

A Modified Perturb and Observe Maximum Power Point Tracking Technique for Single-Stage Grid-Connected Photovoltaic Inverter

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Abstract: - There is an inherent tracking-oscillations trade-off problem in Perturb and Observe (P&O) maximum power point tracking (MPPT) technique for photovoltaic (PV) system. Higher perturbation step-size increases the tracking speed at the cost of greater oscillations around maximum power point (MPP); whereas, smaller step-size slows down the tracking while reducing the oscillations around MPP. In this paper, a modification in P&O method is proposed to reduce this tracking-oscillations trade-off problem by setting an initial approximate perturbation value whenever irradiance changes and continuing tracking with adaptive step-size. Detail simulation results of the modified P&O method are presented and compared with the results obtained considering different values of fixed step sizes. The P&O method with the proposed modifications clearly shows maximum tracking speed with minimum oscillations around MPP. Moreover, due to the modifications, the algorithm can track MPP efficiently in case of sudden irradiance change.

Key-Words: -Photovoltaic (PV), Perturb and Observe (P&O), Maximum Power Point Tracking (MPPT), Grid-connected PV, Inverter, Modulation Index, Phase Angle.

1 Introduction

The electrical energy production by using solar photovoltaic (PV) array has been drawing immense interest since solar energy is an environment friendly, maintenance-free and abundant source of energy. The increasing energy consumption around the world and the continuous depletion of fossil-fuel reserves makes it essential to harvest energy from alternative energy sources like solar energy. However, some drawbacks are associated with PV systems: high installation costs and low conversion efficiency. The commercial viability of PV power generation greatly depends on further improvement of conversion efficiency and reduction of cost. The power generated by a PV array largely depends on solar irradiance and temperature, different atmospheric conditions such as clouding and local surface reflectivity. The non-linear characteristics of PV array and the intermittent nature of sunlight hamper the proper utilization of PV array. For certain irradiance, there is a unique maxima at a particular operating voltage in the power versus voltage (P - V) curve of PV array which is known as maximum power point (MPP). The MPP keeps changing with solar irradiance and ambient temperature. To extract the maximum power at any

environmental condition, maximum power point trackers (MPPTs) are usually employed. An MPPT is basically a dc-dc converter whose duty cycle is adjusted so that PV array is operated at the voltage corresponding to the MPP. The operating voltage and current are sensed and fed to the control unit for computation of duty cycle by any suitable MPPT algorithm that will ultimately lead the system operate at MPP.

For years, research has focused on various MPPT algorithms [1] to draw the maximum power of the solar array. The methods vary in various aspects such as tracking speed, sensors required, oscillations around MPP, complexity, cost and hardware required for implementation. Several MPPT techniques have been reported in the literature such as Perturb and Observe (P&O) [2], [3], Incremental Conductance (InC) [4], [5], Fractional Open-Circuit Voltage [6], [7], Fractional Short-Circuit Current [8], [9], Constant Voltage [10], Neural Network [11] and Fuzzy Logic control [12]. The P&OMPPT algorithm is most popular and widely used due to its simplicity, ease of implementation and the fact that it requires fewer measured parameters. However, in spite of simplicity, this technique is reported to have several

drawbacks which degrade its performance [1], [13]. For fixed perturbation step-size, the steady-state oscillations are proportional to the perturb value and larger step-size causes higher oscillations. The oscillations of the operating point around MPP gives rise to waste of some amount of available energy. Smaller step-size, although reduces steady-state oscillations, results in slower response. Therefore, the famous trade-off problem between steady-state oscillations and speed of response is inherent in the P&O algorithm. To reduce this tracking-oscillations trade-off problem and improve the performance, variable step-size is employed [14], [15], [16]. The perturb value is varied depending on the output power. These techniques are not truly adaptive. Nevertheless, they exhibit better performance compared to that with fixed step-size. There are other modified techniques which are truly adaptive, but high computational burden and complexity make their implementation difficult [17], [18]. Novel MPPT techniques using fuzzy logic [19], nonlinear equations [20], and complicated optimization algorithms [3], [21] show improved performance, but computational complexity and the fact that they need sophisticated controllers for implementation limit their uses [1], [13].

In this paper, a modification in P&O algorithm is proposed to set a suitable initial perturbation value and adaptive step-size. The setting of initial perturbation value accelerates the tracking and adaptive step-size reduces the oscillations around MPP as well as increases the tracking speed.

2 Perturb and Observe Algorithm

Photovoltaic arrays present a nonlinear I - V characteristic. For different solar irradiances and constant temperature, the current vs. voltage (I - V) curves and power vs. voltage (P - V) curves are shown in Fig. 1.

The data to plot the I - V and P - V curves are obtained by loading the PV array from short circuit to open circuit condition. The curves are used to obtain performance level of PV systems (cells, modules, arrays). I - V curve can show the peak power point located on its farthest upper right corner, where, the rectangular area is greatest under the curve. Maximum power is generated at only one point on the power curve; this occurs at the knee of the curve. The slope of the power curve $\partial P/\partial V$ is positive on the left side of the MPP and negative on the right side of MPP. At MPP, the slope $\partial P/\partial V$ equals to zero. The portion of the I - V curve at the left of MPP is called the constant current region since variation of current is very small. Similarly,

the right portion of the curve is called constant voltage region due to very small variation of voltage in that region.

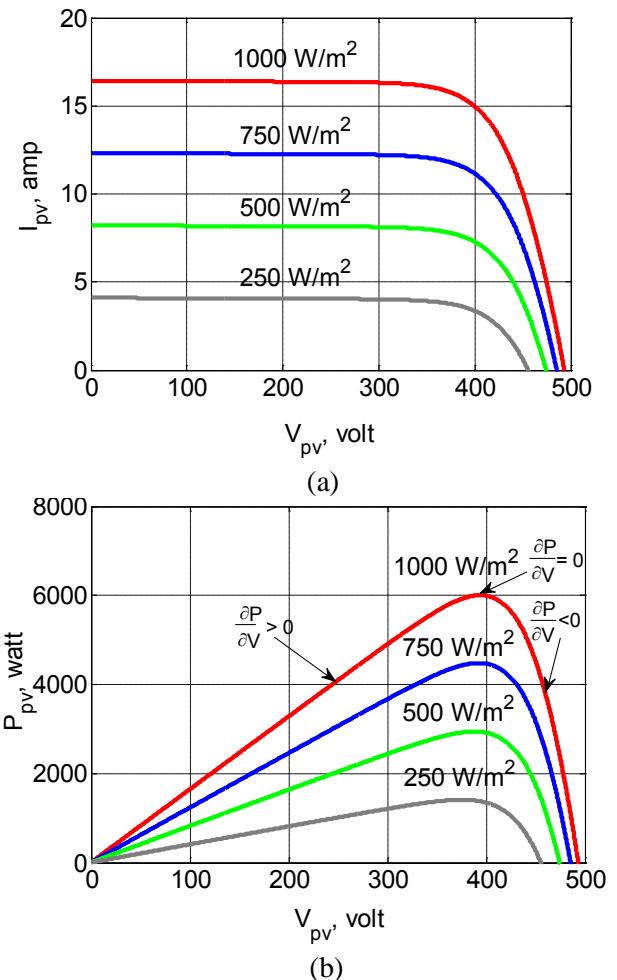


Fig. 1 (a) I - V curves and (b) P - V curves of PV array for constant temperature ($25^{\circ}C$) and different irradiances.

Since the MPP depends on solar irradiation and cell temperature, it is never constant over time; thereby Maximum Power Point Tracking (MPPT) should be used to track its changes. As the MPP changes with time during the day and throughout the year, a suitable power harvesting action must be performed continuously by the power electronic converter that interfaces the PV generator to the load and/or grid, setting its operating point in a manner that allows the modules to produce the most power they are capable of. Then, a control tracking algorithm must be developed to follow the MPP of the PV field that is the MPPT algorithm.

P&O method involves a perturbation in the operating voltage of the PV array. Perturbing the duty ratio of power converter results in perturbation of the PV array current which ultimately perturbs the PV array voltage. It can be understood from Fig. 1(b) that power is increased (decreased) when

voltage is incremented (decremented) and the operating point lies on the left of the MPP. The power decreases (increases) for the increase (decrease) of voltage when the operating point lies on the right of the MPP. Hence, in case of power increase, the subsequent perturbation should be kept the same to reach the MPP and in case of power decrease, the perturbation should be reversed. A summary of the algorithm is presented in Table 1.

Table 1: Summary of Perturb and Observe algorithm

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. Reducing the perturbation step size, this oscillation can be minimized. However, a smaller perturbation size slows down the MPPT. A solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP as shown in [3]. The P&O method cannot track the MPP when the irradiance changes rapidly; and it oscillates around the MPP instead of directly tracking it.

Numerous researches have been undertaken on perturb and observe method to improve its performance. The techniques employ either fixed or variable step-size.

2.1 Perturb and observe with fixed perturbation step-size

A fixed perturbation step-size is used to generate reference signal. Either the array reference voltage [22], [23] or current [24], [25] is perturbed. Usually a hysteresis or PI controller is used to control the power. For small step-size, the tracking is slow but the oscillations around MPP are low. Faster tracking is obtained using larger step-size at the cost of greater oscillations. Thus, the P&O methods with fixed step-sizes suffer from an inherent tracking-oscillations trade-off problem. Some techniques are also proposed [26], [27] where converter duty ratio is perturbed instead of array voltage or current. The hysteresis or PI controller is eliminated that makes the control process easier. However, due to fixed perturbation step-size, the tracking-oscillations trade-off problem persists.

2.2 Perturb and observe with variable perturbation step-size

Perturb and observe methods with variable step-size are proposed to improve its performance and solve the tracking-oscillations trade-off problem. The techniques may be truly adaptive or non-adaptive. Al-Amoudiet. al. [14] proposed a method with variable step-size that gradually decreases towards MPP. But this method is not truly adaptive since the steps are varied in a predetermined way. A model-based approach is introduced by Zhang et. al. [15] that measures the PV array temperature and solar irradiance. For a specific set of irradiance and temperature measurements, a DC voltage value is predicted which leads to the output power delivered by the PV array to be maximum. This is applied as the reference signal for a PI type voltage controller. Though it works well, it involves extra hardware for measuring temperature and solar irradiance. A variable perturb is proposed in [16], where four power ranges are adopted. A specific perturb value is used in each range. Therefore, this method is not fully adaptive. G. Petrone et. al. [28] proposed a multivariable Perturb-and-Observe MPPT technique for single-stage PV inverter. Though it performs well, the need for controlling more than one variable increases the complexity of the operation.

3 MPPT in a Single-Stage GCPV System

A single-stage GCPV system is shown in Fig. 2. A line frequency transformer is used instead of DC-DC converter for voltage boosting. In conventional two-stage topology, the task of MPPT is performed by adjusting the duty cycle of the DC-DC converter. In the single-stage topology as shown in Fig. 2, the control parameters for MPPT are modulation index or phase angle of inverter switching signal. A phase angle based control strategy is proposed in [29] where the MPPT is undertaken adjusting the phase angle of inverter switching signal only keeping modulation index constant. In this paper, a modification is proposed in the P&O method of MPPT considering the topology and control strategy presented in [29] to reduce the inherent tracking-oscillations trade-off problem in P&O method.

Before proposing the modifications in P&O method, the GCPV system shown in Fig. 2 needs to be simulated first to understand the nature of power variation with the variation of phase angle and set necessary equations for the modified MPPT algorithm.

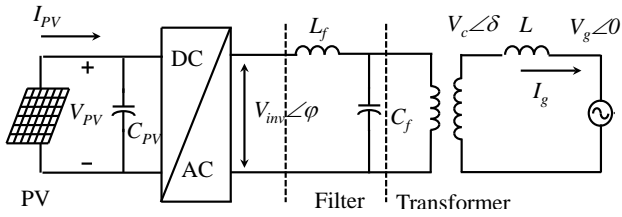


Fig. 2 Single-Stage grid-connected PV system

A PV array with capacity 511 W has been used which is built by connecting six PV modules in series. The ratings of the PV module and the PV array at standard testing conditions (1000 W/m², 25^o C) are given in Table 2.

Table 2: PV module/array rating (at standard testing conditions)

Symbol	Parameter	Value (module)	Value (Array)
I_{sc}	Short-circuit current	5.424A	5.424A
V_{oc}	Open-circuit voltage	22.2V	133.2V
I_{mpp}	Current at maximum power	4.932A	4.932A
V_{mpp}	Voltage at maximum power	17.27V	103.6V
P_{max}	Maximum power	85.16W	511W

The circuit parameters and their values used in the simulation are listed in Table 3. The transformer used is assumed ideal with turns ratio is 1:4.

Table 3: Parameters used in the simulation of single phase GCPV system

PV Array	C_{PV}	L_f	C_f	L
511W	2mF	10mH	10μF	10mH

Considering the PV array rating and the parameters listed in Table 2 and Table 3, simulation is performed where phase angle is adjusted manually at a certain irradiance to extract maximum power. Again simulation is performed where irradiance is changed from one level to another and phase angle is adjusted manually to extract maximum power. The power versus phase angle curves at different irradiances took the form as shown in Fig. 3. The values of phase angles corresponding to the maximum power at different irradiance levels are listed in Table 4.

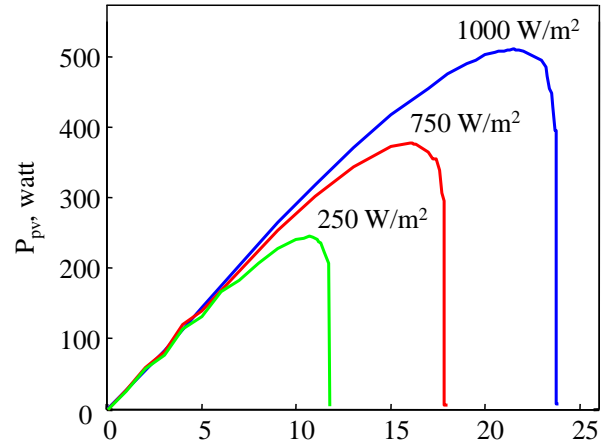


Fig. 3 PV power versus phase angle curves.

Table 4: Phase angles corresponding to MPPs at different irradiances

Irradiance W/m ²	Maximum PV Power P _{max} , W	Phase Angle φ _{max} , deg
1000	511	21.45
900	457.4	19.3
800	403.9	17.1
700	350.7	14.75
600	297.78	12.75
500	245.1	10.8
400	193.1	8.7
300	141.9	6.6
200	92	4.7

From the data of Table 4 it is found that the ratio of difference in φ_{max} to difference in P_{max} at two different irradiances is almost constant.

$$\frac{\varphi_{1\max} - \varphi_{2\max}}{P_{1\max} - P_{2\max}} \cong \frac{\varphi_{2\max} - \varphi_{3\max}}{P_{2\max} - P_{3\max}} \cong \dots \cong \frac{\varphi_{k\max} - \varphi_{(k+1)\max}}{P_{k\max} - P_{(k+1)\max}}$$

In generalized form

$$\beta \cong \frac{d\varphi_{k\max}}{dP_{k\max}} \tag{1}$$

It has been noticed while performing simulation that whenever change of irradiance occurs, the PV array power (vs. time) curve, before being stable around the MPP, crosses a point where the value of power is equal to the maximum value of power corresponding to the changed irradiance. It can be seen in Fig. 4 that PV array power curve, before reaching the MPP, crosses a point where the value of power is equal to the maximum value of power corresponding to the respective irradiance. In each case of irradiance change, it is found that the PV power curve attains a maximum value P_{max-initial} shortly after the change of irradiance before

reaching the actual stable maximum power point $P_{\text{max-stable}}$. Thus, the information of the maximum attainable power $P_{k\text{max}}$ at any irradiance can be obtained at the very beginning of the changed conditions before the operating point becomes stable around the actual MPP. This information of the maximum power can be used to determine an approximate phase angle corresponding to MPP. The value of this phase angle can further be used to set the initial phase angle.

At the beginning, an arbitrary value of initial phase angle and step-size may be chosen for any environmental conditions. Simulation will be carried out until the MPP is reached. Let us consider that for the first irradiance value S , the PV array generates maximum power $P_{S\text{max}}$ at an angle $\varphi_{S\text{max}}$. Now, for a certain irradiance S_k , the approximate phase angle corresponding to MPP can be calculated as

$$\varphi_{k\text{max}} = \varphi_{S\text{max}} (P_{S\text{max}} - P_{k\text{max}}) \times \beta \quad (2)$$

When $\varphi_{k\text{max}}$ is determined, the step-size can be calculated from

$$\Delta\varphi_k = (\varphi_{k\text{max}} - \varphi) / \gamma \quad (3)$$

where, γ is a constant. Since the difference $(\varphi_{k\text{max}} - \varphi)$ decreases as the operating point approaches MPP, the step-size gradually becomes smaller. Choosing a suitable value of γ for step-size calculation may greatly reduce the oscillations around MPP. Thus, the variable step size ensures faster convergence and smaller oscillations at or near MPP. Once $\varphi_{k\text{max}}$ is determined, the initial phase angle to set is obtained from

$$\varphi_{k_initial} = \varphi_{k\text{max}} - \varphi_c \quad (4)$$

where, φ_c is a small phase angle. The smaller the value of φ_c , the faster the operating point approaches MPP. However, too small a value may cause oscillations around MPP.

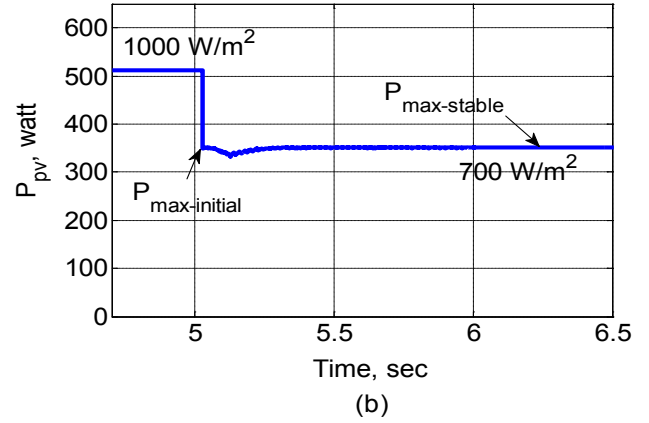
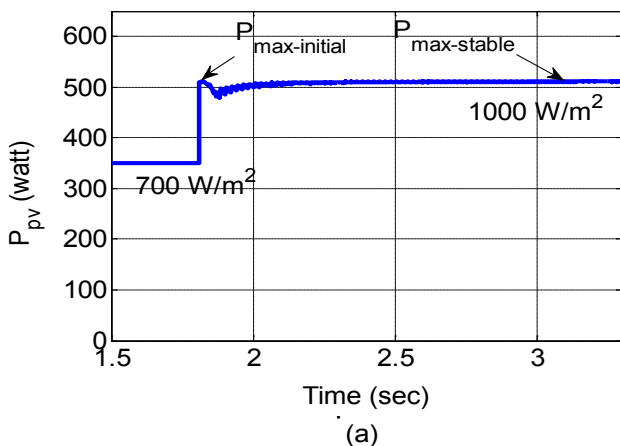


Fig. 4 PV power curves for irradiance changes (a) from 700 W/m² to 1000 W/m² and (b) from 1000 W/m² to 700 W/m².

4 Simulation and Results

For simulation, the value of β is chosen first. Using the values of P_{max} and φ_{max} given in Table 4, we get

$$\begin{aligned} \frac{d\varphi_{1\text{max}}}{dP_{1\text{max}}} &= 0.0411 & \frac{d\varphi_{2\text{max}}}{dP_{2\text{max}}} &= 0.0411 & \frac{d\varphi_{3\text{max}}}{dP_{3\text{max}}} &= 0.0432 \\ \frac{d\varphi_{4\text{max}}}{dP_{4\text{max}}} &= 0.0387 & \frac{d\varphi_{5\text{max}}}{dP_{5\text{max}}} &= 0.037 & \frac{d\varphi_{6\text{max}}}{dP_{6\text{max}}} &= 0.0404 \\ \frac{d\varphi_{7\text{max}}}{dP_{7\text{max}}} &= 0.0410 & \frac{d\varphi_{8\text{max}}}{dP_{8\text{max}}} &= 0.0381 \end{aligned}$$

The approximate value of β has been chosen as 0.04. The values of γ and φ_c are considered 15 and 1⁰ respectively. The PV array voltage, current and power for irradiance levels 700 W/m², 1000 W/m², 400 W/m² and 900 W/m² are shown in Fig. 5. The PV array power is shown separately in Fig. 6. From the PV power curve (Fig. 6), it is seen that at different irradiances the MPP is tracked very efficiently. When irradiance changes, it takes very little time to reach the new MPP. Further, the algorithm performs very well for rapid and drastic change in irradiance. This is due to the new technique to initialize phase angle and adaptive variation of the step size when irradiance is changed. The power oscillations around MPP is found less than 0.5W at different irradiances.

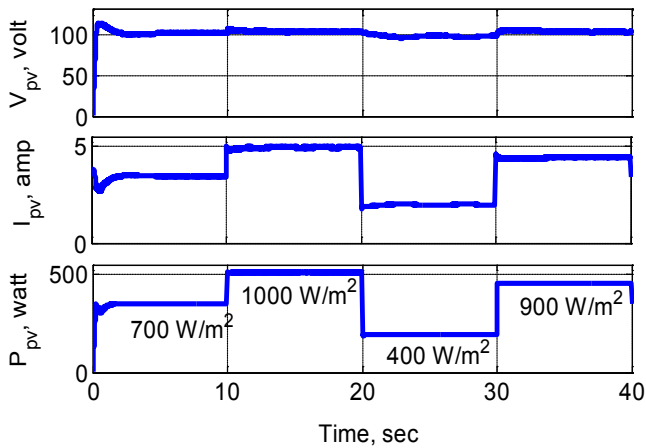


Fig. 5 PV array voltage, current and power for different irradiances simulated with the proposed method.

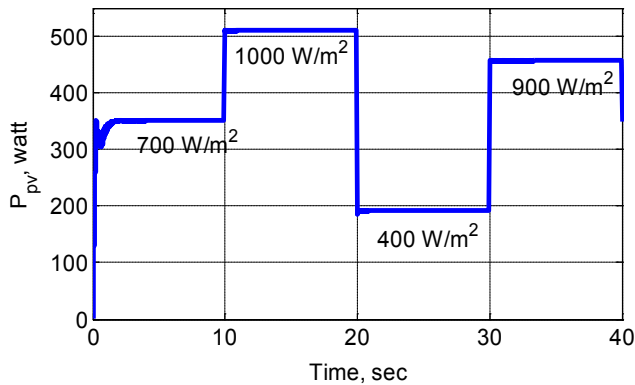


Fig. 6 The PV array power at different irradiances.

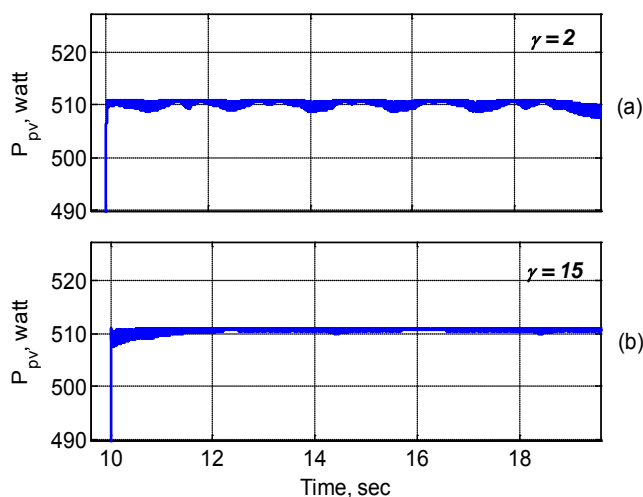


Fig. 7 Oscillations in PV array power at 1000 W/m² when (a) $\gamma=2$ and (b) $\gamma=15$.

It has already been stated that γ is a constant upon which the step-size depends. Larger value of γ results smaller step-size and vice-versa. Smaller value of γ or more specifically larger

step-size results greater oscillations during MPP tracking process as shown in Fig. 7 for two values of γ . Greater oscillations around MPP are noticed in Fig. 7(a) where γ equals 2. Significant reduction in oscillations is noticed in Fig. 7(b) where γ equals 15.

For comparing the results with the proposed modifications, the system is also simulated with the conventional P&O technique of MPPT employing fixed perturbation step-size. The power at 700 W/m² and 1000 W/m² are shown in Figs. 8(a)-(c) for step-sizes 1⁰, 0.5⁰ and 0.2⁰ respectively. When step-size is 1⁰, the oscillation is large (Fig. 8(a)). The oscillation decreases as the step-size is reduced to 0.5⁰ and 0.2⁰ (Fig. 8(b) and Fig. 8(c)). Oscillation is minimum for the P&O technique with proposed modifications (Fig. 8(d)). Again, it is seen that tracking speed is high when step-size is 1⁰ (Fig. 9(a)). As the step-size decreases to 0.5⁰ and 0.2⁰ tracking speed decreases (Fig. 9(b) and Fig. 9(c)). Tracking speed is maximum in case of the P&O technique with the proposed modifications (Fig. 9(d)).

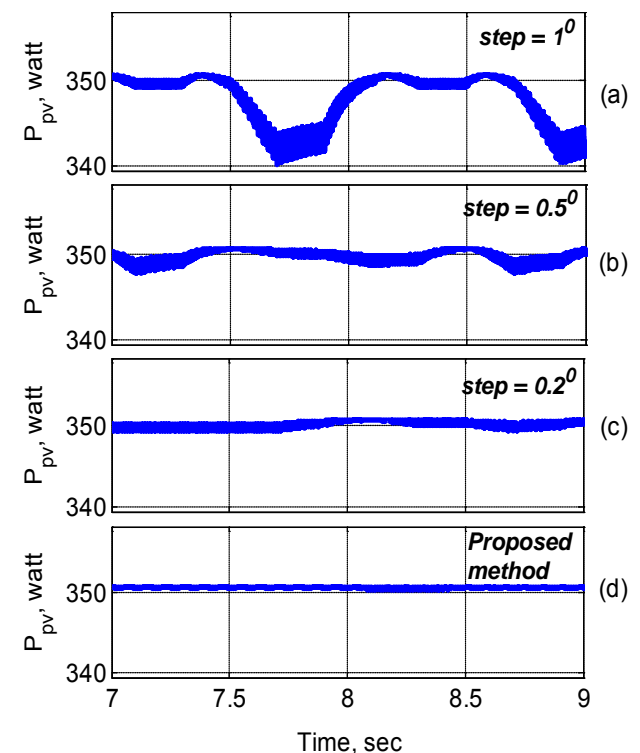


Fig. 8 PV array power for 700 W/m² when perturbation step-size is (a) 1⁰, (b) 0.5⁰, (c) 0.2⁰ and (d) variable according to proposed method.

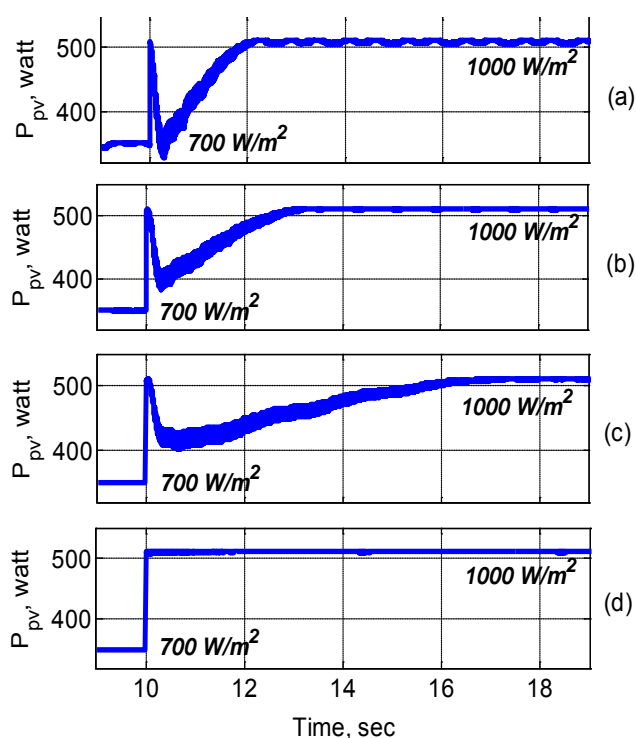


Fig. 9. PV array power for irradiance changes from 700 W/m^2 to 1000 W/m^2 when perturbation step-size is (a) 1° (b) 0.5° (c) 0.2° and (d) variable according to proposed method.

5 Conclusions

A modification in Perturb and Observe MPPT technique is proposed in this paper to reduce its inherent tracking-oscillations trade-off problem. Single-stage grid-connected PV inverter is considered where phase angle of the inverter switching signal is adjusted for tracking MPP. A technique is proposed to set an initial phase angle whenever irradiance changes. The step-size of perturbation is adaptive such that it is larger when the operating point is far from MPP and it becomes smaller gradually as the operating point approaches closer to the MPP. Details of the modification with necessary equations are presented. Simulation results clearly show the improvement in the performance of P&O method with the proposed modifications. The results are compared with the results obtained from the simulation considering different values of fixed step-sizes. It is found that the tracking speed is maximum and the oscillations around MPP are minimum for the proposed modifications. Again the MPPT algorithm performs very well in case of sudden irradiance changes.

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