

Incremental Conductance Algorithm for Tracking the MPP of a Solar PV Panel

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Abstract: *This paper proposes an adaptive and optimal control strategy for the maximum power point tracking of solar photovoltaic (PV) system. The control strategy ensures that the solar PV panel is always perpendicular to sunlight and simultaneously operated at its maximum power point (MPP) for continuously harvesting maximum power. The proposed control strategy is the combination of the solar tracker (ST) and MPP tracker (MPPT) that can greatly improve the generated power from solar PV systems. Regarding the ST system, the research work presents the two drive approaches including open- and closed-loop drives with their merits and demerits. Additionally, this paper also proposes an improved incremental conductance (InC) algorithm for enhancing the speed of the MPP tracking of a solar PV panel under various atmospheric conditions as well as guaranteeing that the operating point always moves towards the MPP using this proposed algorithm.*

Keywords: Maximum power point tracker (MPPT), solar tracker (ST), solar PV panel

1. Introduction

Energy is absolutely essential for our life and demand has greatly increased worldwide in recent years. The research efforts in moving towards renewable energy can solve these issues. Compared to conventional fossil fuel energy sources, renewable energy sources have the following major advantages: they are sustainable, never going to run out, free and non-polluting. Renewable energy is the energy generated from renewable natural resources such as solar irradiation, wind, tides, wave, etc. Amongst them, solar energy is becoming more popular in a variety of applications relating to heat, light and electricity. It is particularly attractive because of its abundance, renewability, cleanliness and its environmentally-friendly nature. One of the important technologies of solar energy is photovoltaic (PV) technology which converts irradiation directly to electricity by the PV effect. However, it can be realized that the solar PV panels have a few disadvantages such as low conversion efficiency (9% to 17%) and effects of various weather conditions [1]. In order to overcome these issues, the materials used in solar panel manufacturing as well as collection approaches need to be improved. Obviously, it is particularly difficult to make considerable improvements in the materials used in the solar PV panels. Therefore, increasing of the irradiation intensity received from the sun is an attainable solution for improving the performance of the solar PV panels. One of the major approaches for maximizing power extraction in solar PV systems is a sun tracking system. The sun tracking systems were introduced in [2], [3] using a microprocessor, and in [4] using a programmable logic controller respectively. The closed-loop control schemes for automatic sun tracking of double-axis, horizon single-axis, and fixed systems were presented and compared in [5]. Furthermore, the idea of designing and optimizing a solar tracking mechanism was also proposed in [6]. Additionally, it can also be realized that the V-I characteristic of the solar cell is non-linear and varies with irradiation and temperature [1]. Generally, there is a unique point on the V-I or V-P curve which is called the maximum power point (MPP). This means that the solar PV panel will operate with a

maximum efficiency and produce a maximum output power. The MPP is not known on the V-I or V-P curve, and it can be located by search algorithms such as the perturbation and observation (P&O) algorithms [7]–[12], the incremental conductance (InC) algorithm [13], [14], the constant voltage (CV) algorithm [15], [16], the artificial neural network algorithm [17], [18], the fuzzy logic algorithm [19], [20], and the particle swarm optimization algorithm [21]–[24]. These existing algorithms have several advantages and disadvantages concerned with simplicity, convergence speed, extra-hardware and cost. This paper proposes an improved InC algorithm for tracking a MPP on the V-I characteristic of the solar PV panel. Based on the ST and MPPT, the solar PV panel is always guaranteed to operate in an adaptive and optimal situation for all conditions. The remainder of this paper is organized as follows. The mathematical model of solar PV panels is described in Section II-A proposal for adaptive and optimal control strategy of a solar PV panel based on the control combination of the solar tracker (ST) and MPP tracker (MPPT) with the improved InC algorithm is presented in Section III. The simulation and experimental results then follow to confirm the validity of the proposal in Sections IV and V. Finally, the advantages of the proposal are summarized through a comparison with other solar PV panels.

2. Solar PV Panel

A solar PV panel is used for generating electricity. A simple equivalent circuit model for a solar PV cell consists of a real diode in parallel with an ideal current source [25]. It is realized that the solar PV panels are very sensitive to shading. Therefore, a more accurate equivalent circuit for the solar PV cell is presented to consider the impact of shading as well as account for losses due to the cell's internal series resistance, contacts and interconnections between cells and modules [25].

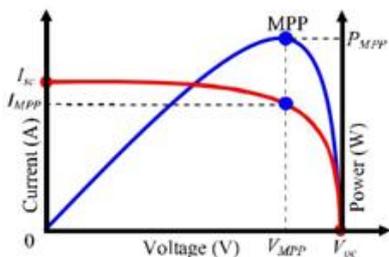


Figure 1: Important points in the V-I and V-P characteristics of a solar PV panel

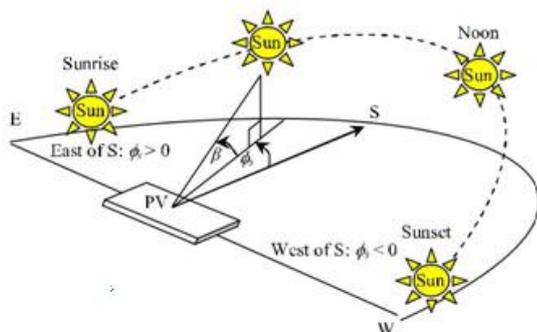


Figure 2: Description of the sun's position

Although, the manufacturers try to minimize the effect of both resistances to improve their products, the ideal scenario is not possible. The maximum power is generated by the solar PV cell at a point of the V-I characteristic where the product (V×I) is maximum. This point is known as the MPP and is unique, Figure 1. It is obvious that two important factors which have to be taken into account in the electricity generation of a solar PV panel are the irradiation and temperature. These factors strongly affect the characteristics of solar PV panels. Thus, the solar PV panel needs to be perpendicular to sunlight to maximize the irradiation obtained. Additionally, as a result, the MPP varies during the day and the solar PV panel is essential to track the MPP in

Additionally, it depends on the hour angle, H, the azimuth angle, ϕ_s can be estimated as follows:

$$\text{If } \cos H \geq \tan L, \text{ then } \phi_s = 90^\circ; \text{ otherwise } \phi_s > 90^\circ. \quad (7)$$

The declination angle, δ is given by:

$$\delta = 23.45 \sin \left(\frac{360}{365} (n - 81) \right) \quad (8)$$

where

L: the latitude of the site (degrees); δ : the declination angle (degrees);

n: The number of days since January 1;

3. Control Strategies for a Solar PV Panel

A. Sun Tracking Control

The sun rises from the east and moves across the sky to the west every day. In order to increase solar yield and electricity production from solar PV panels, the idea is to be able to tilt the solar PV panels in the direction which the sun moves throughout the year as well as under varying weather conditions. It can be realized that the more the solar PV panels can face directly towards the sun, the more power can be generated. This idea is called a ST which orients the solar PV panels towards the sun so that they harness more sunlight. Considering basic construction principles and tracking drive approaches for the motion of the tracker, STs can be divided into open- and closed-loop STs.

In the open-loop tracking control strategy, the tracker does not actively find the sun's position but instead determines the position of the sun for a particular site. The tracker receives the current time, day, month and year and then calculates the position of the sun without using feedback. The tracker controls a stepper motor to track the sun's position. It can be realized that no sensor is used in this control strategy. Thus, it is normally called an open-loop ST. The sun's position can be described in terms of its altitude angle, β and its azimuth angle, ϕ_s at any time of day which depend on the latitude, the day number and the time of day, Figure 2 [25].

The altitude angle, β is given by:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta. \quad (5)$$

The azimuth angle, ϕ_s is given by:

$$\sin \phi_s = \frac{\cos \delta \sin H}{\sin \beta}. \quad (6)$$

H: The hour angle (degrees).

The solar declination angle, δ , is the angle between the plane of the equator and a line drawn from the center of the sun to the center of the earth. The hour angle, H, shows the time of day with respect to the solar noon. It is the angle between the planes of the meridian-containing observer and meridian that touches the earth-sun line. It is zero at solar noon and increases by 15° every hour since the earth rotates 360° in 24 h. Then, the hour angle is described as follows:

$$H = 15^\circ (t_s - 12) \quad (9)$$

where

t_s : the solar time in hours. It is a 24-h clock with 12:00 as the exact time when the sun is at the highest point in the sky.

The open-loop ST must turn the solar PV panel to the east at the sunrise time and stop its motion at the sunset time. It

is realized that the altitude angle, β is equal to zero at the sunrise and sunset moments which is described as follows [25]:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta = 0 \quad (10)$$

$$\cos H = - \frac{\sin L \sin \delta}{\cos L \cos \delta} = - \tan L \tan \delta \quad (11)$$

$$H = \cos^{-1} (\tan L \tan \delta) \quad (12)$$

The hour angle, H , is the inverse cosine function which has positive and negative values. The positive values are used for the sunrise whereas the negative values are used for the sunset.

On the other hand, the closed-loop ST is based on feedback control principles. In the closed-loop tracking control strategy, the search of the sun's position is implemented at any time of day; light sensors are used and positioned on the solar PV panel. In order to determine the sun's position, two similar light sensors are mounted on the solar PV panel. They are located at the east and west, or south and north, to sense the light source intensity. There is an opaque object between two sensors which is to isolate the light from other orientations to obtain a wide-angle search and to determine the sun's position more quickly

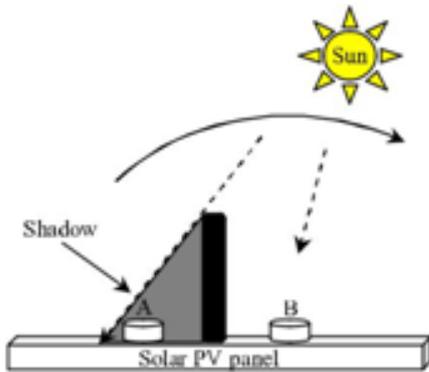


Figure 3: Rotating state of the closed-loop ST

Table I: Comparison between the Open- and Closed-Loop STs

Item	Open-loop	Closed-loop
Structure	Simple	Complicated
Extra-hardware	No required	LDRs
Cost	Cheap	Expensive
Feedback signal	No required	Required
Control	Simple	Complicated

Figure 3 describes the rotating state of the closed-loop ST when the sun's position shifts.

The sensors used are light dependent resistors in the closed-loop ST. The closed-loop ST receives the signals which are the resistance values of two LDRs, R_A and R_B respectively. Then, it makes a comparison between R_A and R_B as follows.

* If $R_A = R_B$, then the solar PV panel will be kept its position.

* If $R_A < R_B$ and $R_A < R_B$, then the solar PV panel will be rotated towards A.

* If $R_A > R_B$ and $R_A > R_B$, then the solar PV panel will be rotated towards B.

The sample time is the t for the comparison and determination of the rotated direction. It is obvious that the solar tracking systems are a good choice for the solar PV systems. The comparisons between the open- and closed-loop STs are shown in Table I. It is easily realized that the open-loop ST is simpler, less expensive, more reliable, as well as in need of less maintenance than the closed-loop ST. Nevertheless, its performance can be sometimes lower than that of the closed-loop ST, because the open-loop ST does not observe the output of the processes that it is controlling. No feedback signal is required in this ST. While the closed-loop ST can produce a better tracking efficiency, its feedback signals tracking the sun's position will be lost when the LDRs are shaded or the sun is blocked by clouds. Additionally, the closed-loop ST is rather expensive and more complicated than the open-loop ST because it requires LDRs placed on the solar PV panel. A comparison is also performed between the open- and closed-loop STs through the experimental designs and results in the next section.

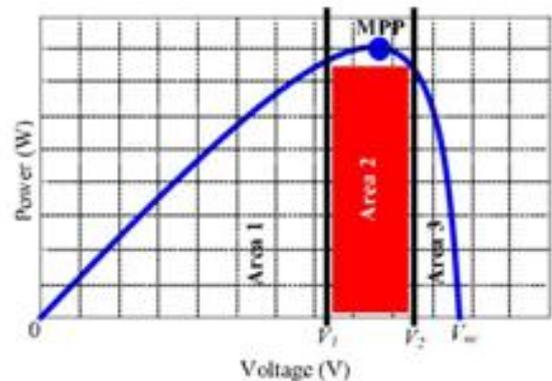


Figure 4: Area partition of the P-V characteristic

B. MPP Tracking Control

The InC algorithm is reviewed in Part 1 of this section followed by a description of the improved InC algorithm.

1) InC Algorithm: The principle of the InC algorithm is that the derivative of the power with respect to the voltage or current becomes zero at the MPP, the power increases with the voltage in the left side of the MPP and the power decreases with the voltage in the right side of the MPP [26], [27]. This description can be re-written in the following simple equations:

Therefore, the voltage of the PV panels can be adjusted relative to the MPP voltage by measuring the InC, di/dv and the instantaneous conductance, I/V . It can be realized that the InC algorithm overcomes the oscillation around the MPP when it is reached. When $di/dv = -I/V$ is satisfied,

this means that the MPP is reached and the operating point is remained. Otherwise, the operating point must be changed, which can be determined using the relationship between di/dv and $-I/V$.

Additionally, the InC algorithm can track the MPP in the case of rapidly changing atmospheric conditions easily, because this algorithm uses the differential of the operating point, dp/dv . Basically, the algorithm can move the operating point towards the MPP under varying atmospheric conditions. Nevertheless, the InC algorithm has the disadvantage of requiring a control circuit with an associated higher system cost. It also requires a fast computation for the InC. If the speed of computation is not satisfied under varying atmospheric conditions, the operating point towards the MPP cannot be guaranteed. Additionally, the search space is larger in the InC algorithm. This directly affects the search performance of the algorithm.

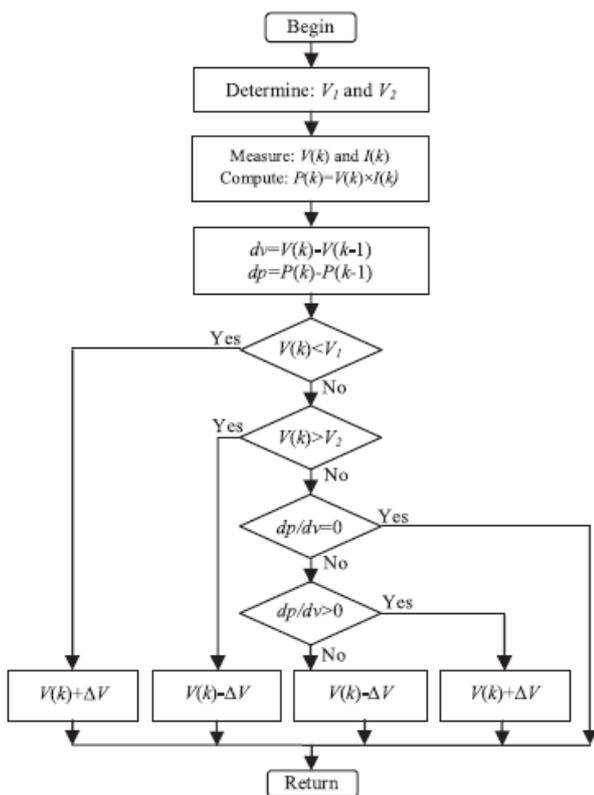


Figure 5: Flow chart of the improved InC algorithm

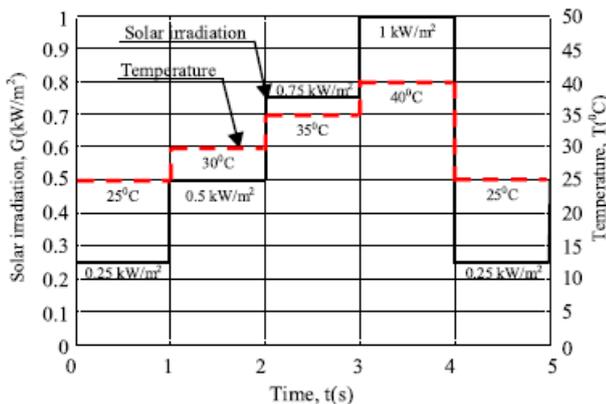


Figure 6: Description of the variations of the solar irradiation and temperature

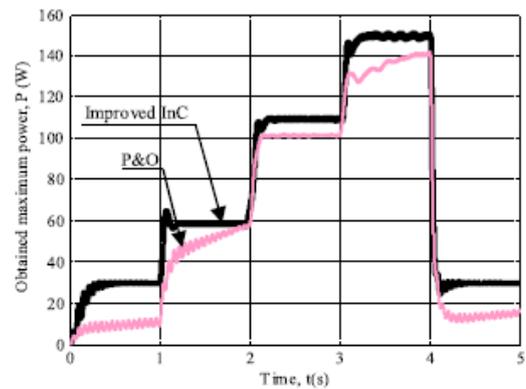


Figure 7: Obtained maximum output power with the P&O and improved InC algorithms under the variation of the solar irradiation

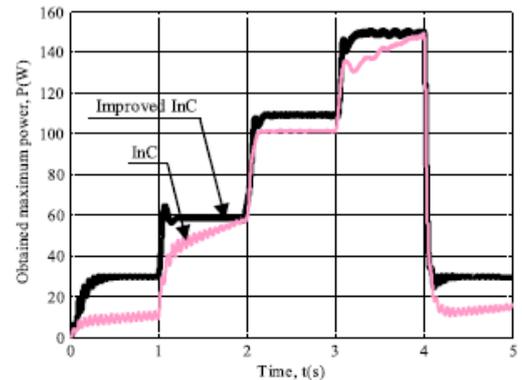


Figure 8: Obtained maximum output power with the InC and improved InC algorithms under the variation of the solar irradiation

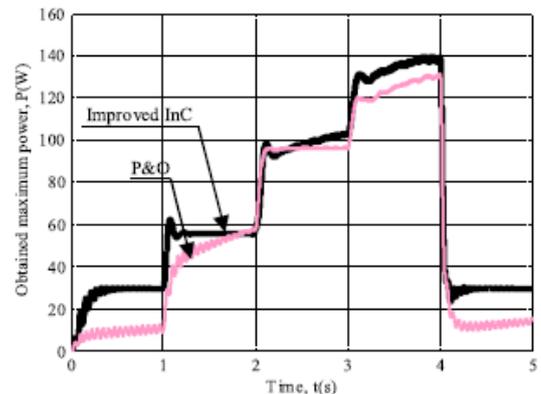


Figure 9: Obtained maximum output power with the P&O and improved InC algorithms under both the variations of the solar irradiation and temperature

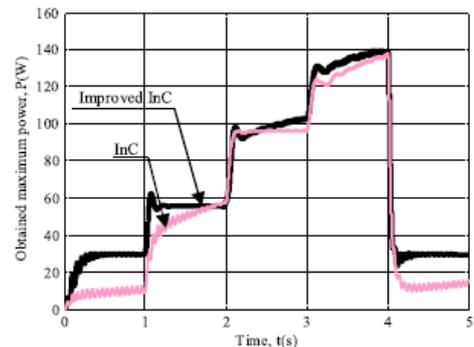


Figure 10: Obtained maximum output power with the InC and improved InC algorithms under both the variations of the solar irradiation and temperature

MPP, Figure 4. It can be realized that the improved InC algorithm only needs to search the MPP within area 2, from 70% V_{oc} to 80% V_{oc} . This means that:

$$V_{ref} = (70\% - 80\%) V_{oc} = (V_1 - V_2) \tag{21}$$

In the improved InC algorithm, the MPPT system momentarily sets the PV panels current to zero allowing measurement of the panels' open circuit voltage. The operation of the improved InC algorithm is shown in the flow chart, Figure 5. Finally, the ST and MPPT are combined to control the solar PV panel so that the obtained electricity is maximized under all atmospheric conditions.

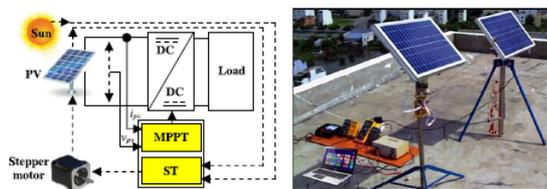


Figure 11: Block diagram of the experimental setup

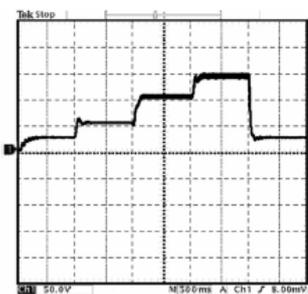


Figure 12: Experimental result of obtained maximum output power with the improved InC algorithm under the variation of the solar irradiation

Table III: Control Strategies For A Solar Pv Panel

Strategy	1	2	3	4	5	6	7
Open-loop ST	X	✓	X	✓	✓	X	X
Closed-loop ST	X	X	✓	X	X	✓	✓
InC based MPPT	X	X	X	✓	X	✓	X
Improved InC based MPPT	X	X	X	X	✓	X	✓

Linearly proportional to the open circuit voltage of PV panels with varying atmospheric conditions. The ratio of V_{MPP}/V_{oc} is commonly used around 76% [30]. Thus, the improved InC algorithm is implemented to divide the P-V characteristic into three areas referred to as area 1, area 2 and area 3, where area 1 is from 0 to 70% V_{oc} , area 2 is from 70% V_{oc} to 80% V_{oc} and area 3 is from 80% V_{oc} to V_{oc} . Area 2 is the area including the MPP, Figure 4. It can be realized that the improved InC algorithm only needs to search the MPP within area 2, from 70% V_{oc} to 80% V_{oc} . This means that:

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4. Simulation Results

Simulations are performed using MATLAB/SIMULINK soft-ware for tracking MPPs of the solar PV array with 7 panels, RS-P618-22 connected in series whose specifications and parameters are in Table II. The solar PV panel provides a maximum output power at a MPP with V_{MPP} and I_{MPP} . The MPP is de-fined at the standard test condition of the irradiation, 1 kW/m² and module temperature, 25 °C but this condition does not exist most of the time.

Table IV: Comparison of the Obtained Powers of the Solar PV Panel between Strategies 1–7

Time	$P_{Strategy1}$ (W)	$P_{Strategy2}$ (W)	$P_{Strategy3}$ (W)	$P_{Strategy4}$ (W)	$P_{Strategy5}$ (W)	$P_{Strategy6}$ (W)	$P_{Strategy7}$ (W)
07:50 AM	0.16	0.48	0.72	0.51	0.54	0.76	0.8
07:50 AM	0.74	1.51	1.98	1.61	1.72	2.01	2.21
08:00 AM	0.76	3.14	3.25	3.50	3.57	3.29	3.63
08:30 AM	1.06	3.60	3.80	4.06	4.10	4.21	4.33
09:00 AM	3.30	5.19	5.23	5.23	5.92	5.18	5.96
09:30 AM	4.76	7.85	8.84	8.22	8.94	9.38	10.08
10:00 AM	11.48	12.86	13.26	13.05	13.75	13.04	14.00
10:30 AM	11.04	13.34	13.35	13.49	14.26	13.62	14.10
11:00 AM	12.43	13.92	13.78	14.30	14.89	13.96	14.55
11:30 AM	12.84	14.66	14.79	14.96	15.68	14.94	15.62
12:00 PM	13.07	15.98	16.17	16.21	16.65	16.54	17.08
12:30 PM	13.53	15.58	15.95	16.18	16.23	16.17	16.83
01:00 PM	13.13	14.90	15.44	15.40	16.19	15.45	16.31
01:30 PM	10.19	11.10	11.42	10.87	12.06	11.12	12.13
02:00 PM	6.57	7.27	8.48	7.36	7.90	8.41	9.00
02:30 PM	5.58	9.19	10.18	8.76	9.98	10.58	11.50
03:00 PM	5.01	6.70	7.64	6.40	7.28	7.75	8.62
03:30 PM	4.37	5.60	5.70	5.36	6.25	5.73	6.20
04:00 PM	3.15	4.22	5.21	4.14	4.71	5.21	5.67
04:30 PM	2.84	3.66	4.28	3.51	4.08	4.47	4.66
05:00 PM	1.89	2.98	3.94	3.23	3.32	4.03	4.28
Total	137.91	173.72	183.42	176.35	188.03	185.86	197.58

Figure 6 and the solar irradiation variation is as in case 1. Then, the obtained output powers are shown as in Figures 9–10 using the P&O, InC and improved InC algorithms under the variation of both the temperature and solar irradiation. Figures 11–12 show the MPPs of the solar PV panel under the variations of the solar irradiation and temperature. It can be realized that the simulation results of the cases using the improved InC algorithm are always better than the cases using the P&O and InC algorithms, Figures 7–8 and Figures 9–10. The better results are shown through the algorithm convergence and the MPPs' tracking ability, especially with the rapid variation of both the temperature and solar irradiation. This means that the drawbacks of the InC algorithm have been overcome using the proposed InC algorithm.

5. Experimental Results

The experimental results are also implemented with the same solar PV panel, RS-P618-22. In the solar tracking strategies, a stepper motor is used as the drive source to rotate the solar PV panel. This motor is run with the output signals which are received from the LDRs. The block diagram and setup of the experiment are shown in Figures 13–14. The experimental result of obtained maximum output power using the improved InC algorithm under the variation of the solar irradiation of the simulation case 1 is shown in Figure 15. This experimental result also shows that the output power always tracks the MPPs. Furthermore, the experiment for the control strategies, described in Table III of the solar PV panel with the

proposed ST and MPPT algorithms, is also implemented outdoors from 07:00 AM to 05:00 PM by measuring the voltage and current for the same load at different times; and calculating the total power. Table III describes the control strategies for the solar PV panel as follows.

* Strategy 1: A PV is not controlled by the ST and MPPT.*

Strategy 2: A PV is controlled by the open-loop ST.

* Strategy 3: A PV is controlled by the closed-loop ST.

* Strategy 4: A PV is controlled by the open-loop ST and the InC algorithm based MPPT.

* Strategy 5: A PV is controlled by the open-loop ST and the improved InC algorithm based MPPT.

* Strategy 6: A PV is controlled by the closed-loop ST and the InC algorithm based MPPT.

* Strategy 7: A PV is controlled by the closed-loop ST and the improved InC algorithm based MPPT.

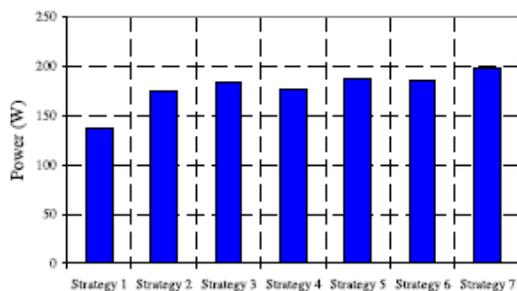


Figure 13: Comparison of the obtained powers of the solar PV panel between strategies 1–7

Table IV shows that the total powers generated by the solar PV panel are 137.91 W using strategy 1; 173.72 W using strategy 2 and 183.42 W using strategy 3. It is obvious that the total power of the solar PV panel using strategy 3 is largest. The total powers generated by the solar PV panel are 176.35 W using strategy 4; and 188.03 W using strategy 5. It is obvious that the total power of the solar PV panel using strategy 5 is larger than that using strategy 4. The total powers generated by the solar PV panel are 185.86 W using strategy 6; and 197.58 W using strategy 7. It is obvious that the total power of the solar PV panel using strategy 7 is larger than that using strategy 6. The comparison of the obtained powers of the solar PV panel between seven strategies is shown in Figure 16.

6. Conclusion

It is obvious that the adaptive and optimal control strategy plays an important role in the development of solar PV systems. This strategy is based on the combination between the ST and MPPT in order to ensure that the solar PV panel is capable of harnessing the maximum solar energy following the sun's trajectory from dawn until dusk and is always operated at the MPPs with the improved InC algorithm. The proposed InC algorithm improves the conventional InC algorithm with an approximation which reduces the computational burden as well as the application of the CV algorithm to limit the search space and increase the convergence speed of the InC algorithm.

This improvement overcomes the existing drawbacks of the InC algorithm. The simulation and experimental results confirm the validity of the proposed adaptive and optimal control strategy in the solar PV panel through the comparisons with other strategies.

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