in MPPT decrease efficiency. Efficiency and losses in converter circuit and algorithms that sets the basis for MPPT are among other factors which may have a negative influence on total efficiency. Slow response rate and less power value of the algorithm together with oscillation are also important problems. These factors force us to improve the algorithm.

## CONCLUSIONS AND RECOMMENDATIONS

This study focuses on improving algorithm, eliminating oscillation problems, and rapidly reaching more power value than conventional P&O algorithm in PV systems. Especially when variability increases because of factors such as partial shadowing and cloudy weather, these oscillations are bound to affect the system more. Therefore, it is suggested that this improvement attempts for the algorithm will derive positive results in terms of system efficiency. It is also possible to suggest that changes in the algorithm will bring out no difficulties in terms of hardware, which makes it suitable for experimental purposes. In the upcoming studies, it is required to improve the algorithm as far as hardware is concerned.

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