



# A P&O Based Variable Step Size MPPT Algorithm for Photovoltaic Applications

Gokhan YUKSEK<sup>id</sup>, Ahmet Naci METE\*<sup>id</sup>

Mersin University, Department of Electrical and Electronics Engineering, 33343 Mersin, Turkey

## Highlights

- This paper focuses on maximum power point tracking problem.
- A modified P&O method is proposed for fast tracking and less oscillations around MPP point.
- Results obtained by simulations are verified by an experimental setup.

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## Abstract

Maximum power point tracking (MPPT) is an indispensable component of the Photovoltaic (PV) systems to maximize efficiency. Perturb and observe (P&O) is one of the prevalent MPPT methods owing to its easier structure for implementation but it suffers from problems of slow tracking and oscillations around the MPP. In this paper, a modified variable step size MPPT algorithm based on P&O method is proposed to obtain maximum power output from the PV system coupled with a boost DC-DC converter. The proposed method employs the scaled power difference as a control variable to enable variation of step size for each cycle. Results obtained by simulation and experimental work verified that the proposed algorithm is potent mitigating the problems related with classical P&O method.

## 1. INTRODUCTION

Solar energy is the most prevailing renewable energy source as obtaining electricity using photovoltaic (PV) systems has become easier and cheaper with recent advances in technology. As the need for PV systems is booming, increasing efficiency of these systems is of imminent importance. Maximum Power Point Tracking (MPPT) methods have been in usage for a long time to obtain steady power output from PV systems with varying terms for instance irradiance, temperature and panel dirtiness [1].

There are numerous techniques proposed as MPPT methods which can be mainly categorized as soft computing (SC) and conventional techniques [2-4]. Fuzzy Logic Control (FLC), Genetic Algorithm (GA), Particle Swarm Optimization (PSA), Artificial Neural Network (ANN), Fireflies Algorithms are the best known soft computing techniques [5]. SC techniques have flexible algorithms requiring no mathematical model of the system considered. Thus, they can be easily adopted to different systems without any need for controller change. SC methods can also handle the irradiance and temperature nonlinearities very well. This is one of the superiorities of SC methods over the conventional MPPT methods [6]. Employment of SC methods did not prevail throughout PV systems due to factors such as high cost of implementation and complex structures.

Conventional MPPT methods use current or voltage sensing of PV modules. Depending on the state of power, current or voltage, MPPT controllers determine the duty cycles of power converters. Widely used conventional MPPT methods differ each other by their cost effectiveness, tracking speed and oscillation amount at steady state maximum power point (MPP). Among them, fractional open circuit (FOC) and fractional short circuit (FSC) methods are moderately complicated but they lack accuracy [7, 8]. FOC

method uses the correlation between MPP operating voltage and open circuit voltage ( $V_{OC}$ ) of PV-arrays which is more or less linear with a proportional constant  $K$  of 0.76. Sampled  $V_{OC}$  of PV panel is used for calculation of the reference operating voltage point and this value is kept constant until the next sampling. This is the main reason for FOC method's poor accuracy [9]. The Incremental Conductance (INC) method was first proposed in 1993 and many improvements have been made until today. Gradient of P-V curve is the basis for INC algorithm. This method can track the MPP under uniform irradiation only [10,11]. By using the proportion of incremental and instantaneous conductance, the MPP can be tracked.

The Perturb-and-Observe method (P&O) is the most frequently employed MPPT method among all MPPT algorithms due to the advantages of simpler structure and low cost [12-14]. But this method fails when panels in an array are subjected to different irradiation levels. High tracking time and high steady state oscillations are also major problems for this method [15]. Classic P&O method employs fixed iteration step size. Picking larger iteration step sizes provides faster tracking but this also causes steady state oscillations around MPP. Step sizes can be made small enough to damp oscillations but at a cost of sluggish tracking. To tackle this trade-off, P&O methods employing variable iteration step sizes were developed. These methods allow using larger step sizes for faster tracking when the output power is climbing to MPP and using smaller steps for less oscillations when the output power is around MPP.

Modifying conventional methods in order to remedy the problems mentioned and getting similar results to that of SC methods with simpler structures is appealing for researchers. That is why many hybrid or modified conventional MPPT methods have been presented in the literature [16-22]. In [16], authors suggested changing step size of MPPT algorithm by observing the change of  $\Delta P/\Delta I$  and updating the duty cycle with  $N \Delta P/\Delta I$ , where  $N$  is a scalar used for finer tuning of step size variation. It was shown that the suggested algorithm was effective overcoming the drawbacks of conventional P&O method. In [18], a three layered ANN was first trained with offline data obtained from classical P&O algorithm then it was employed in online mode to optimize MPP tracking. Based on the results provided, variable step size ANN-MPPT controller concluded to be outperforming the fixed step P&O algorithm. A variable step size MPPT algorithm based on INC method was presented in [19]. Authors introduced a threshold function which is the product of the output voltage and the absolute value of the power derivative with respect to voltage to define four different zones in P-V curve of a solar panel. Proposed INC based algorithm switches between fixed step and variable step modes depending on the operating zone. When it is in fixed step mode, the highest possible step size is picked to ensure speedy response. Although this method achieves improvement over fixed step methods but the downside is high number of design parameters. In [20], another variable step size MPPT algorithm based on INC method was proposed. This algorithm suggested updating current duty cycle by adding/subtracting the term  $N * |dP/(dV - dI)|$  to duty cycle of the previous cycle. Superiority of the proposed variable method over the conventional fixed step INC method was shown by simulation and experimental results. In [21], authors proposed a modified P&O algorithm for better MPP tracking under rapid changes of irradiation. The change of current is added to the flowchart of classical P&O method to indicate rapid changes of irradiation level. When the tracking is diverging from MPP, the algorithm doubles the step size for speedy recovery. In [22], conventional P&O method and INC method was used together as a hybrid technique to improve the performance of MPPT system. Our work here also attempts to achieve this by modifying classic P&O method through the introduction of a control variable to allow variable step sizes. Scaled power difference is proposed to be used as the control variable to remedy shortcomings of classical P&O method.

The rest of this paper is structured as follows: background material is briefly covered in section 2. The proposed algorithm is introduced in section 3. Simulation and experimental results are given in Sections 4 and 5 consequently. Finally, section 6 has concluding remarks.

## 2. PRELIMINARIES

In this section DC-DC power converters and classical P&O method are briefly introduced.

### 2.1. DC-DC Power Converters

PV panels have nonlinear output voltages and voltage ripples. This inhibits direct use of PV output power by electronic devices. DC-DC converters are in use to regulate the PV power output. Output voltage level of a DC-DC converter is determined by the duty cycle of switching equipment [23]. By using switching techniques, output voltage level can be increased (boost), decreased (buck) or both increased-decreased (buck-boost). A Boost DC-DC converter as given in Figure 1 is used in this study. Voltage level conversion is achieved by switching of the Mosfet (G). When the Mosfet is on, the inductor is charged by the power supply. While the Mosfet is off, the power supply and the inductor feed the circuit together and increase the voltage level at the output.

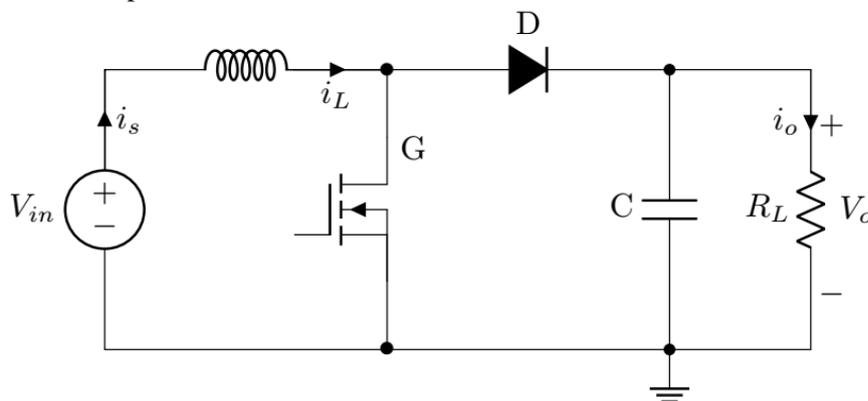
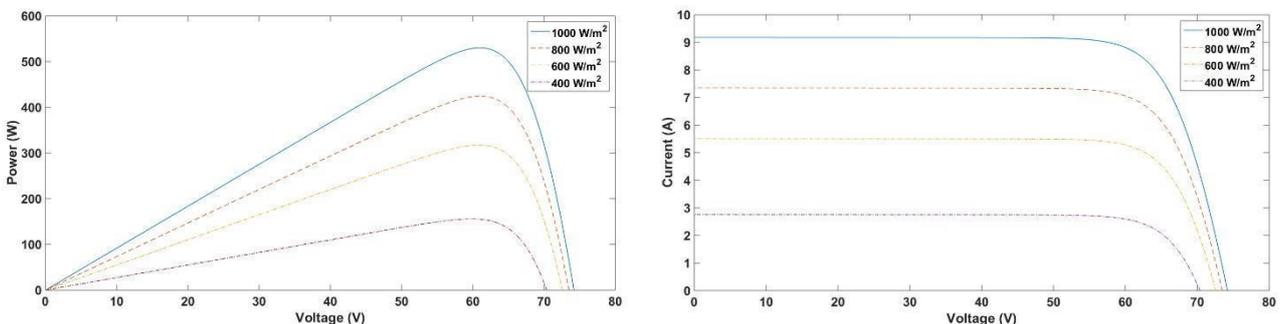


Figure 1. Boost DC-DC Converter Circuit

### 2.2. MPPT Techniques

Solar cells have varying power output with irradiance and temperature. Figure 2 shows the impact of irradiance on voltage-power and voltage-current characteristic curves of a typical PV panel. It is seen that for each irradiation level, there is a unique value of voltage and current pair supplying the maximum power possible. This is called the maximum power point ( $V_{MPP}$ ,  $I_{MPP}$ ). Although it is shown just for the irradiance here, MPP can change depending on other factors such as temperature or weather conditions.



(a) Effect of irradiance on voltage-power characteristic

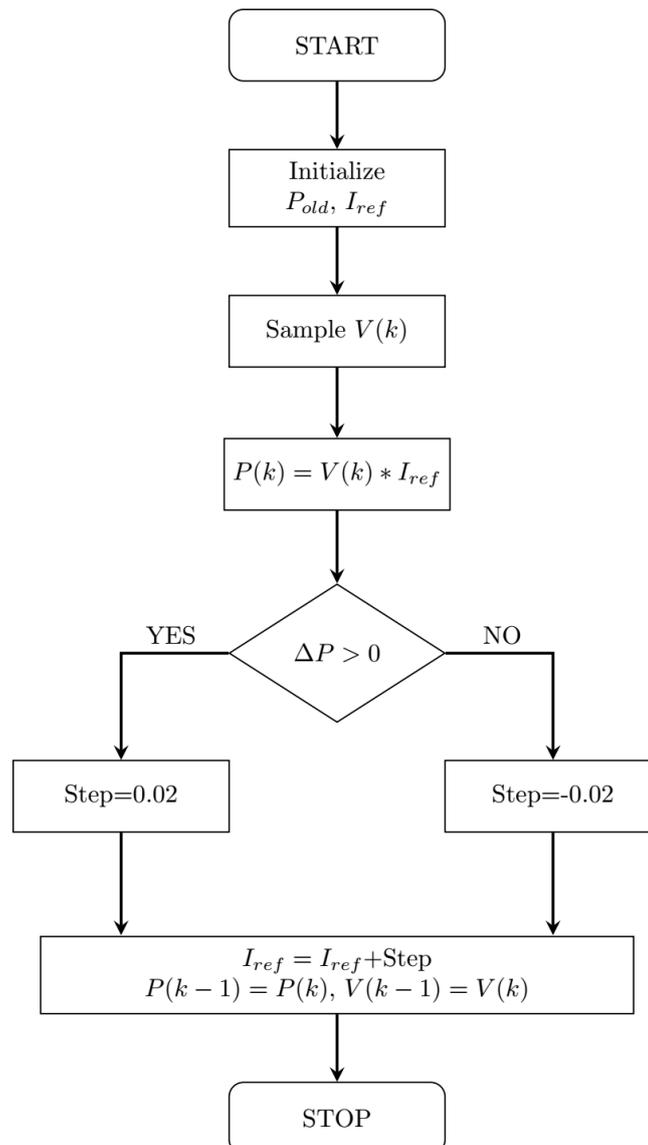
(b) Effect of irradiance on voltage-current characteristic

Figure 2. Effect of irradiance on PV parameters characteristics

MPPT algorithms ensure maximizing power obtained from PV systems with changing terms. In general, this is achieved by measuring the voltage and/or current values of the PV array and comparing them with the reference values. There are many MPPT techniques developed [24-30] but among them P&O is the best-known and the most commonly used one. This is mostly owing to its simpler structure and hence ease of implementation.

The flowchart of the conventional P&O method is given in Figure 3. This algorithm relies on the calculation of PV array output power change in consecutive cycles. PV array's output power value  $P(k)$  (obtained by measuring both the PV current and voltage values) of the current cycle is compared with that of the previous cycle  $P(k-1)$ . Based on the outcome of this comparison, the algorithm decides whether to increase or decrease the current  $I_{ref}$ . If the output power is increasing, then the current change direction is kept the same as the previous direction. When the difference of consecutive cycles is negative for the power, the direction of change for the current is reversed. Since perturbation of the current is fixed in each cycle, power output oscillates around the peak power at steady state.

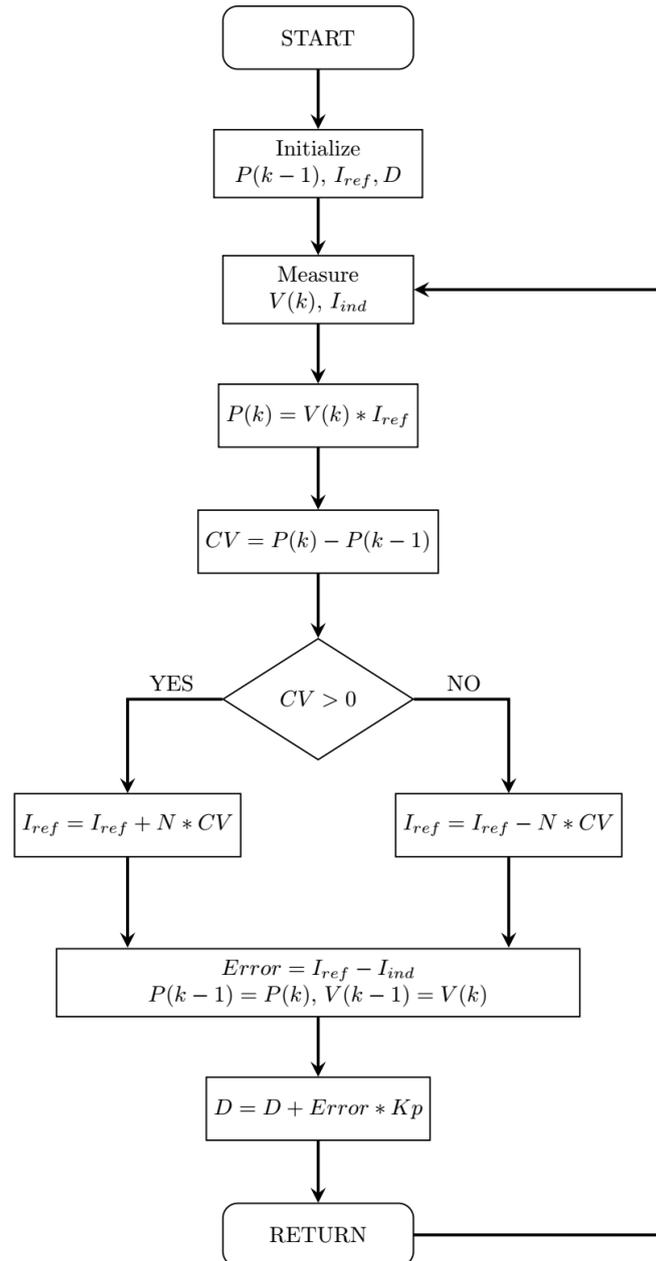
Reaching the MPP quickly and minimizing oscillations around the MPP are two conflicting objectives when the step size is fixed. Using a larger step size ensures reaching the MPP swiftly but the power loss invoked by steady state oscillations increases as well. On the contrary, picking a small step size can lower the power loss near the MPP but the tracking takes a longer time. If both fast tracking and low oscillation around MPP are needed, then fixed step P&O algorithms need to be modified to allow variable step sizes for each cycle depending on the operating point. Such algorithms were developed in recent years. Reader is referred to [17-19] and [31-34] for further discussion of variable step size MPPT algorithms. Next is the proposed P&O algorithm to overcome aforementioned problems.



**Figure 3.** Flowchart of P&O method

### 3. PROPOSED MODIFIED P&O METHOD

To overcome challenges mentioned in the previous subsection, a variable step size MPPT algorithm is proposed here. Figure 4 shows the flowchart of the proposed variable step size algorithm. This method is basically a modification of P&O method such that the scaled power difference is used as a control variable to allow variable step sizes for each cycle. This way, step size is automatically tuned for the current PV operating point. The algorithm adopts larger step sizes when the current operating point is far from the MPP point to enable faster tracking. When it is around the MPP point, step sizes are tuned to be small enough to prevent oscillations.



**Figure 4.** Flowchart of the proposed algorithm

In the proposed algorithm, the converter's inductor current  $I_{ind}$  is enforced to follow the reference current which is calculated by a microprocessor according to the power difference. Initial power is accepted as zero. Reference current  $I_{ref}$  can be accepted as the PV panel current  $I_{PV}$ . After that, the converter's input voltage, which is the PV voltage  $V_{PV}$  is measured and input power  $P(k)$  is calculated. Based on the

difference of power  $P(k) - P(k-1)$ , the system's control variable ( $CV$ ) is calculated.  $N$  is the scaling factor of  $CV$  which is essential part of MPPT performance. It can be tuned manually in order to improve the system response. Picking smaller  $N$  values results in smaller oscillations around MPP but response time and cycle number increases.  $N$  is determined as 0.001 for this system. The algorithm checks  $CV$  in every cycle whether it is bigger than zero or not and decides whether to increment or decrement the reference current. When the system is in a climbing state, current value increases as voltage value drops. The value of the  $CV$  is greater than 0, and as a result, larger step sizes are picked for fast tracking in this region. When at steady state, both the voltage and the current values have negligible changes, in consequence,  $CV$  value becomes 0. In this case, smaller step sizes are required to have less oscillations around MPP. Error is calculated by subtracting  $I_{ind}$  from  $I_{ref}$ . Duty cycle,  $D$ , is calculated by previous duty cycle, error and proportional controller  $K_p$ . Duty cycle must be kept between  $[0,1]$ . However, the error value may be too big to accommodate this range, especially during the climbing process. The error is multiplied by a coefficient to keep the  $D$  within the required range. This coefficient has been chosen as the optimal number that will not take the  $D$  out of the limits under any condition.  $K_p$  is set at 0.01 for the system. The system under consideration with the proposed MPPT method is given in Figure 5.

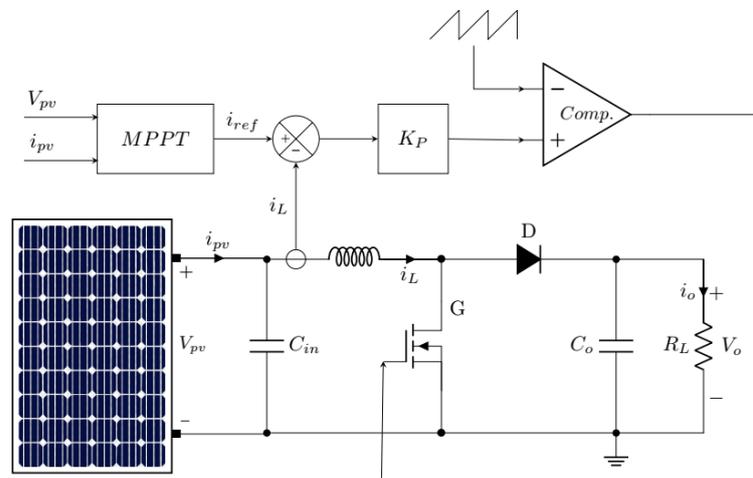


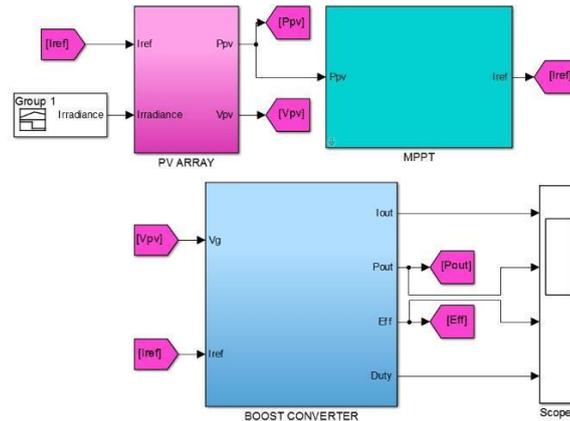
Figure 5. MPPT system under consideration

## 4. SIMULATION RESULTS

In the first part of this section, the proposed MPPT algorithm is tested with different irradiation profiles complying with European Efficiency Test, EN50530 [35] standards. Obtained results are compared with fixed step size P&O algorithm. In the second part, performance of the proposed algorithm is compared to that of three different variable step size MPPT algorithms reported in the literature before.

### 4.1. Simulation of the Proposed Algorithm with Different Irradiation Profiles

The simulation of the proposed system is performed on SimPower System toolbox of Matlab /Simulink. Block diagram of the system is given in Figure 6. The system consists of a PV array, a resistive load, a boost converter and the MPPT controller. For this simulation, an 80 W mono crystalline PV panel has been chosen. Parameters for this panel are given in Table 1. Two PV panels are arranged in series connection.



**Figure 6.** Simulink block diagram of the proposed system

**Table 1.** 80 W monocrystalline solar panel parameters

Parameter	Name	Value
Open Circuit Voltage	$V_{oc}$	29 V
Short Circuit Current	$I_{sc}$	3.50 A
MPP voltage	$V_{mpp}$	25 V
MPP current	$I_{mpp}$	3.2 A
Module Efficiency (STC)	Eff	18.60 %

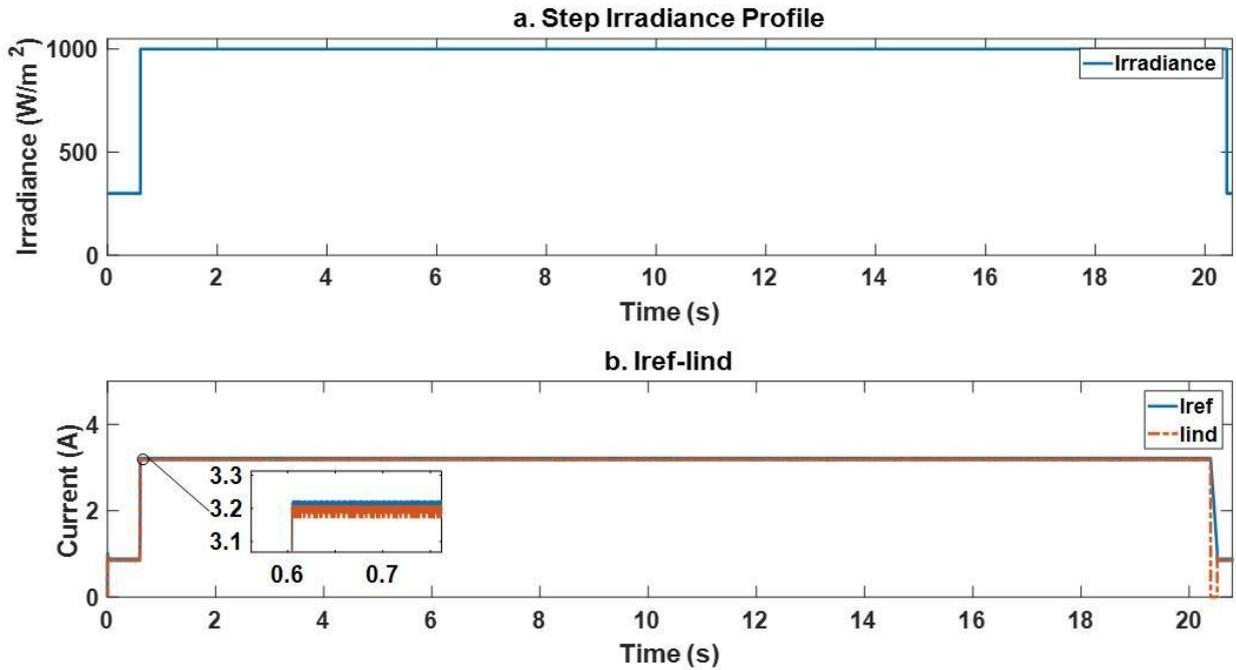
A boost converter is connected to the PV array to provide the maximum power to the load. Boost converter acts as a current source in the system. While the voltage at the output varies according to the power obtained from the panel, it is aimed to keep the current constant at the reference. Table 2 shows the component values for the designed boost converter.

**Table 2.** Boost converter components

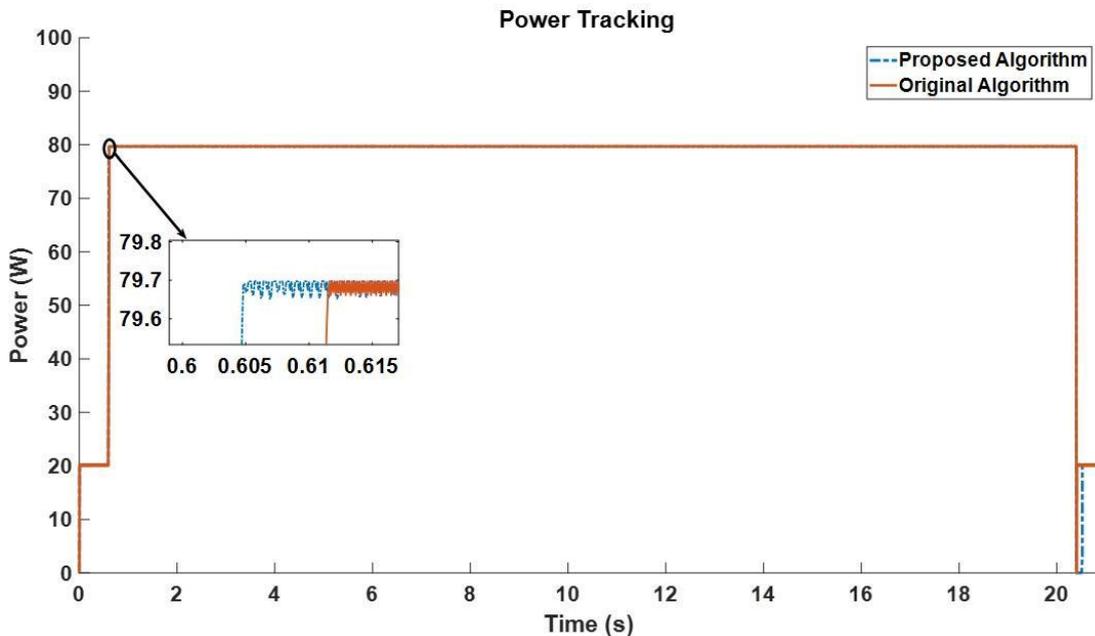
Parameter	Name	Value
MPPT frequency	f	15 kHz
Inductance	L	184 $\mu$ H
Capacitance	C	10 $\mu$ F
Resistance	R	709.25 $\Omega$
Switching Equipment	S	IRF260P

The proposed algorithm was tested under two different solar irradiation conditions including a step and a ramp profiles to prove its effectiveness. Solar irradiation levels were determined according to the European Efficiency Test, EN50530. During all tests, the temperature was fixed to 25 °C. Simulation results were compared with those of fixed step P&O method.

First test is conducted with a step irradiance profile. As it is shown in Figure 7 (a), the initial value of irradiance  $300 \text{ W/m}^2$  suddenly stepped up to  $1000 \text{ W/m}^2$  at  $t = 0.6$  seconds. After the 20 seconds of dwell time, it suddenly decreased back to  $300 \text{ W/m}^2$  again. For this irradiance profile, the proposed algorithm successfully enforces the inductor current to follow the reference current as it is shown in Figure 7 (b). Response of the proposed algorithm is given in Figure 8. It can be concluded that the proposed algorithm is slightly faster than the conventional P&O algorithm in reference tracking.

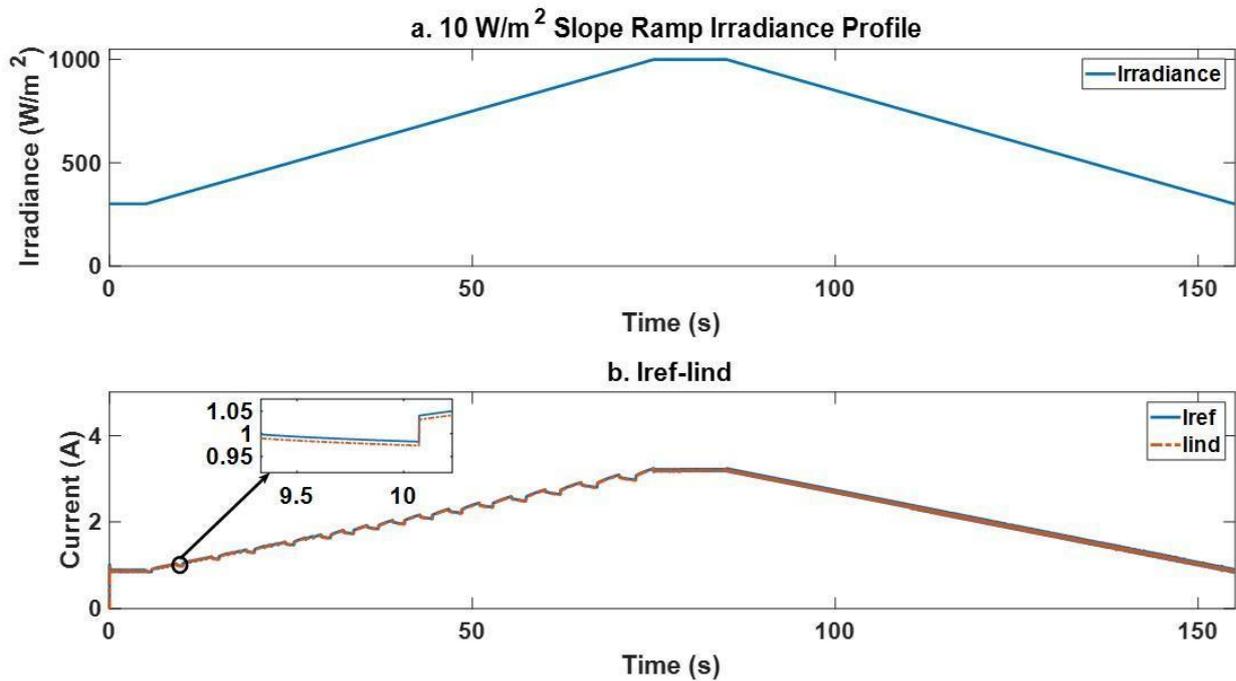


**Figure 7.** Step irradiance profile simulation result. (a) Step irradiance profile (b) Reference current tracking of the proposed algorithm

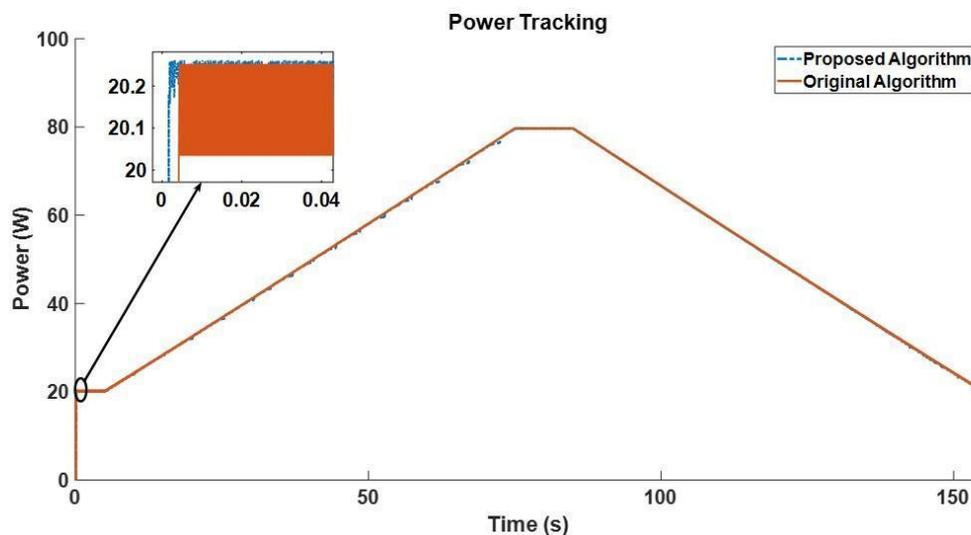


**Figure 8.** Comparison of the proposed algorithm and original algorithm under step type changed irradiance condition

The proposed algorithm is also tested with a ramp up and ramp down irradiance profile. Ramp irradiance profile given in Figure 9 (a) has ramp slopes of  $10 W/m^2$ . Irradiance is started from  $300 W/m^2$  and increased by  $10 W/m^2$  per second for 70 seconds. After this period, irradiance reaches  $1000 W/m^2$  and stays at this level for 10 seconds of dwell time. After that, irradiance is decreased with the same rate for 70 seconds to reach its initial value of  $300 W/m^2$ . For this profile, reference current and power tracking performances are given in Figure 9 (b) and Figure 10 respectively. As in the step irradiance case, the proposed algorithm performs slightly better than conventional P&O algorithm.



**Figure 9.** 10 W/m<sup>2</sup> Slope ramp irradiance profile simulation results. (a) 10 W/m<sup>2</sup> slope ramp type irradiance profile. (b) Reference current tracking of proposed algorithm



**Figure 10.** Comparison of proposed algorithm and original algorithm under 10 W/m<sup>2</sup> ramp type changed irradiance condition

#### 4.2. Comparison with Existing Variable Step Size MPPT Methods

Authors in [36] conducted a comparative study among three different variable step size MPPT methods based on P&O, INC and fuzzy logic control (FLC) techniques reported in [37-39], respectively. A step change in irradiation were applied to PV system to assess the performance metrics of the speed of response, the oscillation and the mean value around MPP and the cycle number. Results were tabulated in Table IV of [36]. The proposed algorithm is tested using the same irradiation profile and the DC-DC boost converter designed in [36]. Obtained results are augmented to Table IV of [36] as the last row to be presented as Table 3 in this work. The proposed algorithm is shown to be superior in terms ripple reduction with a 0.31

W ripple around MPP. Variable INC method has the second smallest ripple among the listed. Falling behind the variable INC method, the proposed method has the second best response time of 0.197 seconds. No significant differences were observed for the mean value of power around MPP for the methods considered. The proposed method suffers having the largest cycle number among others. This can be remedied by tuning the scaling factor  $N$  to have a larger value.

**Table 3.** Comparison of the proposed algorithm with existing algorithms given in [36]

MPPT Method	S=500 W/m <sup>2</sup> , T=25 °C, Sample Time Ts=0.0001 sec			
	Response Time	Ripple (W)	Mean Value	Cycle Number
Variable Step P&O [37]	0.25	0.71	119.855	4335
Variable Incremental [38]	0.1	0.37	120.025	2300
P&O with Fuzzy Logic [39]	0.225	0.51	119.995	4322
Proposed Variable Step P&O	0.197	0.31	120.040	6606

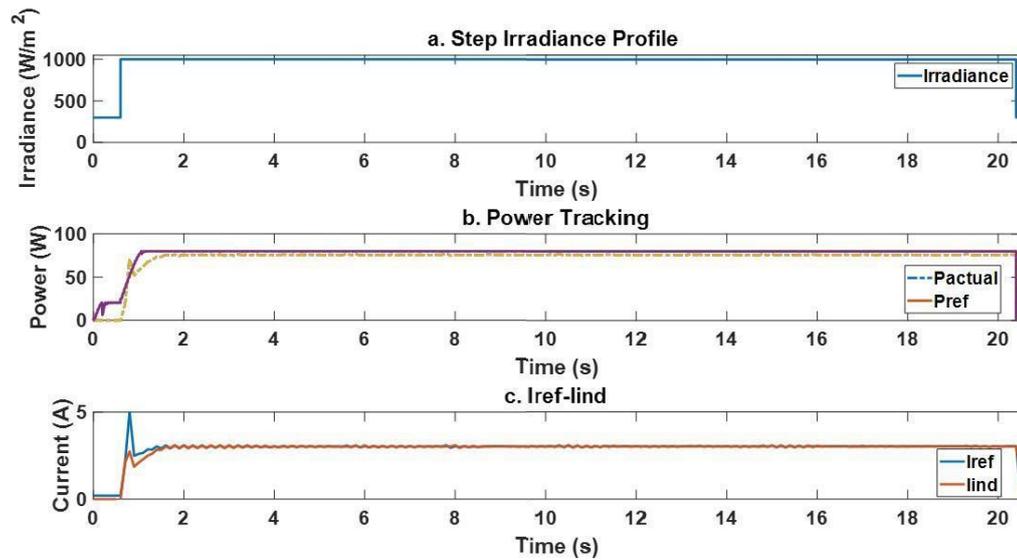
## 5. EXPERIMENTAL RESULTS

The proposed algorithm is tested experimentally with an 80 W solar system setup. This setup consists of a PV simulator, a DC-DC boost converter, a resistive load and an ARM cortex-based microcontroller as it is shown in Figure 11. Irradiance profiles used for the simulations are implemented using a Chroma 62050H-600S PV simulator. The proposed algorithm is embedded to STM32F4 Discovery microcontroller board. To supply necessary readings for the algorithm two sensors are used for voltage and current measurements. DC-DC boost converter is implemented with circuit components listed in Table 2.



**Figure 11.** Experimental setup

For the step irradiance profile, proposed MPPT algorithm's power and reference current tracking performances are shown in Figure 12. Power tracking is achieved with great success as it is shown in Figure 12 (b). Figure 12 (c) shows very close tracking of the microprocessor calculated reference current by the inductor current. MPPT tracking efficiency is calculated %99.99 as shown in Figure 13. Proposed algorithm successfully tracked the MPP and had low oscillation around MPP.

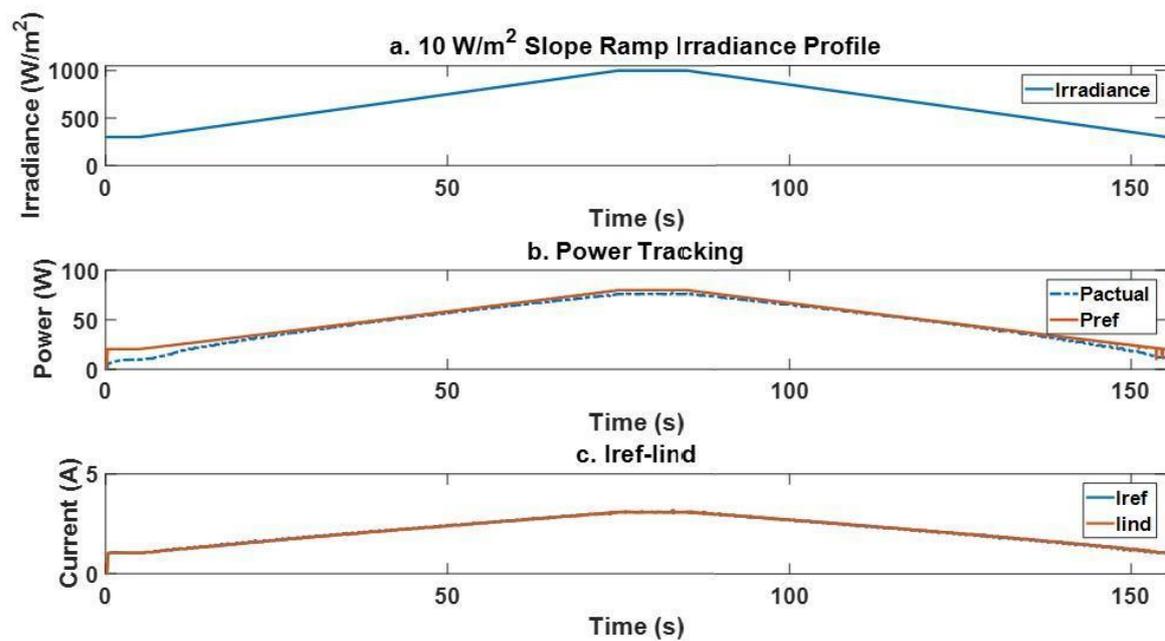


**Figure 12.** Step irradiance profile experimental result. (a) Step irradiance profile. (b) Power tracking of proposed MPPT algorithm under step type changed irradiance profile. (c) Reference current tracking of proposed algorithm

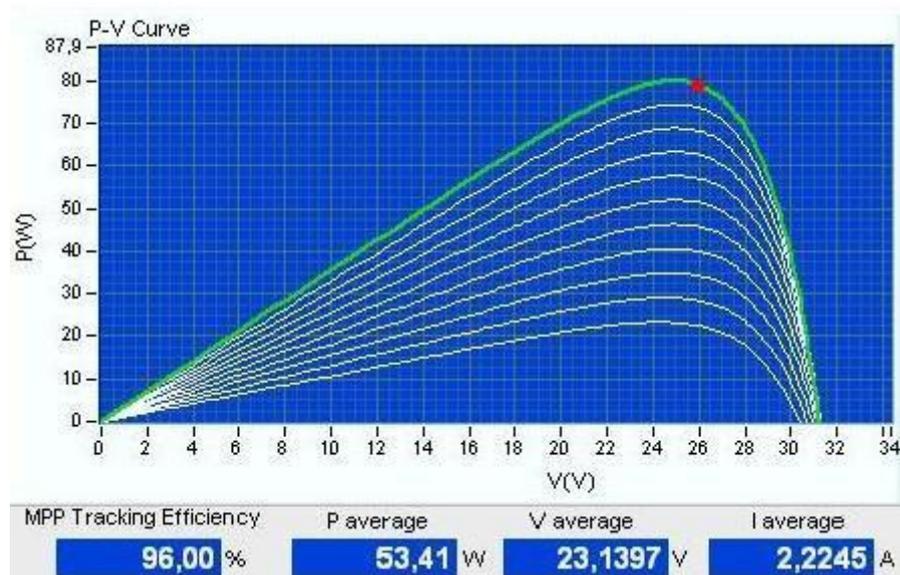


**Figure 13.** MPPT Efficiency monitoring of step irradiance profile

Figure 14 shows power and reference current tracking performances of the proposed algorithm for the ramp irradiance profile. Power tracking is attained successfully as shown in Figure 14 (b). Figure 14 (c) shows that the boost converter's inductor current was successfully enforced to follow the reference current. Figure 15 shows %96 MPP tracking efficiency calculated for the ramp irradiance profile. Proposed algorithm successfully tracks the MPP and has low oscillation around MPP for 10 W/m<sup>2</sup> slope ramp irradiance profile.



**Figure 14.** 10 W/m<sup>2</sup> Slope ramp irradiance profile experimental results. (a) 10 W/m<sup>2</sup> irradiance profile. (b) Power tracking of proposed MPPT algorithm under ramp type changed irradiance profile. (c) Reference current tracking of proposed algorithm



**Figure 15.** 10 W/m<sup>2</sup> Slope ramp irradiance profile efficiency monitoring

## 5. CONCLUSIONS

In this paper, a new MPPT algorithm has been proposed, simulated and experimentally tested. Proposed algorithm achieved improvements on tracking time and oscillation magnitude in steady state around MPP. Simulation of the proposed system was performed on SimPower System toolbox on Matlab / Simulink. Simulation test conditions and irradiance profiles were prepared according to European Standard Test EN 50530. An experimental setup was established to confirm the simulation results.

The proposed algorithm was tested under different irradiance profiles to prove its effectiveness. Simulations show that the proposed algorithm has advantages over the conventional algorithm and provides a solution to the conventional algorithm's drawbacks. Simulations prove that the proposed algorithm has faster tracking time and lower oscillations around MPP. A comparison of the proposed algorithm with respect to

some existing variable step size algorithms was also provided to show the improvements achieved regarding response time and oscillation reduction around MPP. The only downside of the proposed algorithm was the increased cycle number. It is noted that this could be reduced by tuning the scaling factor  $N$ .

For experimental study a DC-DC power converter was designed and implemented. Chroma 62050H-600S PV simulator was used as a PV panel. Simulation test conditions were exactly repeated in the experimental study. Simulation results were confirmed by the results of experiments. Proposed algorithm successfully tracks the MPPT and provides low steady state oscillation.

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## CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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