Comparative study of five maximum power point tracking techniques for photovoltaic systems

Ramdan B. A. Koad, Ahmed. F. Zobaa

Brunel University, London, United Kingdom

Abstract – *Since the output characteristics of photovoltaic (PV) system depends on the ambient temperature, solar radiation and load impedance, its maximum power point (MPP) is not constant. Under each condition PV module has a point at which it can produce its MPP. Therefore, maximum power point tracking (MPPT) methods can be used to uphold the PV panel operating at its MPP. In this survey, five MPPT algorithms are presented and compared under different atmosphere conditions: Perturb and Observe (P&O) Methods, Incremental Conductance (IncCond) Methods, Constant Voltage (CV), Short Circuit Current (SCC) and Open Circuit Voltage (OCV). These algorithms are widely used in PV systems as a result of their easy implementation as well as their low cost. These techniques were analysed and their performance was evaluated by using the Matlab tool Simulink under various types of solar radiation and temperature. The IncCond method was the most efficient, at rapidly changing conditions.*

***Keywords**: Photovoltaic (PV) Systems, Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O) Method, Incremental Conductance (IncCond) Method, Constant Voltage (CV), Short Circuit Current (SCC) and Open Circuit Voltage (OCV).*

I. Nomenclature

I, V -PV cell output current and voltage.
Isc- PV cell short circuit current.
Voc-PV cell open circuit voltage.
I_{ph}-generated current.
I_0 - diode reverse saturation currents.
T - Cell temperature in Kelvin.
G-Solar radiation.
A - The diode ideality factors.
K - Boltzmann's constant.
Q - Electron charge.
V_s - Input voltage,
V_{out} - Output voltage.
f - Switching frequency.
Rs, Rp - series and shunt resistance.
D - Converter duty ratio.
L_1, L_2-Input and output Inductor.
C_1, C_2 - Input and output capacitor.
R – Load resistance.
V_{mpp}- I_{mpp}-Voltage and Current at maximum power point
P_{max}-Maximum power.

II. Introduction

In general, a photovoltaic (PV) cell is a material of semiconductor that can produce direct current electricity once the sunlight hits its surface. The first photovoltaic effect was discovered by a French experimental physicist in 1839, and later in 1954, the first photovoltaic cell was produced in the United States for use in the space programme. However, its high cost, low efficiency and limited power generation ensured its usage remained only the space programme until the oil crises erupted in the 1970s [1]-[2]. Recently, the use of PV systems has become a popular method of power generation, due to its environmental credentials, free energy source, well-known technology, lack of maintenance and increasing efficiency while costs have decreased. In addition, a PV system generates electricity without moving parts and has a long lifespan compared to other renewable sources. Despite the fact that, PV systems have a number of major advantages, it has particular disadvantages that means it is unable to replace conventional sources, including the ability to only produce direct current (DC) electricity; however, most electricity applications require alternative current (AC). The other disadvantages include high costs, limited capacity compared to other renewable sources, low conversion efficiency, and dependence on weather conditions as it generally relies on atmospheric conditions [1]-[5]. Therefore, it can only produce electricity for a limited time during the day depending on the ambient temperature and solar radiation. In addition, variations in atmospheric conditions result in PV systems having nonlinear characteristics. Furthermore, under each weather condition PV module has a point at which it can produce its maximum output current and voltage; known as the maximum power point (MPP). Therefore, it is essential to control the photovoltaic module in order to operate it at its MPP. According to Ref. [4], maximum power point tracking (MPPT) can increase the production of electricity by 25%.

Several MPPT methods have been developed for use in PV systems in order to reach the MPP, ranging from simple to more complex methods depending on the weather conditions and the application [4]-[5]-[14]. The main aim of the MPPT is to extract maximum output power from the PV module under different sunlight radiation and temperatures. Numerous MPPT methods have been discussed in the literature; the Perturb and Observe (P&O) Methods [2]-[5], the Incremental Conductance (IncCond) Methods [6], and the Fuzzy Logic Method [7]-[8]. These methods can be compared through several characteristics: their simplicity, cost, the efficacy of their convergence, application hardware, the number of sensors, etc. [6]. In this survey, five MPPT algorithms are presented and compared under different atmospheric conditions: P&O Methods [10], IncCond Methods [11], Constant Voltage (CV), Open Circuit Voltage (OCV) [6] and Short Circuit Current (SCC) [8]. These algorithms are widely used in PV system as a result of their easy implementation as well as their low cost [5]-[12]-[13].

III. TERMINAL CHARACTERISTICS OF PHOTOVOLTAIC CELLS

Fig. 1 shows the equivalent-circuit model of PV that consist of a generated current (I_{ph}), a diode (D), and series and parallel resistances.

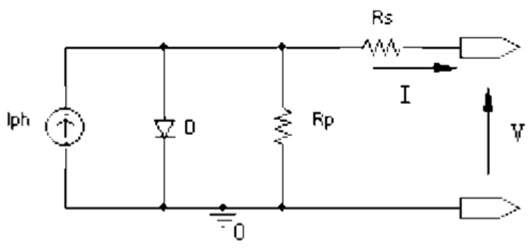

Fig. 1. Single-diode model equivalent circuit of PV cell [14].

The output current-voltage (I-V) characteristics can be calculated as follows:

$$I = I_{ph} - I_{01}\left(e^{(V+I.R_{s/AKT_c})} - 1\right) - \left(V + I.\frac{Rs}{Rp}\right) \quad (1)$$

Where, I is the cell current and V is the PV cell output voltage, I_{ph} is the photon current, and Io is the diode reverse saturation currents. A is the diode ideality factors, T is the cell temperature in Kelvin, K is the Boltzmann's constant (K=1.380 x 10^{-23} J/K), q is the Electronic charge =1.6×10−19C), Rs series resistance and Rp shunt resistance [14].

For this study the selected PV module is MSX-60 PV module, which is able to generate an output power 60 watt. Its electrical specifications are shown in Table I.

TABLE I

ELECTRICAL SPECIFICATIONS OF THE SIMULATED PV MODULE

Maximum Power (*Pmax*)	60 W
Voltage @ *Pmax* (*Vmp*)	17.1 V
Current @ *Pmax* (*Imp*)	3.5 A
Open-circuit voltage (*Voc*)	21.1 V
Short-circuit current (*Isc*)	3.8 A
Temperature coefficient of *Short-circuit current (Isc)*	.(0.065±0.015)%/°C
Temperature coefficient of *Open-circuit voltage (Voc)*	–(80±10)mV/°C
Temperature coefficient of power	–(0.5±0.05)%/°C

III.1. THE PV MODULE PERFORMANCE

By using the equations that were derived above, and the electrical specifications of the selected PV module, the current-voltage (I-V) characteristics of the selected PV module at different environmental conditions, temperature and irradiance are displayed in Fig. 2 and Fig. 3 the performance was simulated in Matlab.

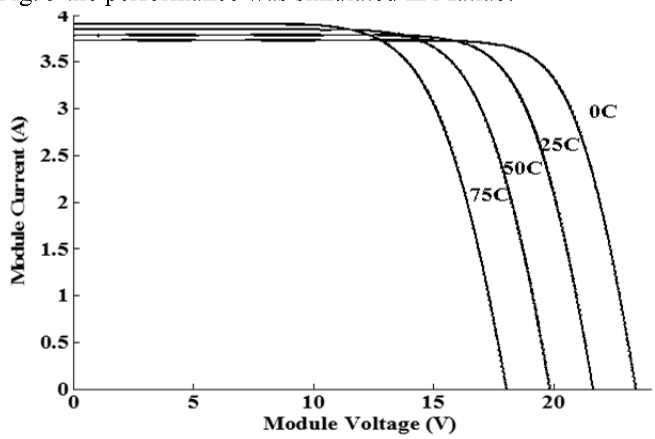

Fig. 2. MSX-60 I-V Characteristics with Variable Temperatures and Constant Irradiance (1KW/m2).

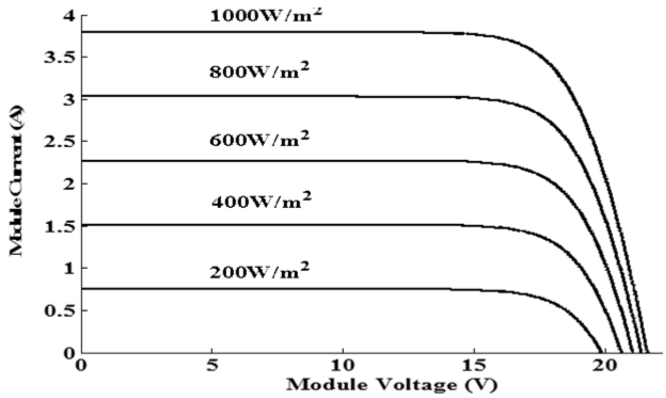

Fig. 3. MSX-60 I-V Characteristics with Different Irradiance Values and a Constant Temperature (25°C).

When connecting the PV module directly to the load, it will operate at the intersection point of its I-V characteristic and the load curve. Fig. 4 shows an example, when a resistive load was directly connected to the PV module. The figure indicates clearly that the PV module operating point is dictated by the load impedances, and in practice this point is rarely the same as the PV module MPP. Ref. [1] reports that when connecting the PV module directly to the load, it generates just 31% of its maximum power.

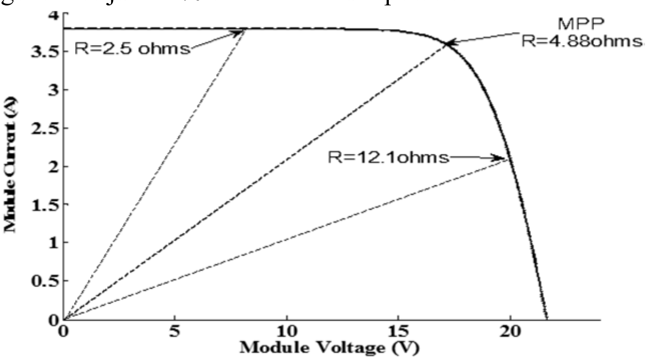

Fig. 4: The PV module operating point

IV. CÙK CONVERTER

Both Cùk and buck-boost converters can provide either lower or higher output voltage. The buck-boost converter has a lower efficiency than the Cùk converter as it has disadvantages such as: the high current stress on the power component discontinues input current, and it takes a longer time than the Cùk one for the transient response. Although the Cùk converter is more expensive than the buck-boost converter it has certain advantages over the buck-boost converter such as its continuous input current, low switching loss, and provision of a ripple-free output current due to the output stage inductor. Therefore, among the various DC-DC converters, the Cùk converter is the most appropriate to be applied in an MPPT system. Fig. 5 illustrates the Cùk converter circuit diagram which uses a capacitor as its main energy storage, and therefore it has a continuous input current, it can extract free current ripple from the PV module, has less switching losses and higher efficiency [14].

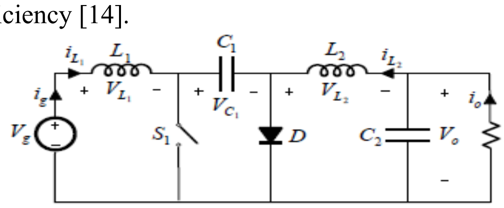

Fig. 5. Basic Electrical Circuit of DC-DC Cùk Converter [14].

Therefore, the voltage transfer function can be written as following;

$$\frac{V_{out}}{V_S} = \frac{D}{1-D} \quad (2)$$

Where: D is the duty cycle, V_s is the input voltage, and V_{out} is the output voltage.

The Cùk converter was designed according to the electric specification shown in TABLE II.
Below;

TABLE II
THE ELECTRIC SPECIFICATION OF CUK CONVERTER

Specification	
Input Voltage (V_s)	12-18V
Input Current (I_s)	0-5A(<5% ripple)
Output Voltage (V_{out})	40V(<5% ripple)
Output Current (I_o)	0-5A(<5% ripple)
Maximum Output Power (P_{max})	60W
Switching Frequency (f)	10KHz
Duty Cycle (D)	0.6≤D≤1

The Cùk converter components that used in simulation were calculated as following:

Input Inductor (LI)

The assumption that was made when calculating the inductor size is that the change in the current across the inductor is not more than 5%, and the change in the inductor current can be calculated as following:

$$\Delta I_L = \frac{V_S.D}{L.f} \quad (3)$$

Where: V_s the input voltage, D the duty cycle, and f the switching frequency.

From the above equation the inductor L can be calculated as:

$$L = \frac{V_S.D}{\Delta I_L.f} \quad (4)$$

And the current ripple is 5% of the average current, therefore ΔI_{L1} is given as:

$$\Delta I_{L1} = 5\%.I_{L1} \quad (5)$$

Therefore the inductor (*L1*):

$$L1 = \frac{V_S.D}{\Delta I_{L1}.f} \quad (6)$$

Using the same assumption, the output inductor (*L2)* size can be calculated as:

$$L2 = \frac{V_S.D}{\Delta I_{L2}.f} \quad (7)$$

Capacitor selection

In choosing the capacitor size, the voltage ripple across it should be no more than 5%.

The voltage cross the input capacitor can be calculated as:

$$Vc1 = Vs + Vout \quad (8)$$

For calculating the load resistance:

$$R = \frac{{V_O}^2}{P_O} \quad (9)$$

The following equation is used to calculate the value of *C1*:

$$C1 = \frac{V_{Out}.D}{R.\Delta V_{c1}.f} \quad (10)$$

Where: V_{out} the output voltage, D the duty cycle, R the load resistance, and f the switching frequency.

By using the output voltage ripple equation, the output capacitor ($C2$) can be calculated as:

$$\frac{\Delta V_{Out}}{V_{Out}} = \frac{1- D}{8.L_2.C_2.f^2} \quad (11)$$

Therefore $C2$ can be given as:

$$C_2 = \frac{1- D}{8.L_2.\left({}^{\Delta V_O}/_{V_O}\right).f^2} \quad (12)$$

V. TECHNIQUES OF MAXIMUM POWER POINT TRACKING

Since the power obtained by using the PV system is primarily dependent on the solar radiation, temperature and the load impedance, it is important to operate the system at its MPP. Recently, a number of authors have given different explanations of the problems relating to the MPPT controller. There are numerous different methods that can maximize the power from a PV system; this variety ranges from using simple methods to more complex analysis [16]-[17].

V.1. *Perturbation and Observation algorithm (P&O)*

This method is based on investigating the relationship between PV module output power and its voltage: the power-voltage (P-V) curve is shown in Figure 6. When the PV module operating point is on the left of the P-V curve (dP is positive), which means the PV module output power increases, then the perturbation of the PV module voltage will continue in the same direction towards the MPP. If the operating point of the module was on the right side of the P-V curve then the controller would move the PV module operating point back searching for the true MPP. This can be achieved by reversing the perturbation direction, the flowchart of this method is shown in Fig. 7 [2]-[10]-[14].

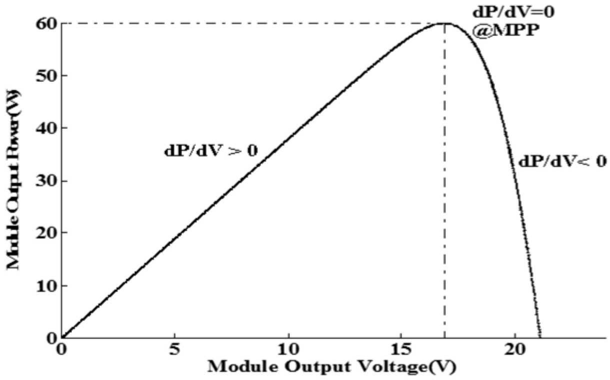

Fig. 6. P-V Curves of MSX-60 PV Module at Standard Test Conditions, Simulated with the MATLAB model (1kw/m^2, 25°C).

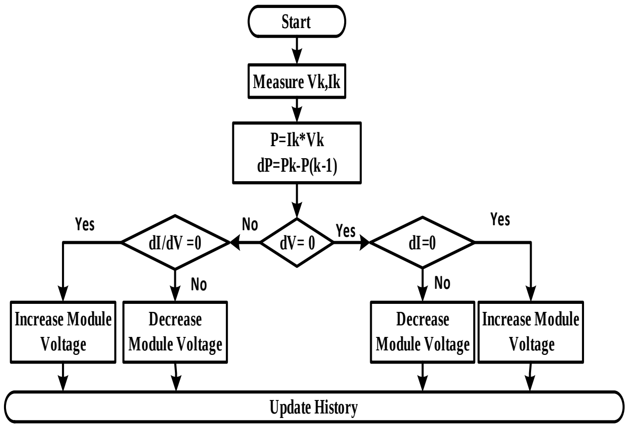

Fig. 7. Flowchart of P&O method

V.2. *Incremental Conductance (IncCond)*

Incremental Conductance **(**IncCond**)** was developed by students of Saga University, and was used to overcome the drawback of the P&O method under rapidly changing environmental conditions. The method is achieved by calculating the sign of dP/dV using the PV module incremental and its direct conductance (dI/dV and I/V) [8]-[19], In the IncCond method only two sensors (the voltage and current sensors) are required in order to measure the PV module output current and voltage, assuming there is only one point on the P-V characteristic in which the PV module can produce its MPP (see Fig. 6).

The relationship between the voltage and power can be expressed as follows;

$$\frac{dP}{dV} = 0 \qquad at\ MPP \quad (13)$$

$$\frac{dP}{dV} > 0 \qquad on\ the\ left\ side\ of\ MPP \quad (14)$$

$$\frac{dP}{dV} < 0 \qquad n\ the\ right\ side\ of\ MPP \quad (15)$$

The P-V characteristic slope (dP/dV) can be calculated using the PV module output voltage and its output current as follows:

$$\frac{dP}{dV} = \frac{d(I)}{dV} = I \times \frac{dV}{dV} = I \times \frac{dV}{dV} + V \times \frac{dI}{dV} = I + V \frac{dV}{dI} \quad (16)$$

Hence, the PV module operating point at its maximum output power can be calculated based on equation (16) as follows

$$\frac{dI}{dV} = -\frac{I}{V} \quad at\ MPP \quad (17)$$

$$\frac{dI}{dV} > -\frac{I}{V} \quad on\ the\ left\ side\ of\ MPP \quad (18)$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad on\ the\ right\ side\ of\ MPP \quad (19)$$

The flowchart of the IncCond algorithm is depicted in Fig. 8.

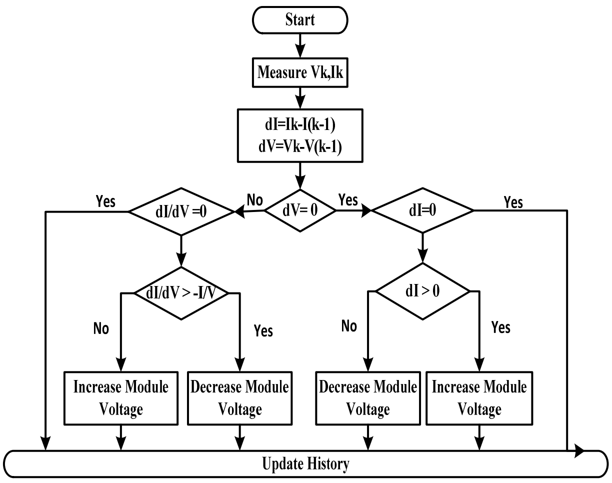

Fig. 8. Flowchart of the IncCond Algorithm

V.3. Constant Voltage (CV)

The constant voltage (CV) method algorithm is the simplest MPPT controller, and has a quick response. The constant voltage methods does not require additional equipment or input except for the measurement of the PV voltage which requires a PI controller to adjust the duty cycle of the converter order to maintain the PV voltage near the MPP [32]-[33]. In this method, the controller regulates the PV module voltage and operates it close to its MPP, by matching the PV module output voltage to a constant reference voltage (V_{ref}). The value of V_{ref} is equal to the measured PV module maximum output voltage at standard test conditions (STC) or set to a fixed calculated value [12]-[25].

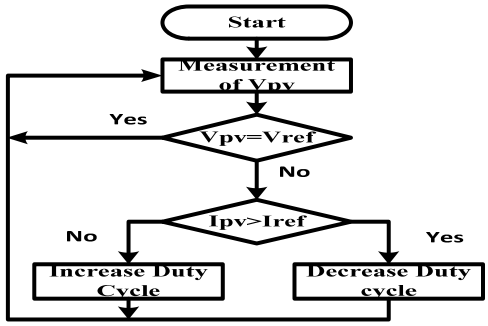

Fig. 9. Flowchart of CV method.

V.4. Open Circuit Voltage (OCV)

The open circuit voltage (OCV) method is another well-known MPPT controller based on the fact that, the ratio between the PV module maximum output voltage and its open circuit voltage is equal to constant K

$$\frac{Voc}{Vmpp} \approx K1 \approx 0.76 \quad (20)$$

Where: V_{mpp} is the PV module maximum output voltage, V_{oc} the module open circuit voltage and K1 is a constant, and assuming that it slightly changed with the solar radiation, then the operating point set to a fixed value of the open circuit voltage, A number of authors have been suggested good values for K1 within the range 0.7–0.80 [7]-[20]-[21]. The OCV flowchart is shown in Fig. 10.

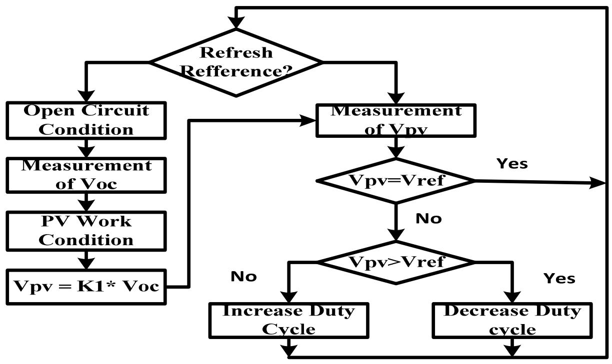

Fig. 10. Flowchart of OCV method

V.5. Short Circuit Current (SCC)

The short circuit current (SCC) technique is based on the measurement of the PV module SCC when its output voltage is equal to zero, and the PV module maximum output current at MPP is linearly proportional to its SCC [3]-[9]-[16]. In order to match the two currents, the error current is used to regulate the duty ratio of DC-DC converter and the relationship between the PV module output current and SCC at MPP is

$$Impp \approx K2 * Isc \quad (21)$$

Where K2 is a constant (K2<1) that can be calculated from the PV curve. Its value has been estimated by a number of authors; according to Ref. [23], it is between 0.78-0.92. Ref.[18], suggests a technique of measuring the true value of K2 by tracking the PV module MPP under changing weather conditions and suggests the value of the proportional K2 to be approximately 0.92 [22]-[23]. The SCC flowchart is shown in Fig. 11.

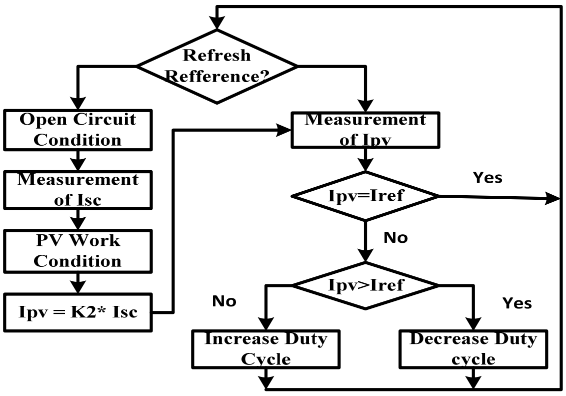

Fig. 11. Flowchart of SCC method.

VI. DESIGN AND SIMULATION OF MPPT ALGORITHMS

The circuit diagram (Fig. 12) illustrates the Simulink module of the MPPT system that was used in this work, in which the PV module output was fed to the DC-DC Cùk converter, and the converter output was coupled to the load. Different MPPT algorithms were used to control the switch of the converter in order to study and compare their efficiency under various conditions.

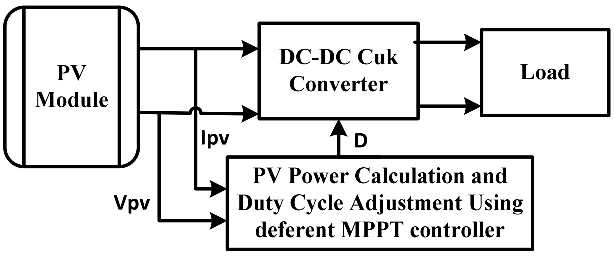

Fig. 12: Simulink Model of the MPPT System.

The simulated model of the system was tested in two stages; first, it was simulated at constant weather conditions; and, second it was simulated under varying atmospheric conditions. The compared MPPT techniques used for comparison were: classical P&O, IncCond, CV, OCV and SCC. Every MPPT technique performance was evaluated when the steady state condition was reached. Fig. 13 shows the PV module output power, when the system was simulated at STC (G=1000W/m^2, T= 25°C). The tracking efficiency of P&O method was about 96%, while the IncCond was 98.5%. However, the CV method efficiency (98%) was better than other techniques under this condition, while the SCC method had the lowest efficiency (94.6%).

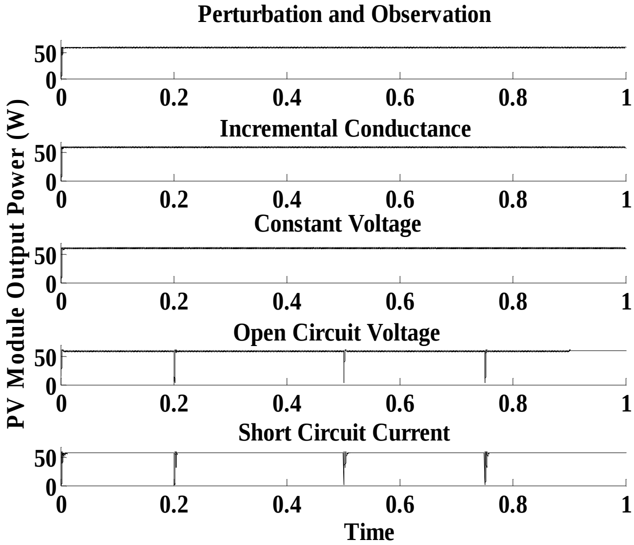

Fig. 13. The PV Module Output Power (w) Simulated with the MATLAB Model at 1000kw/m^2, 25°C.

The simulation results highlight that the tracking efficiency of these algorithms depends mainly on the method of used to optimize output. The tracking process of the IncCond method was around 98.5% efficient, while the P&O efficiency was lower at 96%, However, the IncCond response time is better as a result of its independence from the radiation level. Therefore, this algorithm can be used at high and fast radiance variations. The OCV and SCC are simple and easily implemented with analogue software, but their tracking efficiency was low than other techniques.

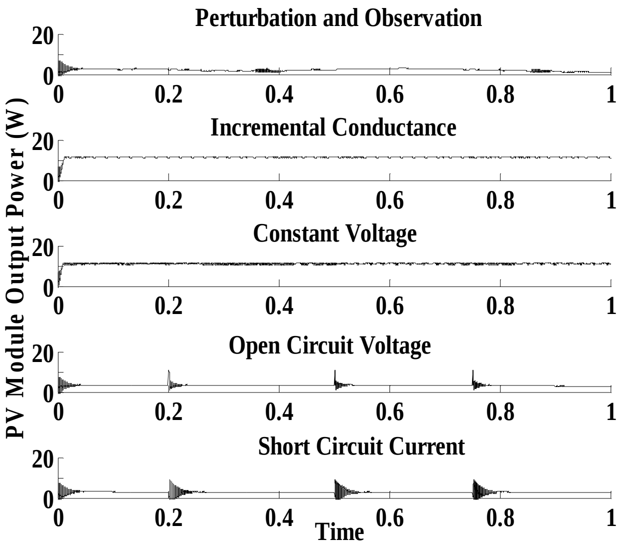

Fig. 14. The PV Module Output Power (w) Simulated with the MATLAB Model at 200w/m^2, 25°C.

Fig. 14 shows the PV module output power, when the system was simulated at low solar radiation ($G=200w/m^2$). The results indicate that at low levels of irradiance, the MPPT tracking efficiency of P&O was less than 60%. As the solar radiation decreased, the output power decreased, while the direction of perturbation changed and the controller remains perturbing in the same direction until the irradiance increases. This is one of the most common disadvantages of the P&O algorithm. The IncCond (87%) and CV's (86.5%) efficiency were better than the P&O algorithm under this condition, while the OCV (51%) and SCC (47%) methods performed worse. Despite the fact that P&O cannot track the MPP at low solar radiation, it has advantages over the IncCond method as it is cheaper and its dynamic response is superior. However, the P&O algorithm has limitations in its performance such as in steady state it causes an oscillation around the MPP and has a lower efficiency at low solar radiation.

Fig. 15 shows the PV module output power under rapidly changing atmospheric conditions. The results highlight that the systems with OCV and SCC method had large volumes of power losses, while the systems with CV and IncCond method had excellent performances. Therefore, both the CV and IncCond algorithms have high efficiency and their performances and dynamic responses were similar. The simulation results of the five MPPT algorithms at rapidly changing radiation of $200W/m^2$, 600 W/m^2, 1000 W/m^2, 800 $W/m^2$and 400 W/m^2show clearly that the tracking efficiency of MPP with the IncCond method is relatively good when irradiation was changing. The PV module operating point when the IncCond method was implemented at $G=1000$ $W/m^2$and $G=600$ W/m^2were 59.4 W and 33.7 W respectively which are close to the MPP of the module while the P&O results were 58 W and 22.8 W under the same condition.

Despite the fact that the IncCond method offers a good performance under different atmospheric conditions, it may not operate the PV model at the MPP. Although it has better tracking efficiency than the P&O method, it requires more sensor devices for the relevant computing which means its response time for conversion is slower, leading to greater power losses. However, this method has an advantage over the P&O method in that it can provide high efficiency under rapidly changing weather conditions.

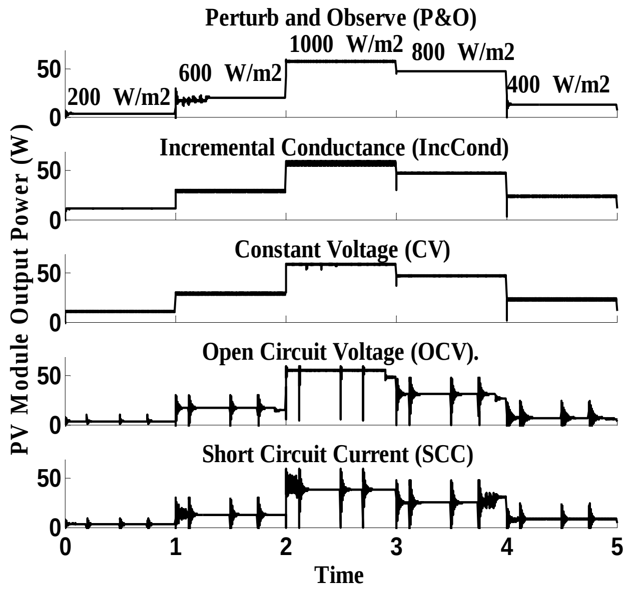

Fig. 15. The PV Module Output Power (w) Simulated with the MATLAB Model at Rapidly Changing Solar Radiation, 25°C.

The CV method is the simplest MPPT algorithm which keeps the operating point of the PV module near to its MPP. This is achieved by adjusting the module output voltage and matching it to a fixed value of reference voltage (V_{ref}). The reference voltage value is equal to the PV module maximum output voltage. This method ignores the impact of temperature and solar radiation as it assumes the reference voltage is equal to the real MPP. Hence, the operating point of the module cannot be the true MPP, and different data needs to be installed for different geographical regions. Furthermore, this method does not require the calculation of the output power as do the previous methods; instead, it measures the PV module output voltage that is needed to set up the duty cycle of the converter. This method is cheaper, its efficiency is high under low solar radiation, and is easy to implement compared to other method. However, it cannot track the MPP correctly under rapidly changing atmospheric conditions. From Fig. 15, it is important to observe that at low insulation conditions, the tracking process of the CV technique was more effective than either the P&O or the IncCond method. As a result, the CV method can be more suitable if it is combined with another MPPT method, such as P&O or the IncCond method.

The SCC method performance was less efficient than other techniques under rapidly changing weather condition, as it failed to operate the PV module at its MPP when the solar radiation was changed at t=2000ms the irradiance was 1000 $W/m^2$and t=3000ms the irradiance level dropped to 800 $W/m^2$and then went down to 400 W/m^2at t=4000ms (see Fig. 15). This is because it shifted the duty cycle in the wrong direction until the new measurement of the SCC was taken, which refreshed the value of the reference current. Therefore, low regulation speed can be better than high speed especially in fast changing weather condition. The main advantages of this method are: ease of implementation without a complicated algorithm; it does not cause any oscillations around the MPP; and it has a relatively fast response. However, it requires additional components such as a current sensor that needs to measure the SCC. Moreover, this method cannot always operate the PV module at its maximum output power as it uses an estimation of the K2 factor which cannot be the real value of the MPP in a real situation. This is because the PV module has a non-linear characteristic that varies with the environmental conditions. Furthermore, the online measurement of the SCC result in reducing the output power of the module and its MPP is not always matched. In addition, in this method the measurement of the SCC (I_{SC}) is frequently required which means shorting the module on each occasion. However, by using several loads this issue may not arise but this requires additional components; thereby increasing the cost of the system.

The OCV algorithm is also simple and easy to implement as it does not required any inputs. However, the PV module voltage needs to be measured to set the reference voltage which requires adjusting the PV module operating point in order that it is close to the MPP. This can be done by regulating the duty cycle of the converter to match the module voltage with the maximum voltage. However, this method, as with the CV method, ignores the impact of solar radiation and temperature on the PV module output. Thus, it is not accurate and the MPP is not achieved at all times. In this technique, the measurement of the OCV is required; therefore, a switch needs to be inserted between the PV module and the converter. Moreover, the OCV method requires additional valves in order to compute the OCV, and also a capacitor needs to be inserted between the module and the converter in order to supply the load with power when the switch opens the circuit. In additions, the ratio of the OCV and the maximum voltage is not constant with the ambient temperature. Therefore, this technique can only optimize the power at a single temperature. Therefore, this technique does not provide the high efficiency of the P&O and IncCond techniques, but it is generally is better than the SCC method.

VII. CONCLUSION

This study presents the performance of five widely used MPPTs in terms of their performance, speed, cost and efficiency. The simulation results show that the best performance was obtained from the IncCond method as it provided the highest efficiency. While the P&O method showed a good efficiency, it experienced low efficiency at low irradiance level. Both P&O and IncCond techniques require a microcontroller with a higher performance than other the three techniques CV, OCV and SCC). Of the three other techniques, the CV method gave acceptable results, and its performance under low solar radiation was better than the P&O method. The CV method is the simplest technique and can provide a good performance when minimizing the cost is required. The OCV and SCC methods proved to be the worst performers in terms of efficiency, especially, under rapidly changing conditions. The IncCond method has several advantages over other algorithm method including: higher efficiency under rapidly changing weather condition; it can operate the module at an accurate MPP without any oscillation around the MPP unlike P&O method. However, the implementation of this method is more complicated than the P&O method as it requires a fast controller with high sampling accuracy resulting in increasing the system cost.

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AUTHORS' INFORMATION

School of Engineering and Design, Brunel University, Uxbridge, UB8 3PH, Middlesex, United |Kingdom.
Corresponding author's email: Ramdan.Koad@brunel.ac.uk

Ramdan B A Koad was born in Ghat, Libya, in 1978. He received the MSc. degrees in electrical Power from the Newcastle University, UK in 2009; he is currently pursuing the Ph.D. degree in renewable energy sources. His main research interests include renewable energy sources and power electronics.

Ahmed Faheem Zobaa received the B.Sc.(Hons.), M.Sc., and Ph.D. degrees in electrical power and machines from Cairo University, Giza, Egypt, in 1992, 1997, and 2002, respectively. From 2007 to 2010, he was a Senior Lecturer in renewable energy with the University of Exeter, Cornwall, U.K. He was also an Instructor from 1992 to 1997, a Teaching Assistant from 1997 to 2002, and an Assistant Professor from 2003 to April 2008 with the Department of Electrical Power and Machines and the Faculty of Engineering, Cairo University, where he has also been an Associate Professor since April 2008. Currently, he is also a Senior Lecturer in power systems with Brunel University, Uxbridge, U.K. His main areas of expertise are lighting applications, power quality, (marine) renewable energy systems, grid integration, smart grids and energy management.

Dr. Zobaa is an Editor-in-Chief for the *International Journal of Renewable Energy Technology*. He is also an Editorial Board member, Editor, Associate Editor, and Editorial Advisory Board member for many international journals. He is a registered Chartered Engineer, Chartered Energy Engineer, European Engineer, and International Professional Engineer. He is also a registered member of the Engineering Council U.K., Egypt Syndicate of Engineers, and the Egyptian Society of Engineers. He is a Fellow of the Institution of Engineering and Technology, the Energy Institute of U.K., the Chartered Institution of Building Services Engineers and the Higher Education Academy of U.K. He is a senior member of the Institute of Electrical and Electronics Engineers. He is a member of the International Solar Energy Society, the European Society for Engineering Education, the European Power Electronics and Drives Association, the British Institute of Energy Economics, and the IEEE Standards Association.