A MATLAB Based Comparative Study between Single and Hybrid MPPT Techniques for Photovoltaic Systems

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Abstract- It is essential to identify the changing maximum available power provided by the Photovoltaic (PV) array under different weather conditions in order to enhance system efficiency by driving the PV system to work at that maximum power point. Hence, it is mandatory to implement a Maximum Power Point Tracking (MPPT) system to maintain optimum power operation at all irradiance levels and at different temperatures. Many MPPT techniques were developed and implemented in literature. These techniques differ in their characteristics and performance such as accuracy, convergence speed, ease of hardware implementation, PV dependency, number of required sensors and their ability to track the Global Maximum Power Point (GMPP) under partial shading conditions. Single MPPT techniques were first presented in literature; however, working on their own, they failed in achieving some of the desired traits mentioned earlier. Hence the merge of two single MPPT techniques in order to add the advantages of each algorithm and eliminate their drawbacks. A lot of effort was put in literature to compare and survey MPPT algorithms in general. Nevertheless, very little literature is available that provides a comparison between Hybrid MPPT techniques and the single ones. This work does so and in simulation, presenting a MATLAB based study that compares single MPPT techniques with their Hybrid combinations in order to validate through simulation results the superior performance of Hybrid MPPT techniques over its single counterparts MPPT techniques.

Keywords PV systems, Maximum Power Point Tracking (MPPT) Techniques, Hybrid MPPT Techniques.

1. Introduction

Due to being abundant, renewable, clean and environmentally friendly, solar energy is becoming a very attractive alternative source of energy. However, its high initial cost, low conversion efficiency along with the fluctuating nature of the source, as well as its low reliability, caused its feasibility and commercial use to be limited. Increasing the reliability and efficiency of solar systems is a challenge that needs to be addressed in order to deliver the merits of solar systems. As a result of the intermittency nature of the source; the power produced by the photovoltaic systems is a function of many parameters of which are solar irradiance, ambient temperature, age, etc.

There are two regions of operation for the PV as illustrated in Fig. 1. The first region, where point A lies, is called the right-hand side (RHS). The voltage in the RHS is almost constant and the current is decreasing, the power is directly proportional to the decreasing current and inversely proportional to the voltage. The second region of operation, where point B lies, is the left-hand side (LHS) in which the current is almost fixed and the voltage is increasing, the power generated in this region increases as the voltage is increased and the current drawn is decreased [1]–[3]. The maximum power point (MPP) separates these two regions, at which the PV resistance is matched to the load resistance seen by the PV. Thus, if the operating point was located in the LHS then it needs to be moved to the right to reach MPP whereas if located in the RHS it should be shifted to the left for MPP operation.

The resistance of the PV is a function of irradiance and temperature; hence, it is a variable resistor depending on weather conditions. This in fact leads to a mismatch between the fixed load resistance, directly powered by the PV, and the variable PV resistance, therefore maximum power transfer from the PV source to the load does not occur under different weather conditions in that case.

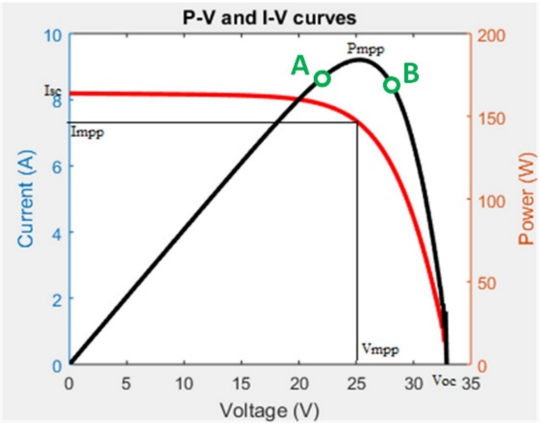


Fig. 1 I-V and P-V curve of a PV module.

To guarantee continuous matching between the variable PV and the fixed load resistances, a DC-DC converter is inserted between the PV system and the load to compensate for the mismatch between the load and the source resistances by varying the duty cycle of the DC-DC converter [4], [5]. Many MPPT algorithms and techniques were discussed and presented in literature to adjust the converter duty cycle at a value that equalizes the resistance seen by the PV system to that of the load, thus driving the PV system to operate at its maximum power. This significantly increases the overall efficiency and reliability of the PV system utilized.

This work presents a comparative study between three individual MPPT techniques and their Hybrid combinations in order to evaluate their performance and validate in simulation that Hybrid MPPT techniques outperform any individual technique. The comparative study was done through simulation on MATLAB/SIMULINK. The paper is organized as follows: section 2 highlights the significance of implementing an MPPT system, whereas section 3 discusses the employed individual and their Hybrid combinations. Section 4 introduces the implemented MATLAB model and the evaluated cases, and sections 5 and 6 presents the results obtained along with detailed discussion and summary of the MPPT techniques performances.

2. Problem Overview

The power produced by the PV significantly varies with temperature, level of irradiance, type of load connected, aging etc. This section discusses the need for MPP trackers by highlighting the impact of irradiance and temperature change on moving, either the one unique MPP value on a single-peaked PV curve, or the ultimate unique Global MPP (GMPP) on a multiple-peaked PV curve resultant due to partial shading conditions.

The current and voltage produced and hence power generated by the PV is affected by the ambient temperature and the PV exposed irradiance. Fig. 2 and 3 demonstrate the effects of temperature and irradiance on the I-V and P-V curves respectively, in which the increase in temperature negatively affects the voltage produced by the PV, whereas the level of irradiance is directly proportional to the current provided by the PV [6].

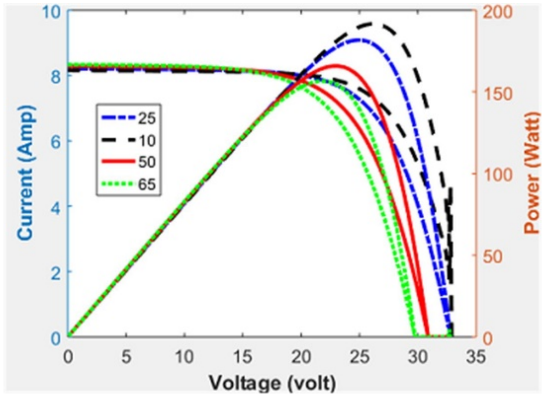


Fig. 2. Effects of temperature change on P-V and I-V curves[6]

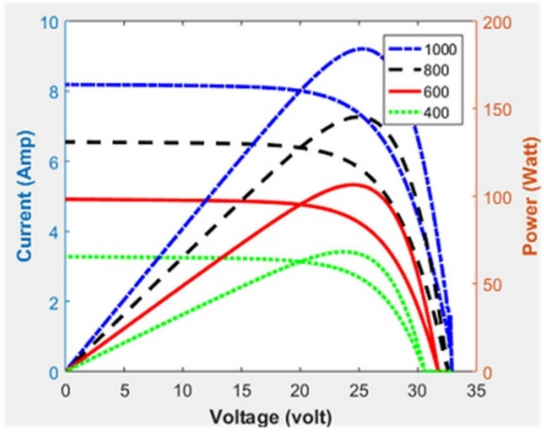


Fig. 3. Effects of irradiance change on P-V and I-V curves[7]

2.1. Impact of irradiance and temperature

2.2. Partial Shading Conditions

The mismatch between the PV panels has been a huge concern for researches as it reduces the power supplied by the PV system. The reasons behind modules mismatch can be summarized to be either manufacturing error and/or partial shading. When a PV module in a string is exposed to an irradiance level different from the others connected in the string or when a PV cell in a module is affected by a different level of irradiance than the other cells, it turns to a passive element absorbing power instead of supplying it. This issue has been dealt with by inserting bypass diodes in parallel with the PV cell and modules. However, introducing a bypass diode solved one part of the mismatching issue. Moreover, having two irradiance levels on the same string or module reshapes the P-V curve into multi-local power maxima with one Global MPP (GMPP), which in turn makes the tracking of the power point more challenging [6], [8]–[13].

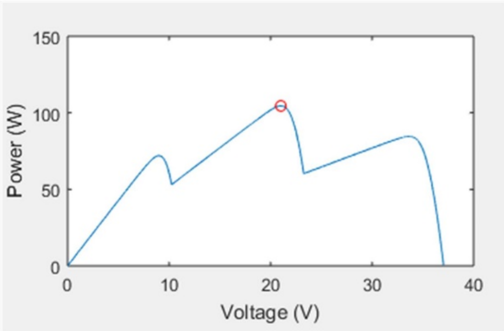


Fig. 4. P-V curve under partial shading conditions.

Fig. 4 depicts a case with three peaks due to partial shading condition, only one of which is the GMPP that needs to be tracked and operated at for maximum efficiency.

2.3. Motivation Behind Maximum Power Point Trackers:

The PV module has one maximum power point for every combination of irradiance and temperature, and that point must be tracked in order to drive the operating point of the system towards it and increase the overall efficiency of the PV system accordingly. To highlight the importance of implementing a maximum power point tracker, Fig. 5 shows the operating point of the system for different irradiances and temperature if directly connected to the load without MPPT. Due to the mismatch of the source and load impedances, maximum power is not transferred from the source to the load, which results in poor efficiency, lower reliability and a considerable amount of power loss. A DC-DC converter is introduced to do the job of matching the source impedance with that of the load by adjusting its duty cycle through different algorithms and techniques.

The overall system configuration that consists of the DC-DC converter and MPPT controller is illustrated in Fig. 6.

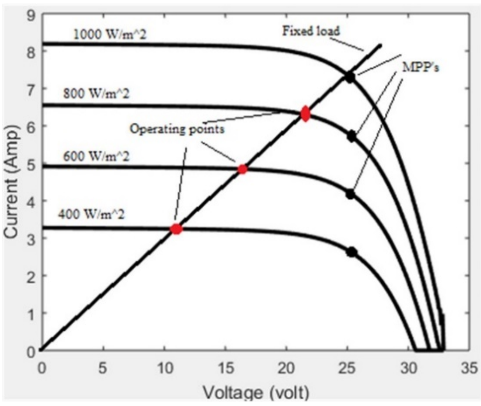


Fig. 5. I-V curve with different irradiance levels and the location of MPP[14]

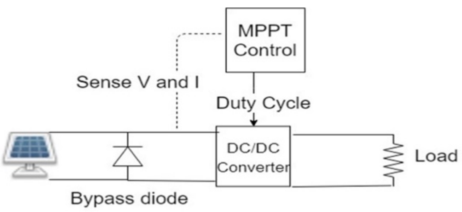


Fig. 6. Overall PV system configuration.

2.4. Maximum Power Point Tracking Techniques

MPPT techniques presented in literature can be classified into Offline techniques, which measure voltage or current by disconnecting the system, like the Fractional Open Circuit Voltage (FOCV) and Fractional Short Circuit Current (FSCC) methods [15], [16]. These methods are distinguished by their simplicity and fast convergence speed but also its inaccuracy. Online techniques [17]–[20]on the other hand avoid the energy loss of disconnecting the system by taking the measurements online. Perturb and Observe (P&O) and Incremental Conductance (IC) are two common and simple online MPPTs, which are more accurate in tracking the MPP yet slower compared to the offline methods. Both the Offline and Online techniques are unable to track the GMPP under partial shading conditions. The Intelligent MPPT techniques [21], [22] as another classification for MPP tracking methods are highly accurate and fast in tracking both the MPP and the GMPP under partial shading conditions. However, Intelligent MPPTs are not universal techniques in the sense that they require prior training, which is considered a disadvantage in addition to their implementation complexity. Combining two MPPT methods proved very efficient in employing the advantages and extenuating the drawbacks of the individual components, hence the need for Hybrid MPPT techniques. For example, one of the Offline techniques can be hybridized with an Online method in order to benefit from the fast speed of the former and the high accuracy of the latter. Moreover, the PV dependency of the Intelligent techniques can also be alleviated by combining with another MPPT method [23]–[28].

Furthermore, it is worth mentioning why the aforementioned traits of accuracy, speed, complexity and ability to track GMPP are desired when implementing an MPPT system. Accurate tracking of the MPP is essential as it increases the power extracted from the PV thus increased efficiency. Fast tracking of the MPP location increases the energy harvested from the PV system. Increased complexity usually increases the cost and PV dependency, whereas the ability of tracking the GMPP increases the overall efficiency of the system especially in locations that are frequently exposed to partial shading conditions.

3. Implemented Maximum Power Point Tracking Techniques

In this section, the implemented single MPPT techniques and their hybrid combinations are presented and discussed in details. Three individual techniques were selected such that each is primarily prominent by one desirable MPP tracking trait, i.e., one is fast, the other is accurate and the third is able to track GMPP.

3.1 Constant Voltage and method – Fast MPPT technique:

The Constant Voltage (CV) method tracks the MPP of the PV system by simply setting a constant operating voltage for the PV to estimate the MPP under different weather conditions [27], [29]. As illustrated in Fig. 3, it is noticeable that when the level of irradiance is almost halved, the power produced is nearly halved as well due to the decrease of the current generated, whereas the voltage is slightly affected by that change. Thus, the change in ambient temperature and level of irradiance slightly affects the voltage, which can be considered as constant.

Due to its ease of hardware implementation, reduced number of sensors, stability and fast estimation of the MPP location, the Constant Voltage gained popularity in low-budget PV systems. However, the overall accuracy of this method is relatively low when compared to other techniques, in addition, it fails in tracking the GMPP under partial shading conditions.

3.2 Power Increment method – Able to track GMPP

The Power Increment (PI) method is one of the few MPPT techniques that is capable of tracking the GMPP of the PV curve in the event of partial shading without any added complexity, unlike the intelligent techniques, which are relatively complex to implement and require prior knowledge or training for the utilized PV system. The PI algorithm finds the GMPP by scanning the entire PV curve and saves the value of the duty cycle at which the maximum power occurs. However, the fact that it scans the entire PV curve affects its speed in locating the MPP [30], [31].

It is also worth mentioning that the selection of the step size of the duty cycle (resolution) determines the convergence speed and accuracy of the PI algorithm; where a small step size (higher resolution) provides a more accurate tracking but on the account of speed and vice versa. The difference in performance due to the step size selection is further illustrated in Fig. 7.

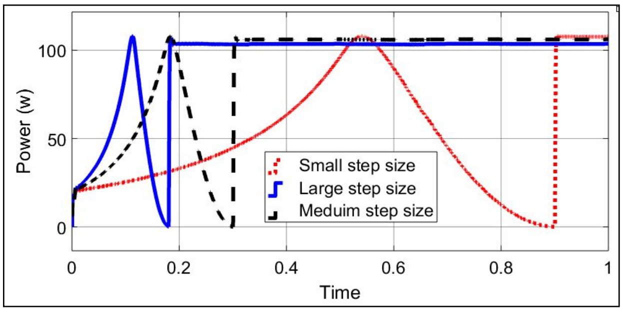


Fig. 7. PI with small and large step size of the duty cycle at fixed irradiance and temperature.

Figure 7 shows that a small step size (high resolution) PI depicted by the dotted red line is more accurate whereas PI with larger step size (lower resolution) shown in solid blue line reaches the MPP faster. However, the selection of the duty cycle-step size depends on the application and the desired MPP tracking trait whether speed or accuracy at the location of the utilized PV system.

3.3 Perturb and Observe (P&O) – Accurate MPP technique:

The P&O algorithm is widely used in MPPT systems due to its relative theoretical simplicity, ease of implementation, universality and accuracy[30]–[35]. The algorithm determines the location of the MPP according the power versus voltage differences, if the power is increased with the increased voltage, the operating point is located in the LHS region and should be shifted to the right to reach the MPP and thus the voltage is further increased. Whereas, if the power is decreased when the voltage is increased, the operating point is in the RHS, the MPP is to the left and hence the operating voltage is decreased by the duty cycle in order to left-shift the operating point for MPP. However, if a small fixed step size of the duty cycle is selected, the algorithm's convergence speed becomes relatively low, nevertheless provides an accurate tracking with reduced oscillations around the MPP. Whereas if the step size is selected to be large, the MPP is reached faster but on the expense of accuracy and with larger oscillations around the MPP. In addition, P&O fails to track the GMPP under non-uniform irradiance as it gets trapped at the first local maximum instead of locating the global. Whereas Fig. 8 shows the effects of changing the duty cycle step size on P&O performance.

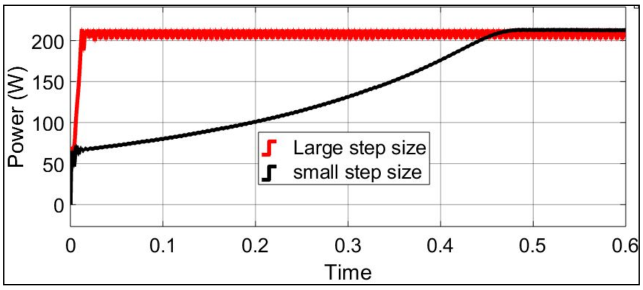


Fig. 8. P&O with small and large step size of the duty cycle.

Figure 8 shows the difference between a small fixed step size P&O (in black trace) needing almost 0.5 seconds to precisely reach the MPP and P&O with large fixed step size (in blue trace) to inaccurately oscillate around the MPP in fraction of the time needed for small step size with only 0.02 second.

3.4 Hybrid of Power Increment with Perturb and Observe (PI + P&O)

As mentioned earlier, the step size of the duty cycle for both algorithms; PI and P&O, determines the convergence speed and accuracy of both algorithms. Hybridizing these two algorithms achieves the desired convergence speed of the large step sized PI with the sought after accuracy of the small step sized P&O, in addition to the ability of tracking the GMPP under partial shading conditions, a merit that is not provided by only implementing the P&O algorithm [31], [38]. These two methods are hybridized sequentially, in which the PI is implemented as a first stage where it estimates the MPP by scanning the entire P-V curve searching for the global maximum of the curve, then for enhanced accuracy, small step sized P&O follows in the second stage. Apart from the improved accuracy, the P&O continuously monitors the MPP location, which boosts the algorithms performance under dynamic weather conditions and small changes in irradiances in terms of accuracy and speed. Overall, this algorithm provides accurate tracking and the ability to locate the GMPP at non-uniform irradiance with good convergence speed at no added complexity or prior training for the utilized PV system. The flowchart of the hybrid algorithm is shown in Fig. 9.

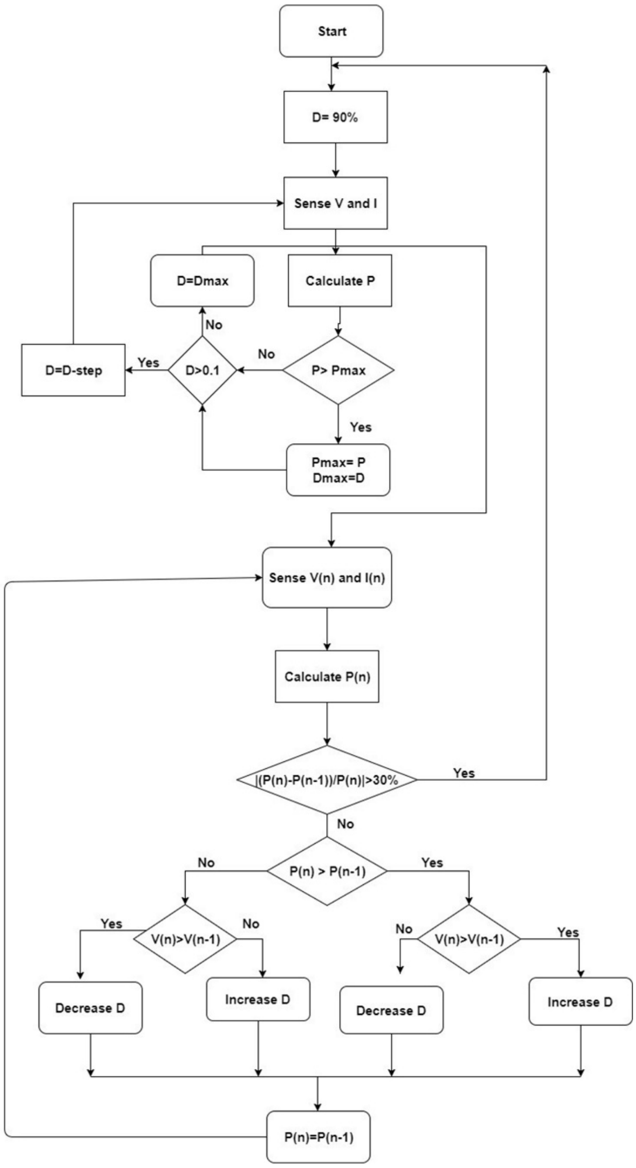


Fig. 9. Hybrid of PI with P&O flowchart

To achieve a fast and accurate tracking system for the MPP of a PV system that is also PV independent and easy to implement; the CV method is combined with the P&O into a sequential hybrid MPPT algorithm. During the first stage, the MPP location is rapidly estimated through the CV algorithm by restricting the operating point between any two points A and B on either side of the MPP as depicted earlier in Fig. 1[39]. After estimating the MPP location, the P&O is then in charge of driving the operating point of the system as close as possible to the actual MPP. The fact that the P&O is activated at a point close to the MPP provides the advantage of selecting a small step size for the duty cycle resulting in a better accuracy and reduced oscillation around the MPP. Moreover, the selection of CV method instead of offline techniques such as Fractional Open Circuit Voltage and Fractional Short Circuit Current as in literature, eliminates the isolation of the PV system from the load for measurements of the open circuit voltage or the short circuit current.

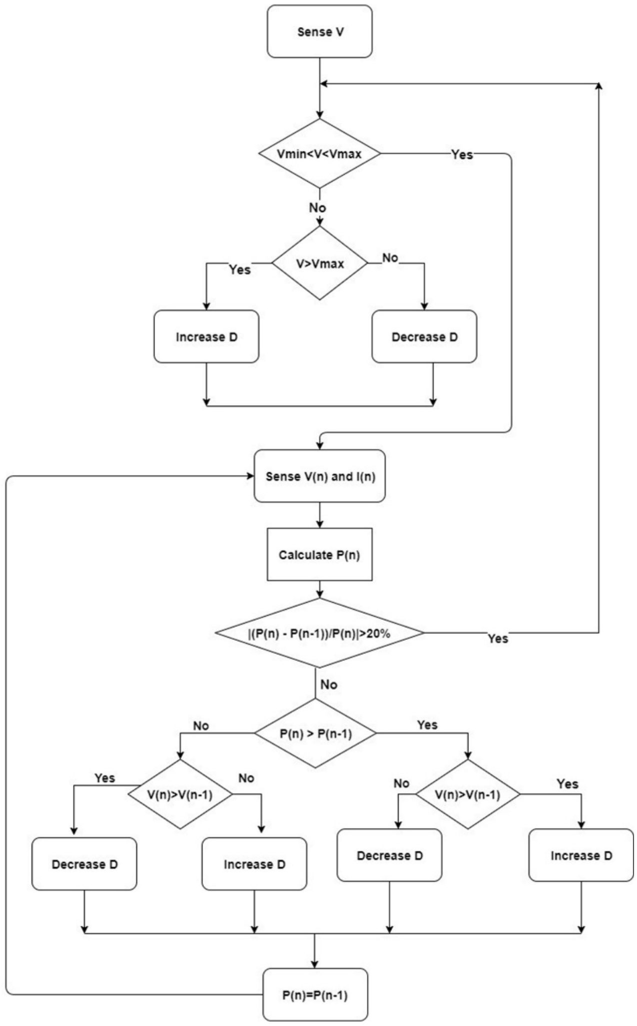


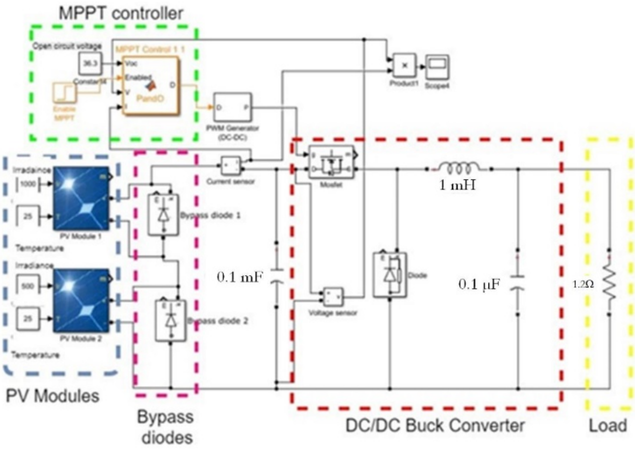
Fig. 10. Hybrid of CV and P&O flowchart.

3.5 Hybrid of Power Increment with Perturb and Observe (PI+P&O)

Furthermore, combining these two algorithms significantly improves the CV performance when the ambient temperature is deviated. However, this algorithm does not offer tracking of the GMPP under partial shading conditions. The flowchart of this algorithm is illustrated in Fig. 10.

4. Simulation Setup

In order to study the performance of each individual and their Hybrid algorithms, a model using MATLAB SIMULINK version 2016b was built as shown in Fig. 11, which also lists the PV parameters used. Converter is operating at 50kHz switching frequency.



PV Specification	*Rating*
Maximum power P_{MPP}	*106.5 W*
Voltage at MPP V_{MPP}	*14.5 V*
Current at MPP I_{MPP}	*7.36 A*
Open circuit voltage V_{OC}	*18.15 V*
Short circuit current I_{SC}	*7.84 A*

Fig. 11. MATLAB SIMULINK model with PV panel parameters.

In order to precisely evaluate the performance of the aforementioned MPPT algorithms; eight different cases of weather conditions were addressed and simulated as summarized in Table 1.

Table 1 Description of the cases simulated

Case No.	Case description	Irradiance on PV Module (W/m^2) 1	2	Temperature (° C)
1	Standard Test Conditions (STC); 1000 W/m^2 at 25° C	1000	1000	25
2	Half uniform irradiance 500 W/m^2 at 25° C	500	500	25
3	Full uniform irradiance 1000 W/m^2 at 45° C	1000	1000	45
4	Full uniform irradiance 1000 W/m^2 at 10° C	1000	1000	10
5	Non-uniform irradiance (Partial shading conditions)	1000	500	25
6	Sudden changes in irradiance level	1000 800 600	1000 800 600	25
7	Extreme dynamic weather conditions	770 +230 $(W/m^2)/s$	770 +230 $(W/m^2)/s$	25
8	Mild dynamic weather conditions	950 +50 $(W/m^2)/s$	950 +50 $(W/m^2)/s$	25

5. Simulation Results

The simulation results of the above-mentioned cases in Table 1 for the Constant Voltage (CV), Perturb and Observe (P&O), Power Increment (PI) and their hybrid combinations are listed in this section.

5.1 Constant Voltage CV, P&O and their Hybrid Combination (CV+P&O)

The results obtained from the simulation of the cases above for the CV, shown in solid blue trace, P&O in dotted red trace and (CV+P&O) in dashed black trace are shown in Fig. 12 to 19.

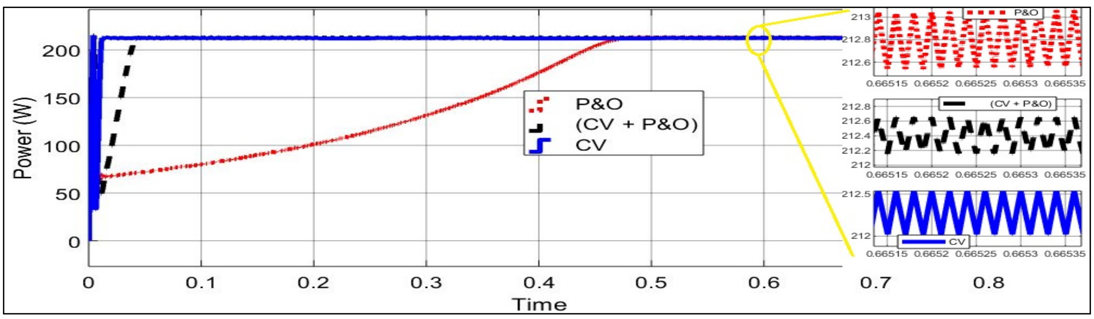


Fig. 12. Case1: STC –CV, P&O and (CV+P&O).

Figure 12 shows the performance of the fast-inaccurate CV in the solid blue line, the slow accurate P&O in dotted red line and their optimal fast and accurate hybrid combination under standard test conditions in dashed black line. The CV method proved its ability to reach the MPP much faster than the P&O algorithm, which is relatively more accurate than the CV. However, the hybrid combination of the CV, implemented in the first stage of the MPPT system, followed by the P&O in the second stage, achieved both merits of the individual techniques whilst eliminating their drawbacks. i.e., the (CV+P&O) rapidly located the MPP with an accurate tracking and low oscillations around the MPP.

The results obtained from the simulation of case 2 for the CV and P&O methods along with (CV+P&O) at half irradiance shows that yet again the hybrid of these two individual techniques achieved a fast and accurate tracking of the MPP as shown in Fig. 13.

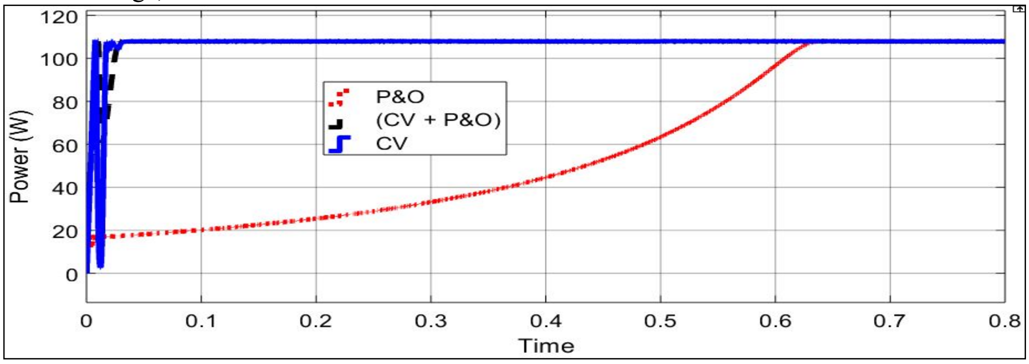


Fig. 13. Case 2: Uniform 500 W/m^2 at 25° C – CV, P&O and (CV+P&O)

It can be shown from Figures 14 and 15 that an increase or decrease in the temperature of the PV highly affects the accuracy of the CV method. This can be explained by the fact that the produced voltage form the PV is in fact affected by the operating temperature, and hence the voltage at MPP significantly change from the assumed constant fixed voltage. Moreover, the P&O still achieves high accuracy despite the change in temperature due to its PV independency at the cost of tracking speed. However again, the hybrid combination (CV+P&O) combines the convergence speed of the former with the accuracy of the latter. Fig. 14 is a solid proof of the merit of hybridization where the inaccuracy drawback of the CV was overcome by the P&O and the inherit low speed of P&O was covered by the CV.

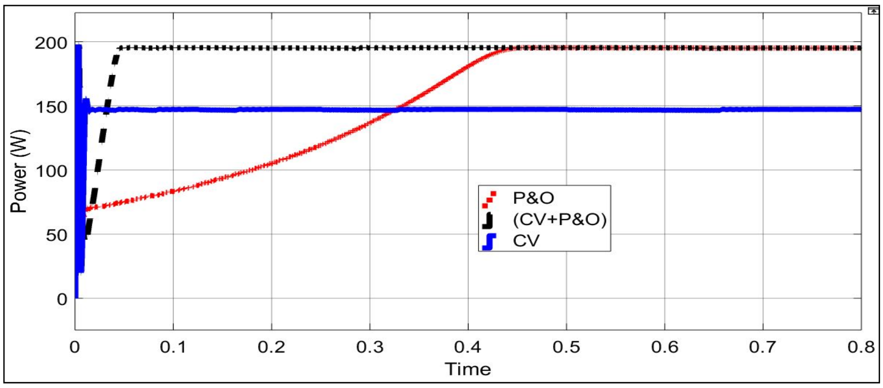


Fig. 14. Case 3: Uniform 1000 W/m^2 at 45° C – CV, P&O and (CV+P&O)

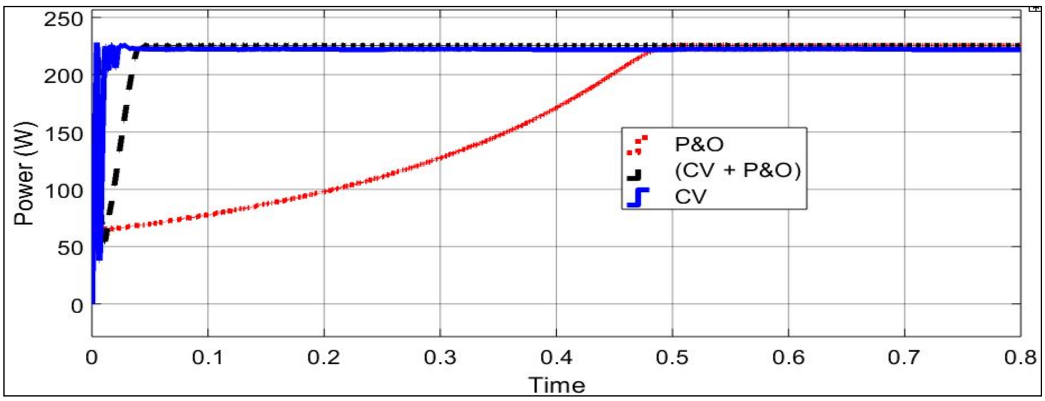


Fig. 15. Case 4: Uniform 1000 W/m^2 at 10° C – CV, P&O and (CV+P&O).

When PV modules are exposed to different levels of irradiance, the P-V curves demonstrates multiple local maxima and only one global MPP. The P&O, the CV and (CV+P&O) all failed to track the global MPP and got trapped in the first local maxima as shown in Fig. 16.

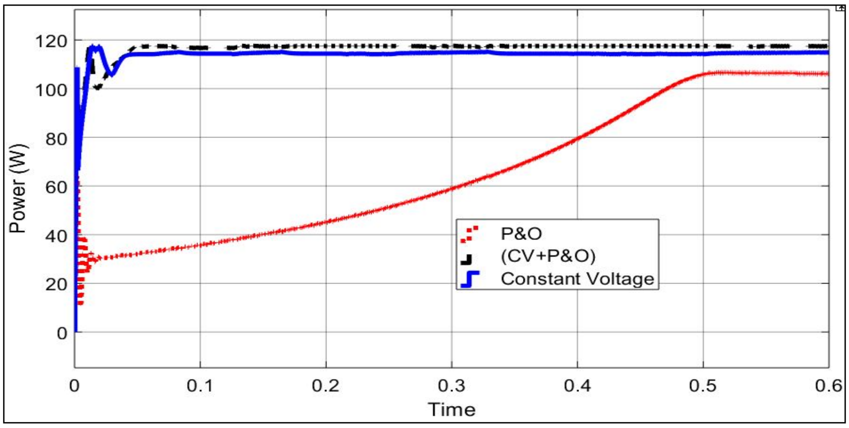


Fig. 16. Case 5: Partial shading conditions – CV, P&O and (CV+P&O).

Figure 17 shows the high convergence speed achieved by the CV method under sudden changes in the level of irradiance. Whereas, accuracy of the P&O is better when compared to the CV method, and hence the hybrid combination of (CV+P&O) achieved higher speed and accuracy than the two algorithms working on their own.

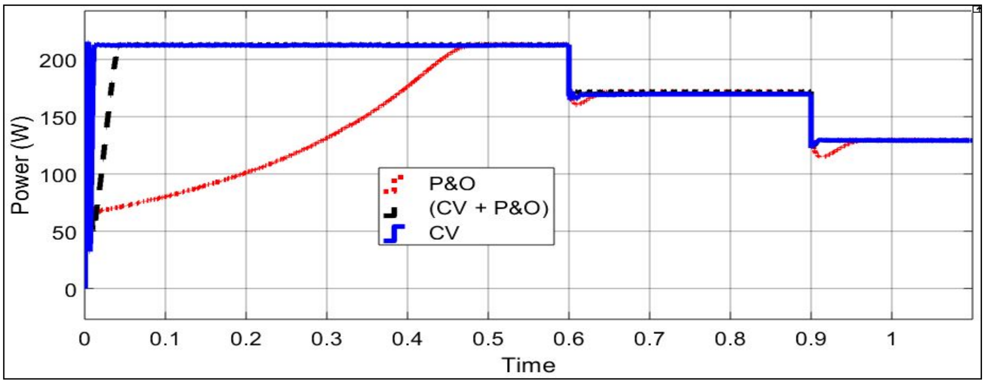


Fig. 17. Case 6: Sudden Irradiance level changes – CV, P&O and (CV+P&O).

The performance of the CV, P&O and (CV+P&O) under dynamic weather conditions is shown in Figures 18 and 19. Due to its continuous monitoring ability for the MPP location; the P&O and the (CV+P&O) achieve better tracking of the MPP under moderate (50 (W/m2)/s) and extreme (230 (W/m2)/s) dynamic weather conditions. Where on the other hand, the CV individually showed a stable yet inaccurate performance, however, its accuracy is enhanced by combining it with the P&O.

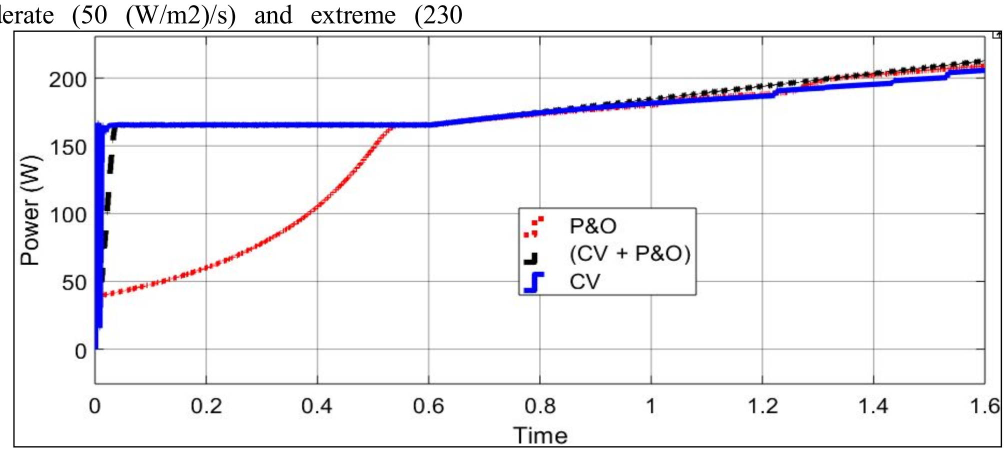


Fig. 18. Case 7: Extreme Conditions – CV, P&O and (CV+P&O)

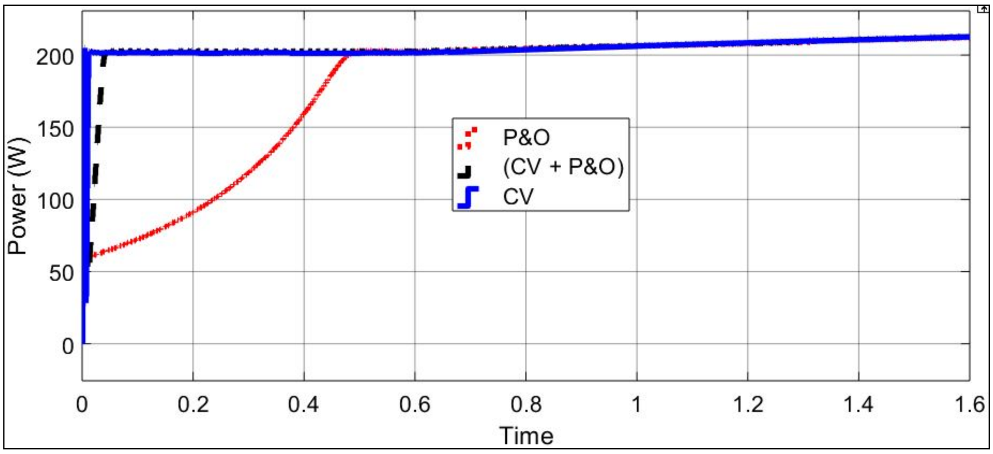


Fig. 19. Case 8: Mild Conditions – CV, P&O and (CV+P&O).

5.2 Power Increment (PI), P&O and their Hybrid combination (PI + P&O)

The simulation results obtained from evaluating the performance of the PI in solid blue line, P&O dotted red trace and (PI + P&O) in dashed black are illustrated in Fig. 20 to 27.

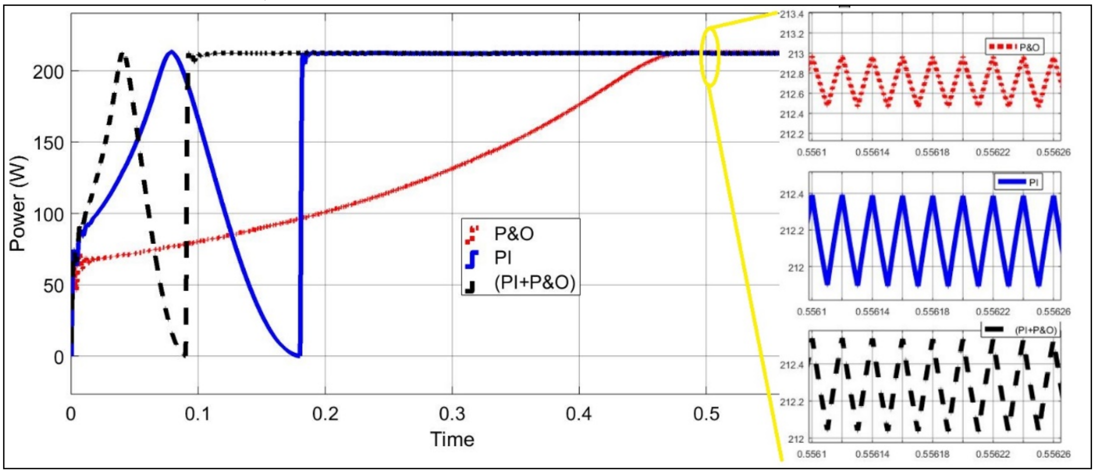


Fig. 20. Case 1: STC– PI, P&O and (PI + P&O).

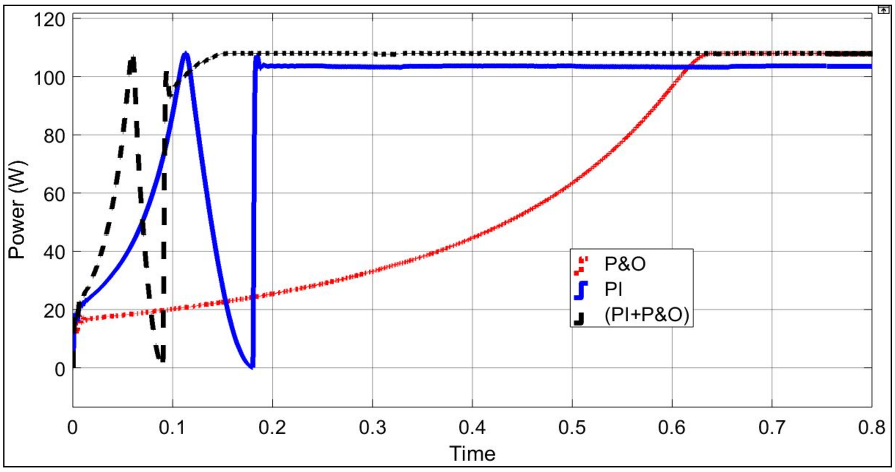


Fig. 21. Case 2: Uniform 500 W/m^2 at 25° C – PI, P&O and (PI + P&O).

Results shown in Figures 20 and 21 demonstrate the relatively high accuracy achieved by the three algorithms; PI, P&O and (PI+P&O) under full and half irradiance test runs respectively. However, the (PI+P&O) achieved the best performance in terms of speed and accuracy. This can be explained since the addition of the accurate P&O to the faster large step-sized PI improved the speed of the individual PI, whereas the accuracy is taken care by the P&O when implemented as a second stage of the Hybrid method.

The performance of the PI, P&O and (PI+P&O) was not affected by the change in temperature as illustrated in Fig. 22 and 23, yet again, the Hybrid algorithm tracked the MPP with the best performance among the three techniques.

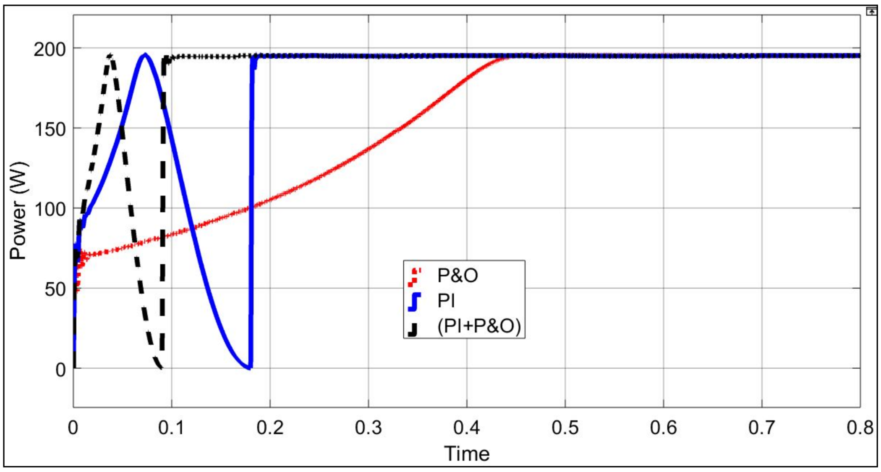


Fig. 22. Case 3: Uniform 1000 W/m^2 at 45° C – PI, P&O and (PI + P&O).

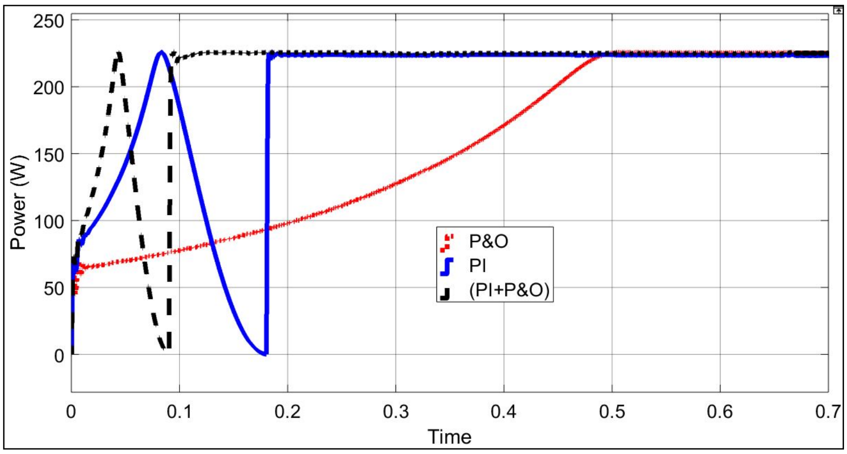


Fig. 23. Case 4: Uniform 1000 W/m^2 at 10° C – PI, P&O and (PI + P&O).

The detection of the GMPP under partial shading conditions is a feature that is not provided by most of the common MPPT techniques. The P&O operating mechanism may lead the system to get trapped in the first local maximum the algorithm locates, a case depicted in Fig. 24. On the other hand, the PI is an algorithm that is capable of locating the GMPP when modules are partially shaded and hence the hybrid combination of (PI+P&O) drives the system to operate at the GMPP. It is worth mentioning that the PI individually is able to track the GMPP, but in the simulated case, the selection for the step size of the duty cycle did not provide the best accuracy for the PI.

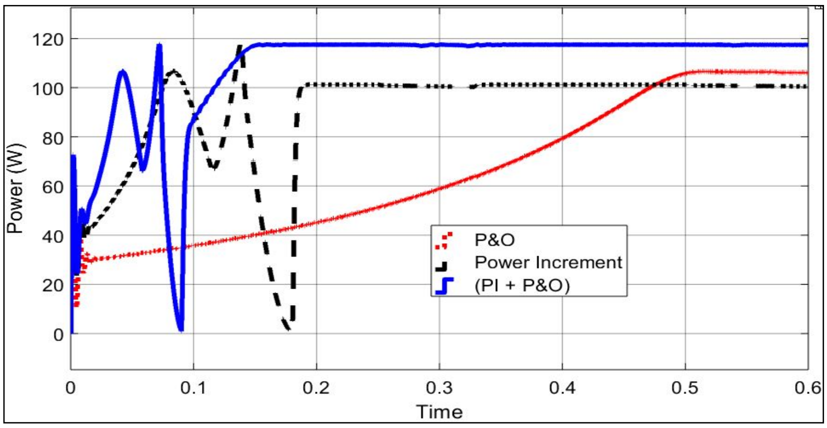


Fig. 24. Case 5: Partial Shading Conditions – PI, P&O and (PI + P&O).

Another advantage of hybridizing the (PI+P&O) appears from the test run under sudden changes of irradiance in Fig. 25, which is the significantly improved speed in locating the MPP when the level of irradiance changes, instead of scanning the entire P-V curve again, the P&O tracks the MPP, which results in improved speed and accuracy.

The performance of the PI, P&O and (PI+P&O) under dynamic weather conditions is shown in Fig. 26 and 27. The PI algorithm does not accomplish a very good performance under moderate and extreme weather conditions, since the PI fixes the duty cycle once the MPP is found and does not detect the occurrence of slight irradiance change.

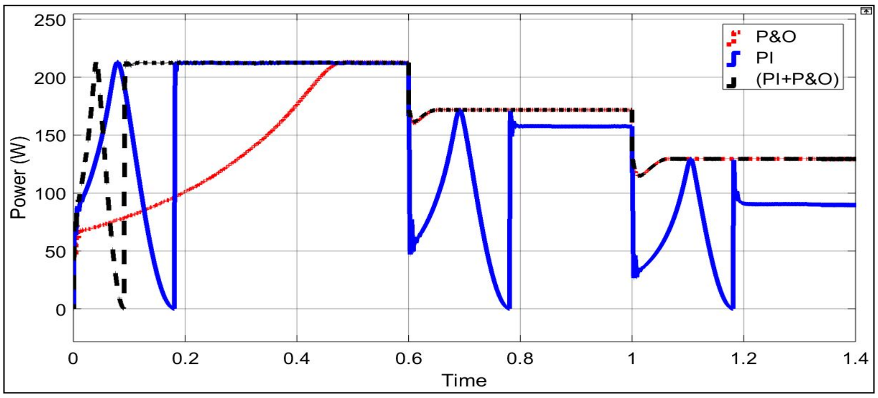


Fig. 25. Case 6: Sudden irradiance level changes – PI, P&O and (PI + P&O).

Unlike the P&O, which continuously monitors the location of the MPP and adjusts the duty cycle accordingly, therefore it achieves better tracking of the MPP when the irradiance changes. Thus, (PI+P&O) enhances the performance of the individual PI.

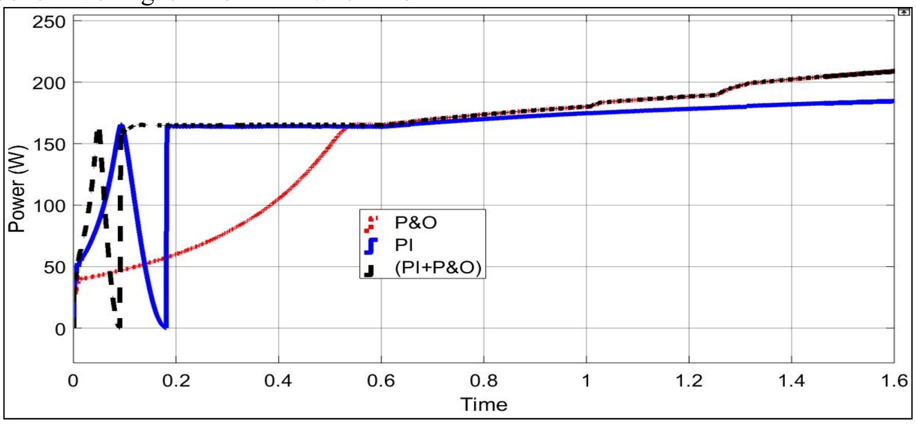


Fig. 26. Case 7: Extreme Conditions – PI, P&O and (PI + P&O).

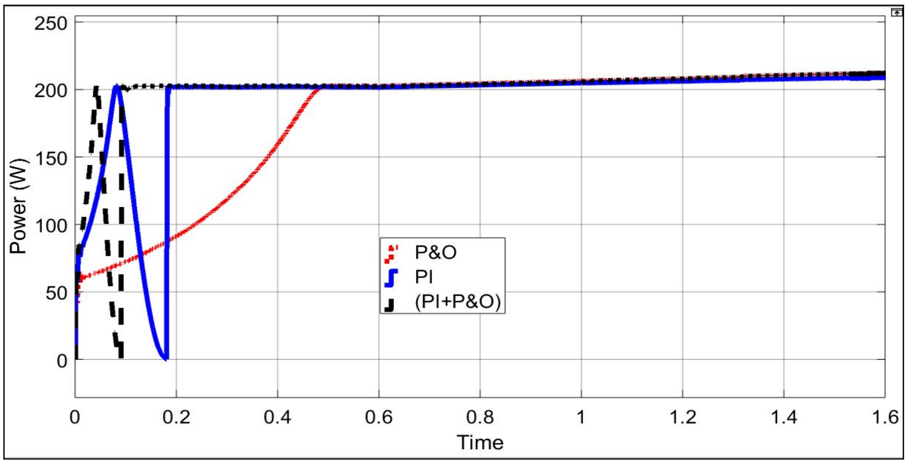


Fig. 27. Case 8: Mild Conditions – for PI, P&O and (PI + P&O).

6. Results summary and discussion

In this section, a detailed summary of the performance of the algorithms is presented along with numerical data.

For better evaluation of the MPPT algorithms performance, more cases than the above-discussed ones were simulated and the results are summarized in table 2. Where, the convergence speed (S), measured in seconds as the time it takes the algorithm to reach the MPP, and the Accuracy (A) in percent, which is the ratio between the MPP tracked by the algorithm and the actual MPP, in order to evaluate the performance of each algorithm under different weather conditions.

For example, at STC conditions, the fastest was the CV with 0.026 seconds speed compared to PI needing 0.19 seconds and 0.48 seconds for P&O, however, P&O was the most accurate with less than 0.2% error. Whereas the Hybrid combinations of (CV+P&O) and (PI+P&O) are both fast and accurate.

Table 2. MPPT Performance Summary.

MPPT algorithm		**CV**		**P&O**		**PI**		**CV + P&O**		**PI + P&O**	
Weather condition		**S (s)**	**A (%)**	**S (s)**	**A (%)**	**S (s)**	**A (%)**	**S (s)**	**A (%)**	**S (s)**	**A (%)**
Irradiance (W/m^2) at 25° C	**200**	0.036	94.32	0.78	97.7	0.195	64.3	0.168	98.6	0.22	99.29
	400	0.023	95.35	0.69	99.7	0.205	92.4	0.108	99.63	0.165	99.76
	600	0.018	94.98	0.60	99.61	0.195	97.68	0.082	99.84	0.145	99.7
	800	0.02	97.26	0.54	99.7	0.19	99.12	0.051	99.56	0.125	99.82
	1000	0.026	97.86	0.48	99.88	0.19	99.6	0.029	99.78	0.11	99.62
Temperature (°C) at 1000 W/m^2	**45**	0.019	77.95	0.46	99.87	0.192	99.63	0.052	99.64	0.12	99.65
	35	0.023	93.1	0.47	99.77	0.194	99.6	0.049	99.7	0.108	99.61
	25	0.026	97.86	0.48	99.88	0.19	99.6	0.029	99.78	0.11	99.62
	15	0.015	94.35	0.51	99.8	0.198	99.3	0.032	99.76	0.13	99.77
	5	0.013	90.96	0.52	99.74	0.191	99.08	0.065	99.79	0.106	99.69
Sudden irradiance changes (W/m^2)	**1000**	0.03	97.4	0.48	99.77	0.19	99.6	0.029	99.78	0.11	99.62
	800	0.018	97	0.06	99.7	0.192	91.9	0.05	99.81	0.06	99.71
	500	0.03	92.2	0.1	99.76	0.194	63.4	0.085	99.62	0.1	99.1
	700	0.016	96.5	0.09	99.79	0.19	81.3	0.055	99.75	0.09	98.6
Dynamic weather conditions (W/m^2/s)	**50**		99.7		99.69		97.65		99.69		99.53
	150		97.6		99.06		92.95		99.35		99.06
	230		92.9		98.7		91.2		99.23		98.5
Partial shading conditions (w/m^2)	**1000** **500**	0.028	94	0.52	89.4	0.195	86.5	0.031	89.5	0.156	99.32
	700 **400**	0.075	90.4	0.6	80.4	0.192	81.5	0.095	96.7	0.17	99.46

A detailed comparison between the simulated individual MPPT algorithms from one hand and between their Hybrid combinations on the other is presented as follows:

6.1 CV, P&O and (CV+P&O)

The results obtained in Table 2 show the difference in performance between individual and Hybrid MPPT techniques mainly in accuracy and speed with irradiance and temperature.

6.1.1 Effect of Irradiance on Accuracy and Speed

The Figures of 28–31 compare the impact of irradiance and temperature on accuracy and speed of the CV and P&O individual MPPT algorithms and their hybrid combination.

It is shown in Fig. 28 that between the two individual techniques, P&O clearly excels over the CV in accuracy achieving a very high overall accuracy (less than 1% error). It is also worth mentioning here that the highest achieved accuracy of the relatively inaccurate and PV dependent CV algorithm occurs at STC irradiance of 1000W/m2 where the constant V_{MPP} was set at STC in this work.

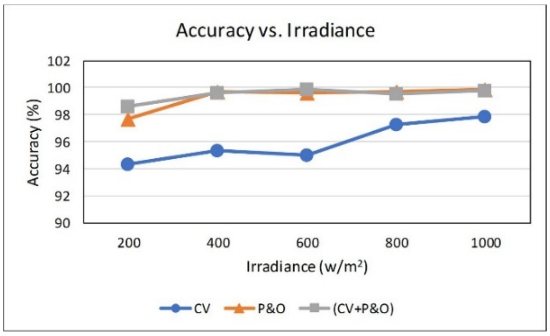


Fig. 28 Accuracy of CV, P&O and (CV+P&O) under different irradiance levels at 25°C.

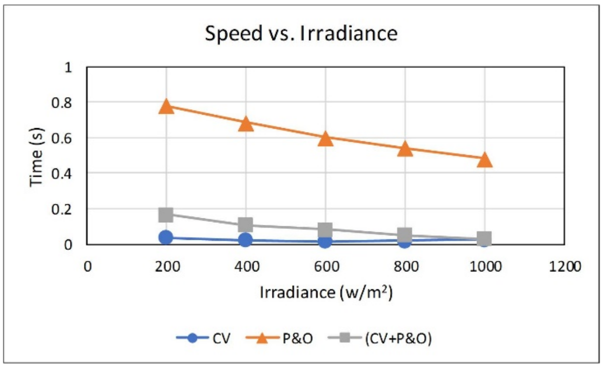


Fig. 29. Speed of tracking for CV, P&O and (CV+P&O) under different irradiance levels at 25°C.

Figure 29 indicates that the MPP is located much faster with the inaccurate CV method (less than 0.1 seconds) which is slightly affected by the change of irradiance, compared to the accurate P&O which requires more tracking time (almost 0.6 second at STC irradiance).

It can be verified from Figures 28 and 29 that the Hybrid combination of the inaccurate but fast CV and the accurate but slow P&O results in a fast and accurate tracking of the MPP, achieving a better overall performance under different irradiance levels.

6.1.2 Effect of Temperature on Accuracy and Speed

Temperature effect on accuracy and speed is illustrated in Fig. 30 and 31 respectively.

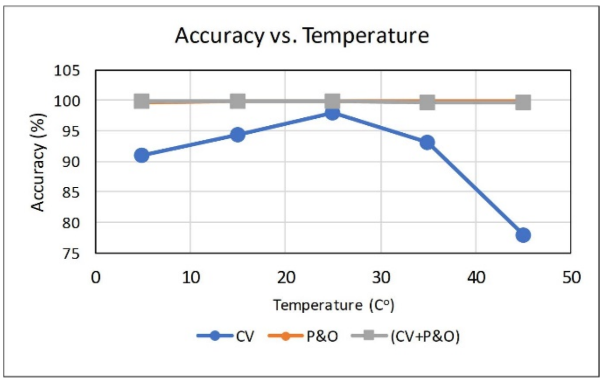


Fig. 30. Accuracy of tracking for CV, P&O and (CV+P&O) under different temperature at 1000W/m^2

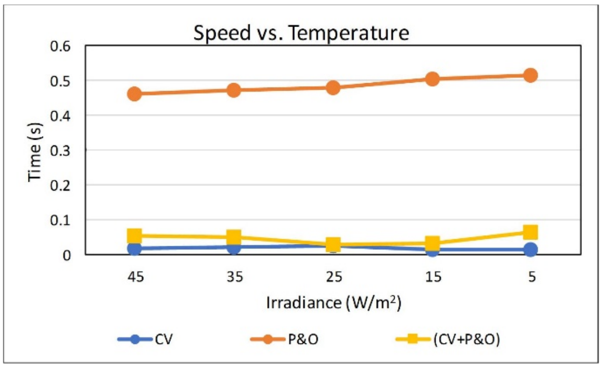


Fig. 31. Speed of tracking for CV, P&O and (CV+P&O) under different temperatures 1000W/m^2.

It is clear, from Fig. 30, that the accuracy of the CV method is significantly affected by the change in temperature. This can be explained by the fact that the PV voltage changes with temperature and so does the V_{MPP}, thus negatively affecting the tracking accuracy of the CV algorithm, which considers a fixed V_{MPP} set at STC conditions. Again, the CV achieved best accuracy under STC temperature of 25°C. Whereas the accuracy of the PV independent method of P&O is not affected by weather changes and maintains a very high accuracy under different temperature conditions (less than 1% error), a trait that will be inherited by the Hybrid combination. The high speed of the CV and the Hybrid combination in reaching the MPP under different operating temperatures compared to the P&O is illustrated again in Fig. 31. It is worth mentioning that the P&O speed is almost fixed under different operating temperatures, unlike in Fig. 29 when the irradiance level changes which significantly affected the tracking speed of the P&O.

Furthermore, and with reference to Table 2, it can be concluded that the performance of the Hybrid algorithm, inheriting the high accuracy from the P&O and the fast speed from the CV, is also optimal under sudden changes in irradiance. Where also the accuracy of tracking the MPP under dynamic conditions is improved when the P&O is combined with the CV due to the P&O ability to continuously observe the location of the MPP. However, the three-aforementioned techniques failed in finding the GMPP under partially shaded conditions, as none of them is capable of tracking the GMPP.

6.2 PI, P&O and (PI+P&O)

6.2.1 Effect of Irradiance on Accuracy and Speed

The P&O whether individually or hybridized with other algorithms attained high accuracy under different weather conditions, whereas the accuracy of the PI with large step size highly depends on the irradiance compared to the small step sized as shown in Fig. 32. In fact, the smaller the step size of the duty cycle, the more accurate it becomes but on the account of convergence speed as illustrated in Figures 32 and 33. On the other hand, those figures also indicate how Hybrid techniques capture the desired trait of its individual components. The convergence speed of the PI is almost constant with irradiance unlike the P&O as shown in Fig. 33.

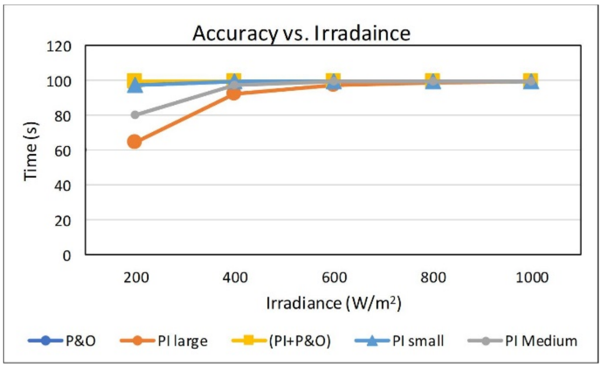


Fig. 32. Accuracy of tracking for PI, P&O and (PI+P&O) under different irradiance levels at 25°C

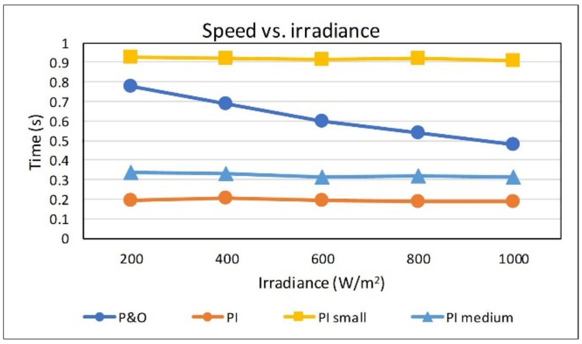


Fig. 33. Speed of tracking for PI, P&O and (PI+P&O) under different irradiance levels at 25°C

The scanning process of the P-V curve undertaken by the PI, which reveals partial shading multiple maxima, can be further accelerated by selecting a larger step sized duty cycle. Nevertheless this will place the algorithm closer to the MPP but not accurately enough. Thus, hybridization of a large step sized PI with P&O realizes a speedy allocation of the MPP region by the former then accurate determination of the MPP by the latter. Moreover, the speed of the individual PI is improved when hybridized with P&O, since a larger step size can be selected without affecting the accuracy which is determined by the P&O as in Fig. 33.

6.2.2 *Effect of Temperature on Accuracy and Speed*

The effect of temperature on accuracy and speed is illustrated in Fig. 34 and 35 respectively.

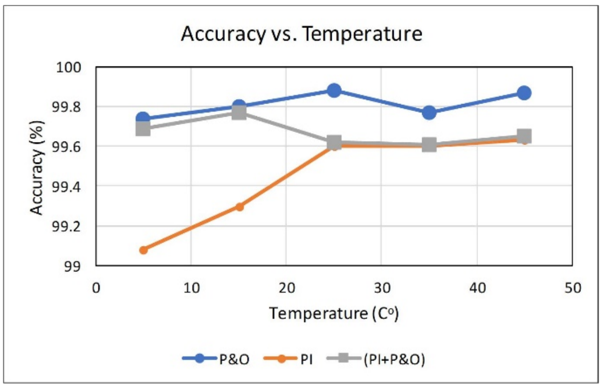


Fig. 34. Accuracy of tracking for PI, P&O and (PI+P&O) under different temperature

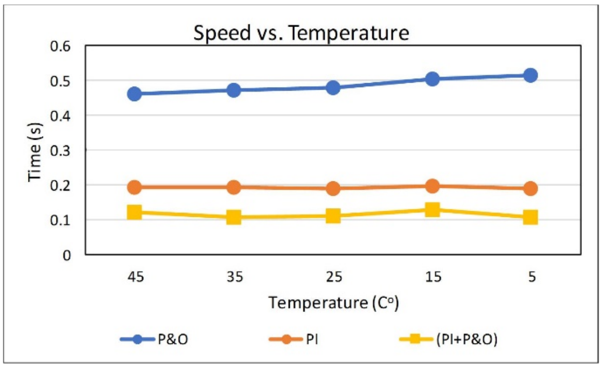


Fig. 35. speed of tracking for PI, P&O and (PI+P&O) under different temperature

From Figures 34 and 35, it can be observed that the temperature change has slight effect on the accuracy and tracking speed of these algorithms, yet again, the Hybrid technique achieved better overall performance in terms of speed and accuracy.

Graphs shown in Figures 32 to 35 further indicate the superiority of the Hybrid algorithm on the individual ones in terms of speed and accuracy under different irradiance levels and temperatures. The high accuracy of the Hybrid algorithm is obtained from the P&O and the fast speed from the large step sized PI. In addition, and with reference to Table 2, the fast speed and the ability of the PI to detect the GMPP under partial shading conditions are added to the accurate P&O in their Hybrid combination resulting in an optimal performance of quickly and accurately locating the MPP in clean and shady conditions.

Another advantage of the Hybrid combination appears under sudden irradiance changes and dynamic weather conditions, due to the P&O ability to continuously monitoring the location of MPP and hence better tracking accuracy under dynamically changing irradiance, which eliminates the requirement of reinitializing the PI under sudden changes in irradiance.

Finally, the characteristic features of the CV, P&O, PI and their Hybrid combinations from Table 2 and Fig. 28– 35 are summarized in table 3.

7. Conclusion

A MATLAB MPPT system model for Photovoltaics was developed in order to compare the performance of the Constant Voltage, Perturb and Observe, Power Increment, Hybrid of Constant Voltage with P&O and Hybrid of Power Increment with P&O under different weather conditions. This study was conducted in order to compare and evaluate the performance of each implemented individual MPPT technique and to demonstrate how Hybrid MPPT techniques outperform individual techniques when working on their own without any added complexity since Hybrid techniques combine the merits of each algorithm and eliminate their drawbacks. The Hybrid of Constant Voltage with P&O achieved the higher tracking accuracy of a small step size P&O with the faster convergence speed of the Constant Voltage. Whereas, the Hybrid of Power Increment with P&O achieved better accuracy and higher speed than the two individual algorithms along with the ability of tracking the GMPP under partial shading conditions provided by the Power Increment. Also, the performance of the Hybrid algorithms under both sudden and dynamic weather conditions were significantly enhanced when compared to their performance individually; as the presence of the P&O provided high performance under dynamic weather conditions. Moreover, the addition of the P&O to the Power Increment improved the speed of the latter under sudden changes in irradiance, while the convergence speed of the former under sudden irradiance changes was also boosted when hybridized with the fast Constant Voltage.

Table 3 MPPT techniques characteristics

	Speed	**Accu-racy**	**Ease of implem-entation**	**Track GMPP**	**Sudden changes in irradiance**	**Dynamic weather conditions**	**Analog or digital**	**PV depen dency**
CV	High	Good	Very Easy	Unable	Good performance	Very good performance	Both	Yes
P&O (small step size)	Low	High	Easy	Unable	Good performance	High performance	Both	No
PI	Good	Very good	Easy	Able	Poor performance	Poor performance	Both	No
CV+ P&O	High	High	Easy	Unable	High performance	High performance	Both	Yes
PI + P&O	Very good	High	Easy	Able	High performance	High performance	Both	No

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