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# Performance Comparison of Widely-Used Maximum Power Point Tracker Algorithms under Real Environmental Conditions

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*Abstract*—**Maximum power point trackers (MPPTs) play an essential role in extracting power from photovoltaic (PV) panels as they make the solar panels to operate at the maximum power point (MPP) whatever the changes of environmental conditions are. For this reason, they take an important place in the increase of PV system efficiency. MPPTs are driven by MPPT algorithms and a number of MPPT algorithms are proposed in the literature. The comparison of the MPPT algorithms in literature are made by a sun simulator based test system under laboratory conditions for short durations. However, in this study, the performances of four most commonly used MPPT algorithms are compared under real environmental conditions for longer periods. A dual identical experimental setup is designed to make a comparison between two the considered MPPT algorithms as synchronized. As a result of this study, the ranking among these algorithms are presented and the results show that Incremental Conductance (IC) algorithm gives the best performance.**

*Index Terms*—**Maximum power point trackers, outdoor conditions, performance evaluation, photovoltaic system.**

## I. Introduction

Different MPPT algorithms are used for the determination of MPP. These algorithms are divided into two groups: direct and indirect. In indirect algorithms, the operating point, where PV generator operates with maximum power, is estimated either measuring current, voltage and radiation values or with numerical approximations-mathematical expressions using experimental data. In direct algorithms, the maximum power point is not obtained by procedures on the contrary to indirect algorithms; the system is forced to operate at MPP. Direct and indirect methods used for determination of maximum power point are examined in the literature. A detailed review of these algorithms is done by V. Salas et al. [1] and advantages and disadvantages of the algorithms are given. In a study conducted by M. Berrera et al. [2], experimental comparison of seven widely adopted MPPT algorithms carried out for two different radiation profiles under standard test conditions. Among the seven generally adopted algorithms, Perturbation and Observe (P&O) algorithm shows the best performance for two different radiation profiles. M. Berrera also states that, Incremental Conductance (IC) algorithm can be a good alternative to P&O algorithm under rapid and continuous irradiance variations. T. Esram at al. [3], made a comparison of nineteen different MPPT methods according to their cost and performance. The authors state that different algorithms can be suitable for different practice areas. D. P. Hohm et al. [4] focus on comparison of three MPPT methods i.e., P&O, IC and Constant Voltage (CV) algorithms, using a PV array simulator. Their performance comparison results show that P&O algorithm is very competitive against other MPP tracking algorithms and can have a better performance in excess of 97%. The study carried out by C. Hua et al. [5] shows the performance comparison of voltage feedback control, power feedback control and widely used P&O and IC MPPT methods for two different radiation condition. In result of their comparison, among three algorithms IC method shows best performance under two radiation conditions. A. R. Reisi et al. [6] compares different MPPT methods with simulation models under Matlab/Simulink. Their study introduces a classification for MPPT methods based on three categories: hybrid, online and offline methods. As a result of their study, they provide a selection guide of appropriate MPPT methods. B. Subudhi et al. [7] makes a comprehensive comparison study based on features, like control variables, control strategies, circuitry and approximate costs. Their comparison results offer a useful tool not only for the MPPT users but also the designers and manufacturers of the PV systems. M. A. G. Brito et al. [8] performs the comparison of usual MPPT methods using solar array simulator. They made a comparison between twelve methods with respect to the amount of energy obtained from PV. The authors state that performance differences among the best MPPTs are very slight, and these algorithms must be evaluated according to each situation.

In this study, unlike the above mentioned studies, four commonly used MPPT algorithms are compared under real environmental conditions to comprehend the effect of temperature, cloudiness, wind and the radiation on the PV panel performance. The MPP tracking systems are realized with an experimental setup, which is capable of running four widely adopted MPPT algorithms (P&O, IC, Only Current Photovoltaic (OC), and Short Circuit Photovoltaic (SC)). As a result, the performances of the MPPT algorithms are measured and compared under real environmental condition.

## II. Background and Notations

This part gives the description of four algorithms that are compared with each other in terms of performance. It also

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included in this section how each algorithm determines the MPP. P&O algorithm uses an iterative method to determine MPP. It measures the PV panel current and voltage, and then it changes the operation point of PV to reach the MPP. The operation point of PV catches the MPP when *dP/dV=0* [1],[9]. P&O method measures the power (current and voltage) of the PV panel and then compares this power with the prior one. If the error in power change is positive, then it continues to change (perturb) the voltage error in same direction until it reaches the MPP. On the other hand, if the power change of error is negative, then it changes the direction of perturbation to the reverse side. Disadvantages of P&O algorithm appears when the radiation changes rapidly. Under rapidly changing radiation, P&O algorithm diverges from MPP [10-11]. In addition, operating point on power versus voltage curve oscillates around the maximum power point in the case of stable radiation. This oscillation leads in reduction of maximum power transfer. The advantages of this method can be summarized as follow; it is a very simple method [12], there is no need for PV panel characteristic and it can be optimized by controlling the speed of this method under different environmental conditions [13].

IC method tracks MPP according to the differential equation, *dP/dV* aiming to set the slope to zero. This algorithm shows a robust performance under fast changing solar radiation [14], which is the most important advantage of the method. When the P&O algorithm is optimized, its performance is basically same with the IC algorithm. However, IC algorithm still oscillates around the MPP less than P&O algorithm. On the other hand, IC algorithm needs complex control circuit, which may affect the cost of the system [1].

In the above mentioned MPPT methods, PV current and voltage must be measured. In the Only Current (OC) Photovoltaic method, the PV is forced to operate at the maximum power point by using only PV current [15]. In the first iteration, the PV current is measured and PV power is determined based on this current and duty-cycle. In the second iteration, the duty-cycle is increased and PV current is measured then PV power is determined again. After this process, the OC algorithm increase/decrease the duty-cycle ($D$) depending on the operation conditions [1]. It is a fact that using only PV current to track MPP has a major advantage in terms of cost and easiness in control. This algorithm is suitable for step-up or step-down dc-dc converter topologies [15]. In this study, OC algorithm is used in a boost converter system, with the known equations (1)-(2), where $V_o$ is battery voltage, $V_{PV}$ is PV voltage, and $I_{PV}$ is PV current.

$$P_{PV} = V_{PV} x I_{PV} = V_o x(I_{PV} x(1-D)) \quad (1)$$

$$P_{boost} = I_{PV} x(1-D) \quad (2)$$

The Short Circuit (SC) Photovoltaic algorithm works based on the linearity between current of the PV at MPP and at short circuit [16]. The linearity is called as proportional constant ($k$). The proportional constant mainly depends on the fill factor [17], solar cells fabrication technology and the environmental conditions [1]. The constant $k$ is given in Eq. (3), where $I_{MPP}$ is PV current at MPP, and $I_{SC}$ is short circuit current of PV.

$$k = \frac{I_{MPP}}{I_{SC}} < 1 \cong Constant \quad (3)$$

## III. EXPERIMENTAL SETUP

In order to compare the performances of four algorithms, the experimental setup is realized, which is constituted of five main elements: the dc-dc converters, two identical PV panels, control unit, battery and a power analyzer for measuring PV panels output power. Fig. 1 shows the block diagram of the comparison system. Identical PV panels are fixed at same position and they are connected to identical boost type dc-dc converters. Control of these dc-dc converters are made by the same controller. 24 V battery bank is connected to outputs of the dc-dc converters.

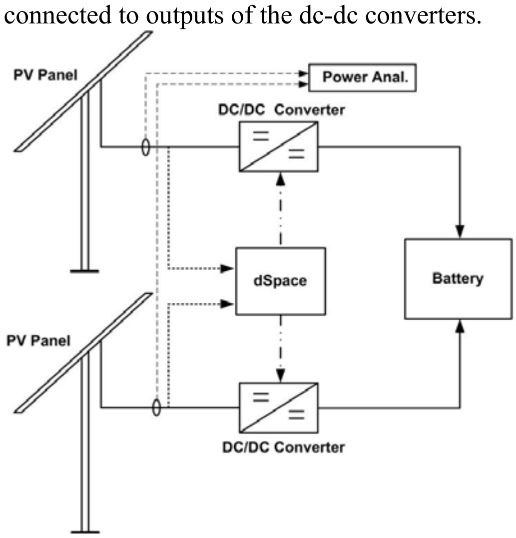


Figure 1. The experimental test system for performance evaluation of MPPT methods

### A. PV Panels

The PV panels used in this study are the mono-crystalline 50 W panels. PV panel's main specifications under 1000 W/m$^2$ and 25 $^0$C (STC) are specified in Table I and PV panels are given in Fig. 2. Fig. 2 also shows that, there is a mini PV module calibrated with a pyranometer to measure solar radiation.

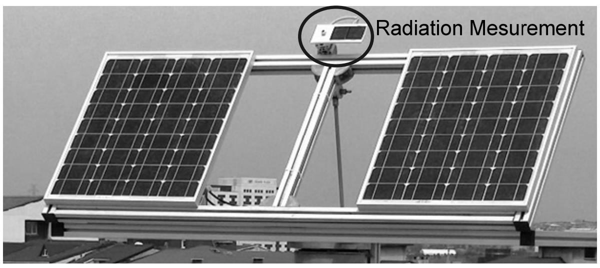


Figure 2. PV panels

TABLE I. PV PANEL'S MAIN SPECIFICATION

| Quantity | Value |
|---|---|
| Maximum power (Wp) | 50 W |
| Maximum power voltage | 17.98 V |
| Maximum power current | 2.78 A |
| Open circuit voltage | 22.30 V |
| Short circuit current | 2.99 A |

### B. DC-DC Converter

Dc-dc converters used in this study are step-up type converters. All of four above mentioned MPPT algorithms

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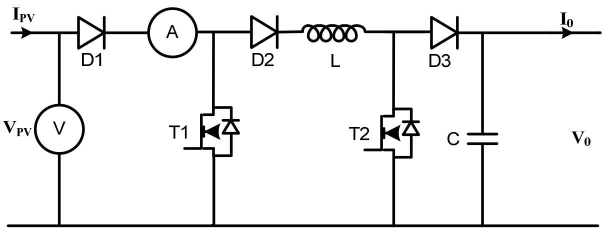
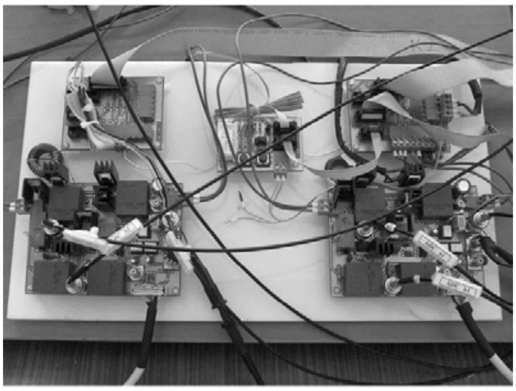
can be easily obtained by changing the control algorithm in the control system. Detailed information about dc-dc converter is given in [2]. These dc-dc converters are controlled by the same controller. Converters are operated at 35 kHz frequency. Dc-dc converters control is based on the current and voltage measurements of PV panels which are obtained by hall-effect sensors. Dc-dc converter circuit and designed power boards are illustrated in Fig. 3 and the dc-dc converter components in power circuit are given in Table II. Fig. 3 also shows that, there is a T1 switch which is necessary for the SC method for measuring the short circuit current of PV.




a)Dc-dc converter circuit[2]



b) Dc-dc converter power boards

Figure 3. Dc-dc converter circuit and power boards

TABLE II. DC-DC CONVERTER COMPONENTS

| Components | Types |
|---|---|
| D1,D2,D3 | IXYS DSEI8 |
| V | LEM LV-25P |
| A | LEM LA 25-NP |
| L | 515 µH |
| T1,T2 | IXTP182N055T |
| C | 35 V 2200 µF |

## *C. Control Unit*

In this study, a dSpace is used for the control of dc-dc converters. MPPT algorithms are designed in Matlab-Stateflow Toolbar. Dc-dc converters are controlled by running the algorithms in the dSPACE-MicroAutoBox. Herein, algorithm codes are generated in Matlab-Simulink. Basic control scheme of the test bench is shown in Fig. 4 [18].

The performance comparison of four different MPPT algorithms, i.e. SC, IC, OC and P&O, carried out with dSpace control based Matlab-Stateflow. Simulation diagrams for each of algorithm modeled in Matlab-Simulink individually. The algorithm in Fig. 4 is a subsystem of the control unit, which is designed in Matlab-Stateflow. The "C" coefficient in Fig.4 is the step size of the algorithms, which is selected as 0.01 to compare all algorithms under the same conditions [18].

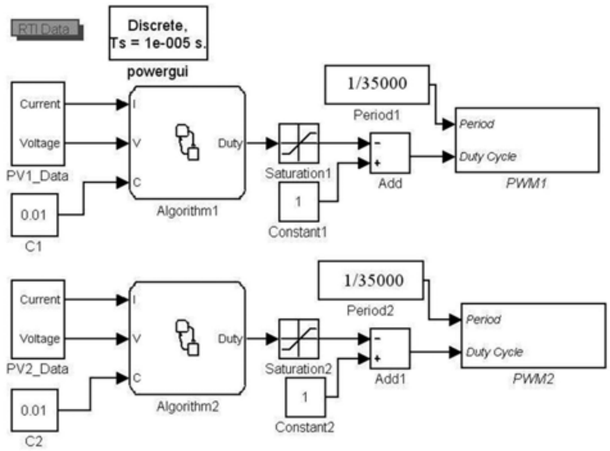



Figure 4. Basic control scheme of the test system[18]

In the experimental setup, power of each PV panel is measured with Fluke-Norma 5000 power analyzer. 24 V battery bank is formed by two identical serially connected 12 V batteries. Both of the dc-dc converters are connected to the same battery bank in order to meet the same operating conditions.

## IV. Result and Discussion

In this section, the experimental system performances of four algorithms are presented. In this study two identical PV panels are connected to two identical dc-dc converters. These dc-dc converters are controlled by two different MPPT algorithms for a period of 240 seconds. This comparison process is carried out until all algorithms' comparisons with each other are done. Because two algorithms are compared together on same platform and environmental conditions are same for each PV panel in all comparisons.

In order to analyze the performance of four MPP tracking algorithms, algorithms are experimentally compared under medium-high (540-640 W/m2) radiation level. This comparison process is carried out between 13:35 pm - 14:35 pm time intervals on December 26, 2012. Fig. 5 shows the wind speed and ambient temperature variation between 13:35 pm – 14:35 pm (1 h) during the comparison process. As it can be seen in Fig. 5, while ambient temperature is almost stable, wind speed change between 1-5 m/s. Wind speed decreases the PV temperature which is one of the affecting factor of PV performance. Wind speed variation is neglected in this study due to the PV performance is mainly affected from temperature and radiation [19]. The output power values of each algorithm and incident solar radiation on PV panels are depicted in Fig. 6 - Fig. 11.

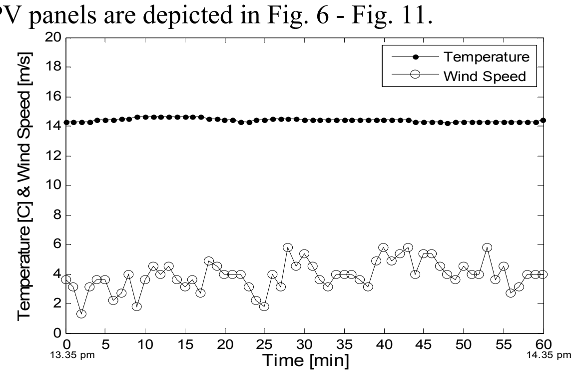



Figure 5. Wind speed and temperature variation during the comparison process

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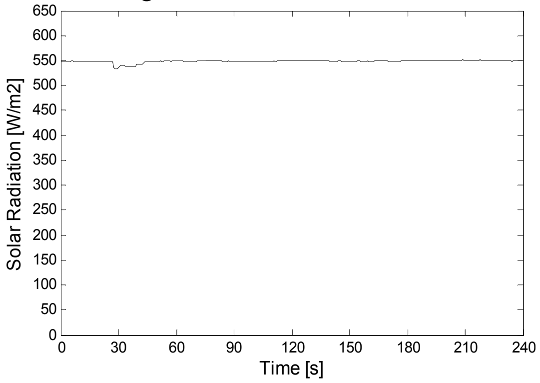
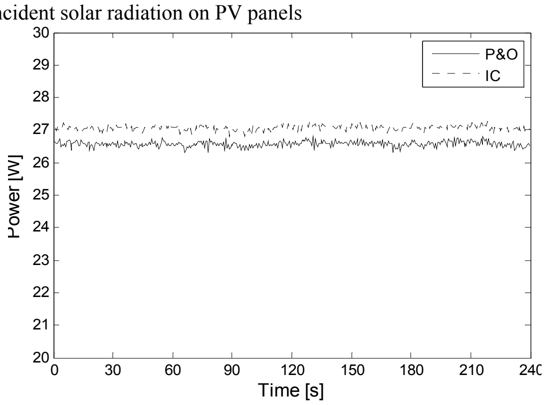
In Fig. 6b, IC and P&O algorithms are compared it shows that the power outputs of both algorithms are similar. On the other hand, it is clear from power versus time graph in Fig. 6 that IC algorithm is more successful than P&O algorithm in finding MPP. Total energy data acquired from the power analyzer is given in Table III and it also proves the success of IC algorithm. Energy difference between these two algorithms, which is named as "delta energy" in this paper, indicates that efficiency of IC algorithm is 1.835% higher than that of P&O algorithm.



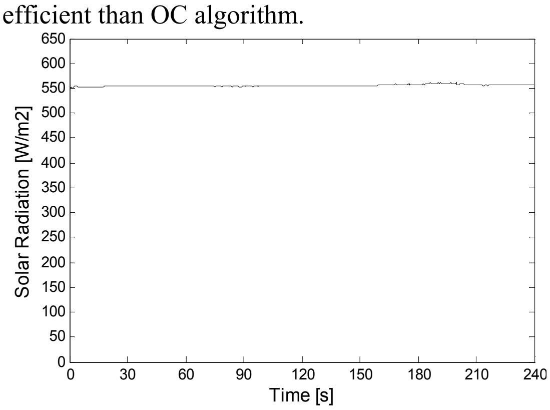

a) Incident solar radiation on PV panels



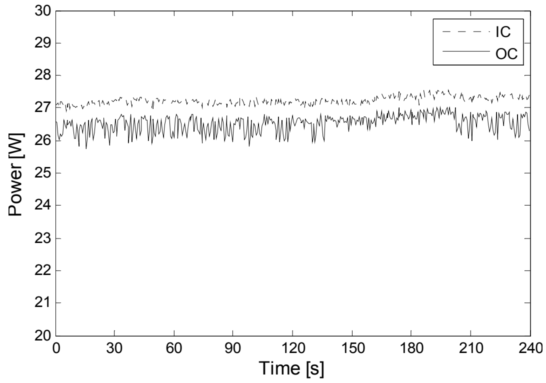

b) Power output of each algorithm

Figure 6. Comparison result of IC and P&O algorithms

Second comparison is performed between OC and IC algorithms. Fig. 7b represents generated power of each algorithm and the incident solar radiation on PV panels. Fig. 7 also represents that IC algorithm is more successful in tracking MPP. Total energy data acquired from the power analyzer verify this success (Table III). It is revealed with "Delta Energy" data in Table III that IC algorithm 2.806% more efficient than OC algorithm.




a) Incident solar radiation on PV panels

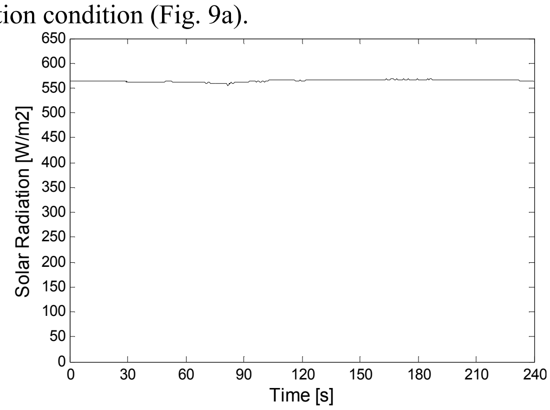



b) Power output of each algorithm

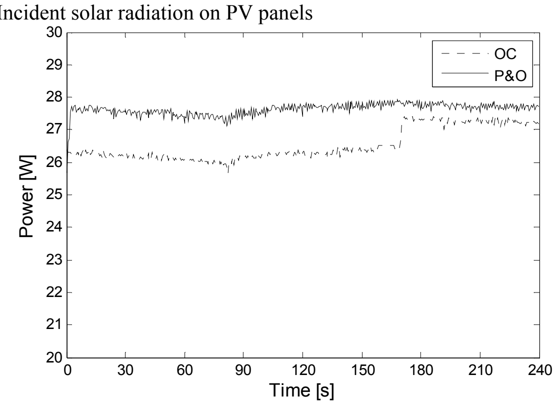
Figure 7. Comparison result of OC and IC algorithms

Third comparison carried out between OC and P&O algorithms and it is shown in Fig. 8b that P&O algorithm is more successful than OC algorithm in tracking MPP. Total energy data in Table III also reveals the success of P&O algorithm. P&O algorithm is 4.991% more efficient than OC algorithm (Table III).

Fourth comparison is performed between SC and OC algorithms. Fig. 9b shows that power outputs of both algorithms are similar. On the other hand, it is clear from power versus time graph in Fig. 9 that OC algorithm is more successful than SC algorithm in finding MPP. Total energy data, which are given in Table III also proves the success of OC algorithm. Energy difference between the algorithms indicates that efficiency of OC algorithm is 14.347% higher than SC algorithm. It is also shown in Fig. 9a that solar radiation is changed between 90-190 s time intervals as a result of moving clouds. OC algorithm shows a better performance than SC algorithm under rapidly changing radiation condition (Fig. 9a).




a) Incident solar radiation on PV panels




b) Power output of each algorithm

Figure 8. Comparison result of OC and P&O algorithms

Fifth comparison is carried out between IC and SC

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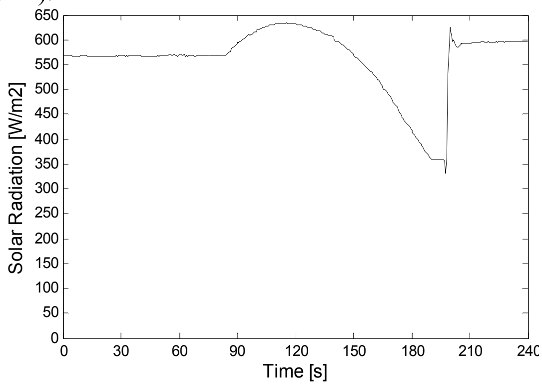
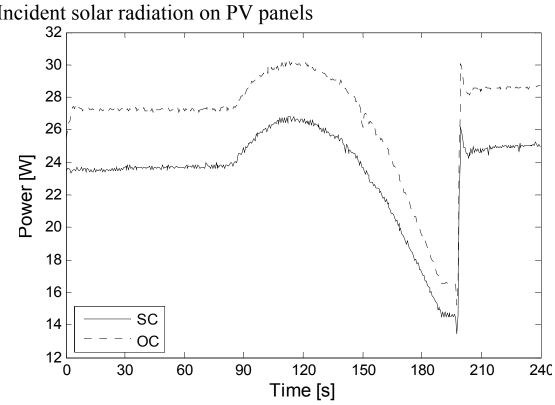
algorithms. IC algorithm is more successful than SC algorithm in tracking MPP (Fig. 10b). Total energy data in Table III also reveals the success of IC algorithm. IC algorithm is 4.991% more efficient than OC algorithm (Table III).

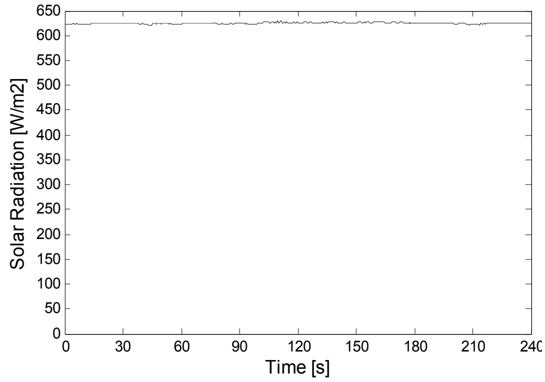



a) Incident solar radiation on PV panels

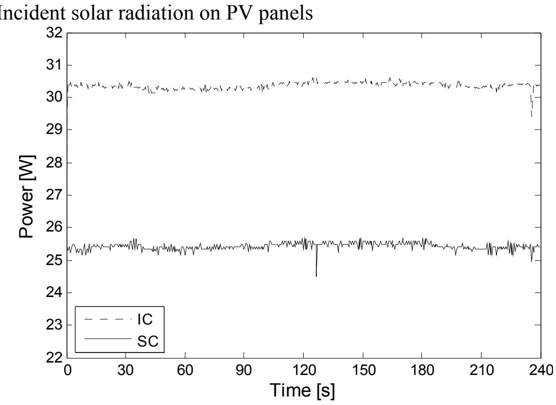



b) Power output of each algorithm

Figure 9. Comparison result of SC and OC algorithms




a) Incident solar radiation on PV panels




b) Power output of each algorithm

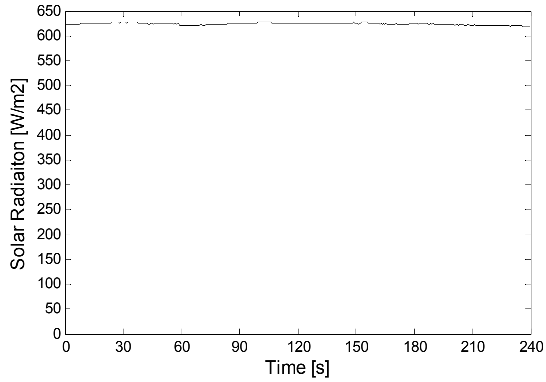
Figure 10. Comparison result of IC and SC algorithms

Last comparison is performed between P&O and SC algorithms. Fig. 11b represents that SC algorithm is less successful than P&O algorithm in finding MPP and the energy data in Table III gives the numerical results. It is revealed with “Delta Energy” data in Table III and P&O algorithm 2.806% more efficient than SC algorithm.

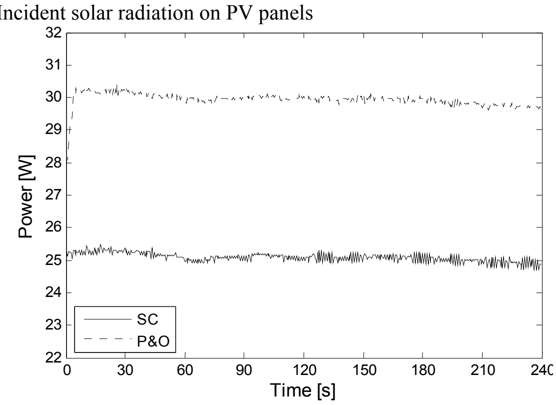
Large differences in energy outputs between SC algorithm and the other algorithms are due to the SC algorithm. In SC method, measurement of short circuit current of PV takes a time. During this time the system is running without power generation. Therefore SC algorithm fails to deliver maximum power continuously.

The test results show that real environmental conditions, the most successful MPPT algorithm is IC algorithm. However P&O algorithm performance is very close to the IC algorithm. When the P&O algorithm is optimized, the MPP tracking performance of IC and P&O algorithms are will be the same. The IC algorithm success based on;

- IC algorithm oscillates around the MPP less then P&O algorithm,
- IC algorithm does not diverge from MPP under rapidly changing radiation,
- IC algorithm uses PV current and voltage to track the MPP,
- IC algorithm does not cut the power flow for measuring the PV current/voltage.




a) Incident solar radiation on PV panels




b) Power output of each algorithm

Figure 11. Comparison result of SC and P&O algorithms

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TABLE III. ENERGY OUTPUTS OF ALGORITHMS AND PERCENTAGES OF ENERGY DIFFERENCES

| Comparison | Algorithm | Energy[J] | Delta Energy[%] | |
|---|---|---|---|---|
| | | | Delta | [%] |
| P&O & IC | P&O | 6376 | IC | 1,835 |
| | IC | 6493 | | |
| OC & IC | OC | 6342 | IC | 2,806 |
| | IC | 6520 | | |
| OC & P&O | OC | 6291 | P&O | 4,991 |
| | P&O | 6605 | | |
| SC & IC | SC | 6097 | IC | 19,288 |
| | IC | 7273 | | |
| SC & P&O | SC | 6035 | P&O | 19,271 |
| | P&O | 7198 | | |
| SC & OC | SC | 5862 | OC | 14,347 |
| | OC | 6703 | | |

## V. CONCLUSION

In this study, four adopted MPPT methods (P&O, IC, OC and SC) are compared under outdoor environmental conditions. Performance test of each algorithm is realized with a designed test system. The detailed information about test system components and their functions are presented. The results of comparison are discussed in detail. As a result of this comparison, it is found out that under outdoor conditions IC algorithm is the most successful MPPT algorithm between four algorithms. Total energy difference result also depicts that IC algorithm is able to provide at least 1.835% more energy when compared to other three algorithms. It is shown in experimental results that SC algorithm turned out to be the worst one.

For future work, these algorithms will be compared under different, i.e. low, low-medium, medium and high, radiation level. In addition, the same study will be done for different, i.e. poly-crystalline and thin-film, PV technologies.

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