Comparison of Perturb & Observe and Hill Climbing MPPT Schemes for PV Plant Under Cloud Cover and Varying Load

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*Abstract***— This paper entails the performance comparison of the Perturb and Observe (P&O) as well as the Hill Climbing (HC) maximum power point tracking (MPPT) techniques for photovoltaic (PV) systems. The system is simulated in MATLAB/Simulink under fast and slow cloud cover variation and distinct loading conditions. It has been found that the HC MPPT scheme performs better than the P&O scheme under slow and fast variation of cloud cover. Under fast cloud cover, the HC scheme can track up to 97.9 % of the maximum PV module output power, while the P&O can track up to 85.31 % of the maximum PV module output power. Moreover, the HC MPPT scheme tracks more PV module output power when operating under distinct loading conditions and enables for more active power to be delivered to the load, when compared to the P&O MPPT scheme.**

Keywords— Solar PV, Maximum Power Point Tracking, Perturb and Observe, Hill Climbing, Cloud Cover, Loading Conditions

I. INTRODUCTION

High dependence on fossil fuels in power generation is leading to the depletion of this resource and harmful environmental emissions [1]. In addition, the growing world population is also resulting in higher energy demand. Hence, renewable energy sources such as solar PV have gained popularity as supplementary sources of clean energy. Solar PV energy has experienced fast growth amongst other renewable energy sources due to its abundant availability and pollution-free direct conversion to electricity [2].

Although the use of solar energy has environmental advantages, the solar PV plants suffer from low power generation efficiency and are highly dependent on weather conditions. Moreover, the output power produced by these plants is affected by distinct loading conditions [3]. Thus, to guarantee optimal extraction of solar power from the PV module operating under various conditions, a reliable Maximum Power Point Tracking (MPPT) scheme should be utilized [2]. There are many MPPT techniques available, however, this paper focuses on the Perturb and Observe and the Hill Climbing MPPT [18].

A. Maximum Power Point Tracking in solar PV system

Electric power generated from solar PV arrays is endlessly changing with various weather conditions such as cloud cover, partial shading conditions and varying temperature. Different loading conditions also influence the PV array output power. Hence, a Maximum Power Point Tracking (MPPT) scheme is implemented in a solar PV system to ensure that maximum PV array's power is tracked and delivered to consumers. Fig. 1, shows a simple PV system with an MPPT controller, power converter and a dc load.

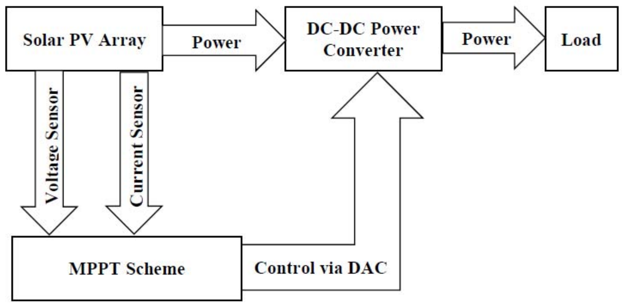

Fig. 1. A solar PV system with a power converter and MPPT scheme [4]

As shown in Fig. 1, the MPPT controller senses the voltage and current from the PV array. It then computes the maximum power point (MPP). The output of the MPPT is the duty cycle, which then controls the power electronic converter [5]. This enables the converter to extract maximum power from the PV array. DC-DC switch mode converters are widely used to convert a DC unregulated input voltage to a controlled DC regulated voltage [6]. A boost converter is mostly used in MPPT systems since it is simple to implement, relatively cheap and has a high efficiency [7].

This paper models the Perturb and Observe MPTT and the Hill Climbing MPPT techniques in MATLAB Simulink and investigates their performance under cloudy conditions and different loading conditions in a PV system.

II. Maximum Power Point Tracking Techniques

There are various Maximum Power Point Tracking (MPPT) techniques utilized and some reported in literature. These schemes vary by the complexity of algorithms used, cost of implementation, types of sensors required, and their ability to function efficiently under varying weather conditions [2]. This paper focuses on the Perturb and Observe MPPT and Hill Climbing MPPT scheme.

A. Perturb and Observe (P&O) MPPT scheme

The P&O scheme is the most commonly used technique in practice, since it is easy to implement [8][9]. Its cost of implementation is relatively cheap because it uses only one current and voltage sensor, to measure the PV array's current and voltage [10]. Moreover, it shows more suitability for an on-grid PV converter system due to its well-regulated output voltage and fast dynamic performance [11]. This method is summarized in form of a flowchart as illustrated in Fig. 2.

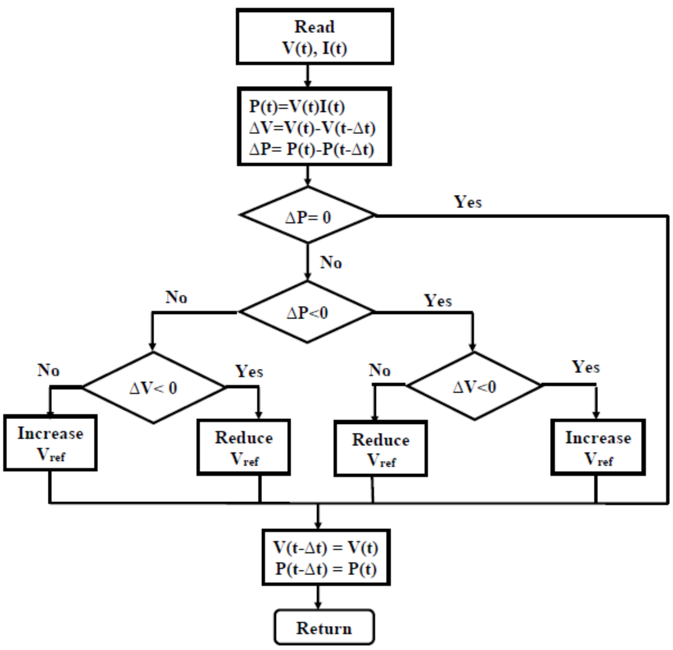

Fig. 2. Flowchart of the P&O MPPT algorithm [12]

As depicted in Fig. 2, the P&O MPPT senses the operating voltage, V(t), and current, I(t), from the PV array and calculates the output power, P(t), using the latter instantaneous values. It then compares the calculated power value with the previously calculated power, P(t-1). If the difference between these power values is greater than zero, another comparison between the sensed voltage and the previously sensed one will be made, and the reference voltage will be adjusted accordingly. The same procedure applies if the difference between the calculated power and the previously calculated one is less than zero. This algorithm is followed until the maximum power point (MPP) has been tracked.

The P&O method does not adjust well to a rapidly changing solar radiation. That is, a fast variation in irradiance results in a rapid variation in the PV array's MPP [13]. This may result in a wrong calculation of the MPP due to perturbation. Moreover, this technique is not capable of differentiating if the output power has been changed by the rapid variation in irradiance or by the perturbation voltage. Thus, an incorrect MPP tracking may result [14]. Furthermore, an unexpected change in irradiation results in more oscillations around the MPP, which makes the system incur more power losses. Also, due to a fixed perturbation step size, this scheme has a slow response to fast solar variation [15].

B. Hill Climbing (HC) MPPT Scheme

The HC scheme encompasses perturbation of the power converter's duty cycle [12] [16]. The HC MPP is simple, relatively cheap and easy to implement. Furthermore, it is suitable for a battery charger, wherein fast dynamic response is not a necessity [11]. The distinction between the P&O and HC schemes is that in the HC method, the MPP is tracked when equation (1) is true [1].

$$\frac{dP}{dD} = 0 \qquad (1)$$

where: *dP* = change in the Output Power and *dD* = change in the duty cycle. The algorithm of the HC scheme is shown in Fig. 3.

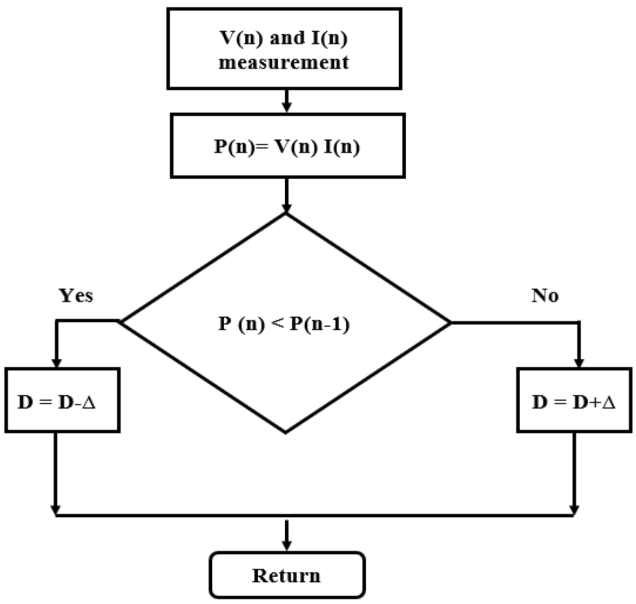

Fig. 3. Flowchart of the HC MPPT algorithm [3]

As shown in Fig. 3, this MPPT measures the operating voltage, V(n), and current, I(n), from the PV array and then calculates the output power of the array. After comparing the two power values, P(n) and P(n-1), the duty cycle (D) is incremented or decremented depending on the comparison of these power values. That is, incremented when P(n) is greater than P(n-1) and decremented when P(n) is less than P(n-1) [1]. During steady state, HC scheme may also incur oscillations around the MPP. Under fast irradiance variation, this method may not be able to track the MPP [17].

III. MODELLING OF THE SOLAR PV SYSTEM

In this section, an entire solar PV system is modelled in MATLAB/Simulink to examine the performance of the P&O and HC MPPT schemes under cloud cover and different loading conditions. This PV system is shown in Fig. 4.

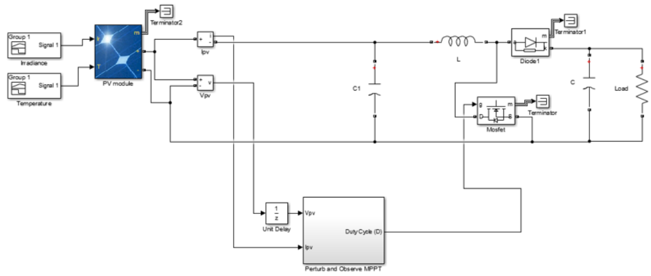

Fig. 4. Solar PV system in Simulink

As shown in Fig. 4, the PV system consists of a PV module, an MPPT controller, boost converter, filter capacitor (C1) of 20 µF and a resistive load. The electrical characteristics of the PV module are shown in Table I.

TABLE I. ELECTRICAL DATA OF SUNPOWER 285W PV MODULE

Parameter	Magnitude
Nominal power	285 W
Efficiency	14.5 %
Rated voltage	35.1 V
Rated current	8.12 A
Open-circuit voltage	44.1 V
Short-circuit current	8.51 A
Number of cells	72

A. The Boost Converter Model

The main function of the boost converter is to ensure impedance matching between the load impedance and the internal characteristic impedance of the PV module, thereby ensuring maximum power extraction from the PV module independent of the weather and load variations [1]. Furthermore, it ensures that the voltage at the load's terminals is constant and higher than its input voltage. The design specifications of the boost converter of interest are shown in Table II.

TABLE II. THE BOOST CONVERTER DESIGN SPECIFICATIONS

Specification	Magnitude
Input voltage	35.1 V
Output voltage	53.4 V
Input current	8.12 A
Switching frequency	20 kHz
Output current ripple	9.39 %
Output voltage ripple	4.69 %

In modelling the boost converter, the following equations are used to calculate the duty cycle, capacitor (C) value and inductor (L) of the converter [6].

$$\frac{V_o}{V_{in}} = \frac{1}{1 - D} \tag{2}$$

$$C = \frac{D}{R \cdot \left(\frac{\Delta V_o}{V_o} \right) \cdot f_s} \tag{3}$$

$$L = \frac{V_{in} D}{\Delta i_L f_s} \tag{4}$$

where V_o = DC regulated output voltage in volts, Vin = unregulated DC input voltage in volts, D = duty cycle, R = resistance in ohms, $\Delta V_o/V_o$ = ripple output voltage, f_s = switching frequency in hertz, Δi_L = peak to peak inductor current variation in amps. With reference to the design specifications in Table II and equations (2)-(4), the duty cycle and passive elements of the boost converter were computed. The calculated values are shown in Table III.

TABLE III. THE COMPUTED BOOST CONVERTER PARAMETERS

Parameter	Magnitude
Duty cycle	0.34
Inductor	625.19 µH
Capacitor	35.5 µF
Resistive load	10.2 Ω

B. The P&O MPPT Model

In modelling the P&O MPPT, a perturbation step size of 0.01 is chosen, wherein a saturation block ranging from 0 to 1 is used to limit the duty cycle between 0 and 1 (0% and 100%). The main purpose of this scheme is to output the duty cycle that is fed to the boost converter, to ensure maximum power extraction from the PV module.

C. The HC MPPT Model

The HC MPPT is the easiest to implement, since it has only one stage of comparison [16]. Similarly, a perturbation step size of 0.01 is chosen. Furthermore, the main purpose of this scheme is to output the duty cycle that is fed to the boost converter, to ensure maximum power extraction from the PV module.

IV. CASE STUDIES

The P&O and HC MPPT schemes were implemented and simulated in Simulink to evaluate the performance of each scheme under similar cloud cover and different loading conditions. This was done to compare the performance of the schemes under the aforesaid conditions.

A. Case 1: Fast Variation of Cloud Cover

The two schemes were tested under the same conditions. The environmental temperature was kept at 21.5°C. Fig. 5 shows the irradiance pattern for fast cloud cover variation.

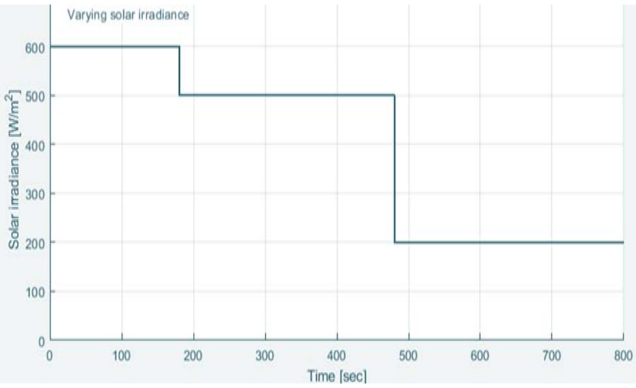

Fig. 5. Irradiance pattern for fast cloud cover variation

As depicted in Fig. 5, the operating solar radiation starts off at 600 W/m^2 and remains at this value for a period of 3 minutes (180 seconds). At time t = 180 seconds, there is a rapid decrease in irradiance from a value of 600 W/m^2 to 500 W/m^2. Moreover, the 500 W/m^2 irradiation lasts for 5 minutes (300 seconds). Thereafter, at time t = 480 seconds, there is a rapid decrease in solar irradiation from 500 W/m^2 to 200 W/m^2. Then, irradiance stays at this value (200 W/m^2) for the remaining time.

B. Case 2: Slow Variation of Cloud Cover

The two schemes were tested under the same conditions. The environmental temperature was kept at 21.5°C. Fig. 6 shows the irradiance pattern for slow cloud cover variation.

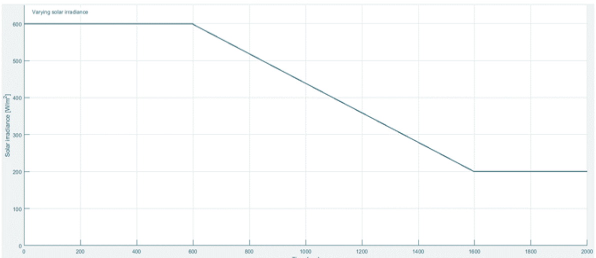

Fig. 6. Irradiance pattern for slow cloud cover variation

As shown in Fig. 6, the PV module is initially operating at an irradiance of 600 W/m^2 for a period of 10 minutes (600 seconds). Thereafter, there is a gradual decrease in solar irradiance from 600 W/m^2 to 200 W/m^2, for a period of 16.67 minutes (1000 seconds). Subsequently, solar irradiance remains at this value (200 W/m^2) for the remaining period.

C. Case 3: Different Loading Conditions

With reference to the fast variation of cloud cover shown in Fig. 5, different loading conditions were evaluated to validate the performance of the Perturb and Observe MPPT scheme as well as that of the Hill Climbing MPPT scheme. For each scheme, three loading conditions were examined at solar irradiances of 600 W/m^2 and 500 W/m^2. That is, the PV system as shown in Figure 4 was loaded with distinct resistive loads, namely R = 10.2 Ω, R = 15 Ω and R = 21 Ω. Moreover, the solar PV system was firstly loaded with a resistive load of R = 10.2 Ω, thereafter the latter load was changed to R = 15 Ω, lastly, the R = 15 Ω load was changed to the R = 21 Ω load.

V. Analysis of Results

A. Performance of P&O - Case 1

The performance of the P&O under fast cloud cover is shown in the Fig. 7. Power versus time curve show that the P&O MPPT can track fast variation of cloud cover. At time t = 180.35 seconds, the output power decreases from 130 W to 121 W. Then there is a massive rapid decrease at time t = 480.35 seconds, from a value of 121 W to 30 W.

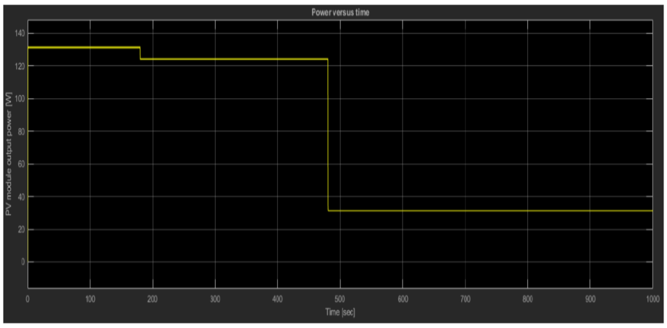

Fig. 7. PV module output power with P&O for Case 1

B. Performance of HC - Case 1

The performance of the HC MPPT under fast cloud cover is shown in the Fig. 8. The power versus time curve show that the HC MPPT can track fast variation of cloud cover. At time t = 180.25 seconds, the PV module output power rapidly decreases from 150 W to 140 W. Furthermore, it decreases from 140 W to 30 W, at time t = 480.25 seconds. This drastic reduction in the PV module output power is due to a rapid variation of cloud clover. Wherein, solar irradiance rapidly decreases from 600 W/m^2 to 500 W/m^2 at time t = 180 seconds, and from 500 W/m^2 to 200 W/m^2 at time t = 480 seconds.

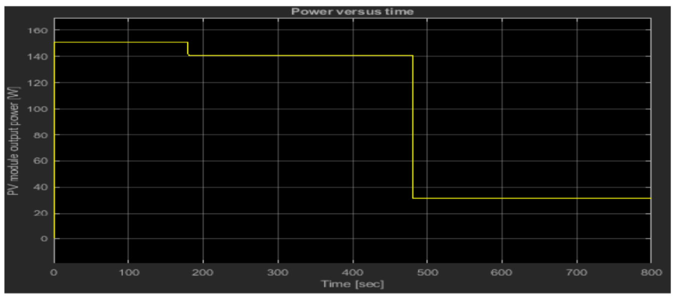

Fig. 8. PV module output power with HC for Case 1

C. *Performance Comparison of P&O and HC Schemes under Case 1*

Table IV summarizes and compares the obtained results of MPPT schemes under fast variation of cloud cover. It also includes the equivalent PV module output power from the P-V characteristic curves. From Table 4, at a solar irradiance of 600 W/m^2, the P&O method can track 78.79 % of the maximum output power of the PV module. While, the HC scheme can track 90.91 % maximum PV module output power. At 500 W/m^2, the P&O scheme can track 85.31 % of the maximum PV module output power. Whereas, the HC scheme can track 97.9 % maximum PV module output power. At 200 W/m^2, both MPPT schemes can track 61. 22 % maximum PV module output power. This shows that the HC scheme averagely results in a greater percentage of the maximum output power of the PV module, compared to the P&O scheme.

TABLE IV. PERFORMANCE COMPARISON OF P&O AND HC MPPT SCHEMES UNDER CASE 1

MPPT scheme	Irradiance [W/m2]	Output power from simulation [W]	Output power from PV-curves [W]
P&O	600	130	165
	500	122	143
	200	30	49
HC	600	150	165
	500	140	143
	200	30	49

D. *Performance of P&O under Case* 2

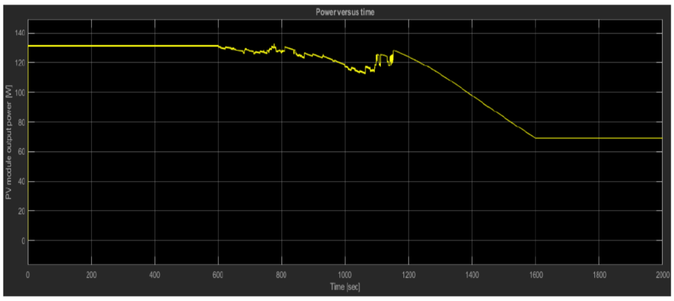

Fig. 9. PV module output power with P&O for Case 2

The PV power versus time curve of Fig. 9 shows that the P&O MPPT can effectively track slow variation of cloud cover. That is, the output power decreases with decreasing solar irradiance between time t = 600 seconds and t = 1600 seconds. However, significant oscillations are experienced in the output power of the PV module, between time t = 600 seconds and t =1150 seconds.

E. *Performance of HC under Case 2*

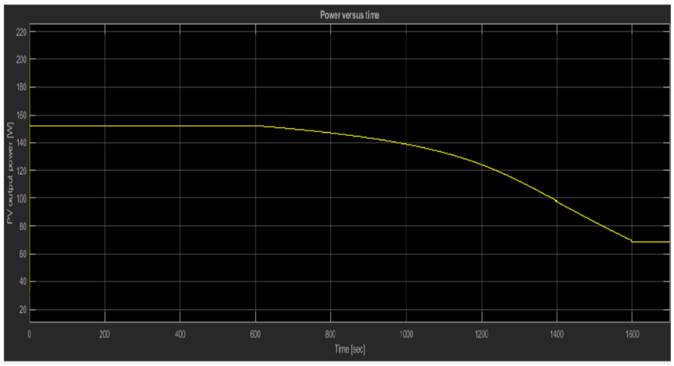

Fig. 10. PV module output power with HC for Case 2

Fig. 10, shows that the HC scheme can smoothly track slow variation of cloud cover. Furthermore, this curve shows that the HC MPPT scheme does not suffer significant oscillations.

F. *Performance Comparison of P&O and HC Schemes under Case 2*

Table V summarizes the obtained results of MPPT schemes under slow variation of cloud cover. As shown in this table, P&O scheme tracks a lower PV module output power than the HC scheme, at a solar irradiance of 600 W/m^2. However, at an irradiance of 200 W/m^2, the P&O scheme tracks 2.5 W more power than the HC scheme.

TABLE V. PERFORMANCE COMPARISON OF HC AND P&O SCHEMES UNDER CASE 2

MPPT scheme	Irradiance [W/m^2]	Output power from simulation [W]
P&O	600	130
	200	70
HC	600	155
	200	67.5

G. *Performance of P&O under Case 3*

As shown in Table VI, changing the load affects the PV module output power as well as the power fed to the load. For example, at 600 W/m^2, when the load is increased from 10.2 Ω to 15 Ω, the PV module output power and the load's power decrease from 132 W, 127 W to 100 W, 96 W, respectively. Furthermore, when the load is increased from 15 Ω to 21 Ω, at the same irradiance, the PV module output power and the load's power further decrease from 100 W, 96 W to 81 W, 78 W, respectively.

TABLE VI. PERFORMANCE OF THE P&O SCHEME OPERATING UNDER CASE 3

Resistive load [Ω]	PV module output power [W]		Load's active power [W]	
	@600 W/m^2	@500 W/m^2	@600 W/m^2	@500 W/m^2
10.2	132	126	127	124
15	100	96	96	92.5
21	81	76.5	78	72

H. Performance of HC under Case 3

As shown in Table VII, changing the load affects the PV module output power as well as the power fed to the load. For example, at 600 W/m^2, when the load is increased from 10.2 Ω to 15 Ω, the PV module output power and the load's power decrease from 150 W, 147 W to 110 W, 108 W, respectively. Furthermore, when the load is increased from 15 Ω to 21 Ω, at the same solar irradiance, the PV module output power and the load's power further decrease from 110W, 108W to 82 W, 80W, respectively.

TABLE VII. PERFORMANCE OF THE HC SCHEME UNDER CASE 3

Resistive load [Ω]	PV module output power [W]		Load's active power [W]	
	@600 W/m^2	@500 W/m^2	@600 W/m^2	@500 W/m^2
10.2	150	140	147	138
15	110	108	108	106
21	82	80	80	78

VI. CONCLUSION

Under fast and slow variation of cloud cover, the Hill Climbing MPPT scheme tracks more PV module output power than the Perturb and Observe MPPT scheme. Furthermore, no significant oscillations are experienced for the Hill Climbing scheme operating under the latter conditions. However, Perturb and Observe MPPT scheme suffers from significant oscillations when operating under slow cloud cover variation, which results in power losses. During different loading conditions, the Hill Climbing MPPT scheme also tracks more PV module output power and enables for more active power to be supplied to the load than the Perturb and Observe MPPT scheme.

Thus, the Hill Climbing MPPT scheme is more efficient than the Perturb and Observe MPPT scheme and can be used to maximize power extraction from the PV module operating under fast and slow variation of cloud cover. Furthermore, it can be used in households during the latter conditions to supply electrical appliances such as light bulbs, phone charger and other suitable appliances.

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