

Design and implementation of a high-performance technique for tracking PV peak power

ISSN 1752-1416
 Received on 20th January 2016
 Revised 16th July 2016
 Accepted on 25th July 2016
 doi: 10.1049/iet-rpg.2016.0023
 www.ietdl.org

Abdelhakim Belkaid^{1,2,3}, Jean-Paul Gaubert² ✉, Ahmed Gherbi³

¹Department of Electromechanics, University of Bordj Bou Arreridj, El-Anasser, 34030 Bordj Bou Arreridj, Algeria

²Laboratory of Information Technology and Automatic Control for the Systems – LIAS ENSIP, Bat B25, 2 Rue Pierre Brousse, BP 633, 86022 Poitiers, France

³Automatic Laboratory of Setif (LAS), University of Setif 1, El Maabouda, Street of Bejaia, 19000 Setif, Algeria

✉ E-mail: jean.paul.gaubert@univ-poitiers.fr

Abstract: Most maximum power point tracking (MPPT) techniques based on sliding-mode control (SMC) use another method such as perturb and observe or incremental conductance (IncCond) to provide current or voltage reference which makes the system more complex. To reduce the complexity and to increase the photovoltaic (PV) array efficiency, a direct control high-performance MPPT based on improved SMC has been investigated in this study. Using two different step sizes can follow the PV peak power at different operating conditions with rapid convergence and greater accuracy. The new SMC-based MPPT designed for boost-type DC/DC converters is compared with a conventional and modified IncCond method, and to a classical SMC method which is very similar to that applied by Chu *et al.* The proposed PV-MPPT system is tested during a stringent profile of sunshine variation as recommended by the European Norm 50530, by simulation within MATLAB/Simulink™ tools and verified by implementation using a test bench based on DS1104 R&D controller board. The obtained results are satisfactory and demonstrate that the new SMC can track the MPP quickly within 0.003 s and with good accuracy close to 99%.

1 Introduction

Solar energy is an interesting alternative to fossil fuel energy. It is one of the quickest increasing renewable energy resources. The direct conversion of the Sun's radiation into electricity is known under the name of photovoltaic (PV) effect. PV energy is sustainable, clean, without environmental pollution and is of a multidisciplinary nature, involving power systems, power electronics and control theory. However, there are also some potential drawbacks to these systems such as high panel prices and low-energy conversion efficiency [1]. PV output power generation is influenced by climatic conditions (e.g. irradiance, panel temperature) and load variation. Therefore, a maximum power point tracking (MPPT) technique intended to control the DC/DC converter duty cycle is required to guarantee an optimal operation of the PV array under different operating conditions [2]. An overview of more than 30 of these MPPTs has been done in [2]. Perturb and observe (P&O) [3] and incremental conductance (IncCond) [3, 4] are widely used in the literature, but they fail under fast-varying climatic conditions. This is why many researchers made modifications to these algorithms in order to improve PV performance. Tey and Mekhilef [5] have proposed an improved IncCond to mitigate inaccurate responses under quickly varying sunshine level. There are also other techniques such as fractional short circuit current [6] that approximates the optimal current as a fraction between 0.78 and 0.92 of the short-circuit current [7], fractional open-circuit voltage [8] that estimates the optimal voltage as a fraction between 0.7 and 0.78 of the open-circuit voltage [9]. These methods with simple configuration are not as precise and have a smaller performance. On the other hand, some MPPT solutions exhibit good performance in both static and dynamic states, but they need particular conception and knowledge of specific topics such as neural network [10], fuzzy logic [10], particle swarm optimisation [11] etc.

Amongst the techniques cited above, the sliding-mode control (SMC)-based MPPT [12–15] has a great importance because of its benefits such as stability, robustness against the parameter variation, fast dynamic response and finally simplicity of implementation.

SMC is mostly used to control the electronic power converters which constitute variable structure systems [16, 17]. Recently, a few of those methods have been used in PV systems mainly for regulating the current injected into the grid [15]. A sliding-mode current-based MPPT approach that is based on the combined action of a traditional P&O MPPT technique and an SMC has been addressed in [13, 15]. Bianconi *et al.* [15] apply SMC to synchronous boost with the objective of regulating the input capacitor current to the current reference obtained by P&O. The same idea applied to the same type of converter is repeated by Mamarelis *et al.* [13], the authors use the sliding-mode theory with P&O-MPPT and propose a hybrid analogue–digital implementation of the controller. The sliding-mode ripple-correlation MPPT was proposed in [14] to ensure a desired dynamic behaviour in answer to irradiance transients. Those methods are a combination of SMC and an MPPT technique such as P&O, IncCond, ripple-correlation control or fuzzy logic, which make the system more complex. To minimise the complexity of the PV system and to enhance its performance, Chu and Chen [12] use a direct MPPT-based SMC with a sliding surface as a derivative of power to current.

The SMC-based MPPT proposed in this paper is not complex and has the objective of optimising the PV system. This paper may be regarded as an extension of the work of Chu *et al.* The difference consists of using two different steps and of selecting the sliding surface as a derivative of power to voltage. The proposed method exhibits its best performance in dynamic and steady states. To the best knowledge of the authors, there has been no paper that reports this idea. Another contribution is the using of a stringent irradiance profile as recommended by the EN 50530 which can verify truthfully the effectiveness of the proposed MPPT system [18, 19]. Consequently, this effort is conducted to enhance the dynamic efficiency of PV system with an improved SMC, which can reduce the probability of diverging away from the maximum power. To compare the proposed SMC with other MPPTs three indicators are considered as mentioned in [18]: tracking accuracy, tracking efficiency and tracking speed.

This paper contains seven sections. After the introduction, Sections 2 and 3, respectively, provide a modelling of a PV array

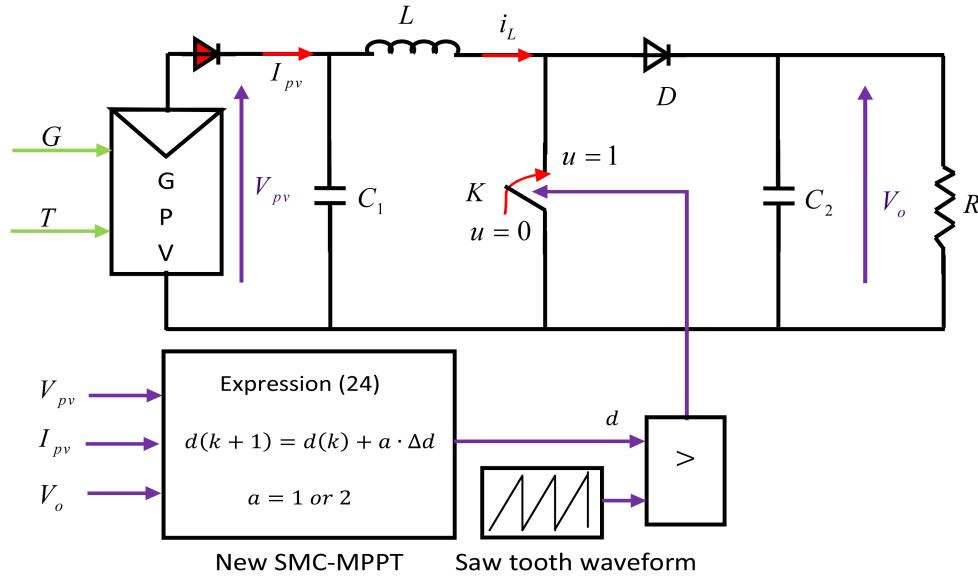


Fig. 1 Boost-type converter PV system

and boost converter. Section 4 contains two sections. First, in Section 4.1 basics of conventional and modified IncCond technique are illustrated, next in Section 4.2 the basics of classical and improved SMC algorithms are given too. Thereafter, Sections 5 and 6 depict the results of simulation and experimentation, respectively. Finally, some conclusions are presented at the end of this paper.

2 PV array mathematical model

The basic component which directly converts the Sun's radiation into electricity is called solar cell. It can produce ~ 2 W under 0.5 V. The equivalent electrical circuit which has been adopted for the PV cell is based on the one diode model [20, 21].

Thus the mathematical PV array model is given by (1) as in [5, 22]

$$I_{pv} = N_p I_{ph} - N_p I_s \left[\exp \left(\frac{V_{pv} + \left(\frac{N_s}{N_p} \right) R_s I_{pv}}{n_s a v_t} \right) - 1 \right] - \frac{V_{pv} + \left(\frac{N_s}{N_p} \right) R_s I_{pv}}{\left(\frac{N_s}{N_p} \right) R_p} \quad (1)$$

where N_s and N_p are the number of PV modules connected in series and parallel, respectively; n_s is the number of PV cells connected in series in one string, I_{pv} is the PV array output current, V_{pv} is the PV array output voltage, R_s and R_p are, respectively, the PV module series and parallel resistances, a is the ideality factor, $v_t = k_b T/q$ is the thermal voltage, $k_b = 1.38065 \times 10^{-23}$ J/K is the Boltzmann's constant, $q = 1.60218 \times 10^{19}$ C is the electronic charge and T is the temperature.

The photo-current I_{ph} depends on T and solar irradiance G

$$I_{ph} = [I_{sc}^* + k_i(T - T^*)] \frac{G}{G^*} \quad (2)$$

where k_i is the short-circuit current temperature coefficient, I_{sc}^* is the short-circuit current at standard test conditions (STCs) which are: $G^* = 1000$ W/m², $T^* = 298$ K and a spectral distribution of Air Mass 1.5.

The reverse saturation current I_s is calculated using

$$I_s = \frac{I_{sc}^* + k_i(T - T^*)}{\exp \left(\frac{(V_{oc}^* + k_v(T - T^*))}{n_s v_t} \right) - 1} \quad (3)$$

where V_{oc}^* is the open-circuit voltage at STC and k_v is the open-circuit voltage temperature coefficient.

3 Modelling of the step-up DC/DC converter

The non-isolated boost converter is inserted to interface the PV output to the DC load as shown in Fig. 1, not only to adapt the voltage levels, but also to track the MPP of the PV array [23]. This converter is widely used in stand-alone PV systems due to its simplicity, efficiency and low cost compared with other converters. The dynamic model of the step-up DC-DC converter in a state space form is obtained by the application of basic laws governing the operation of the system. It can be written as [17, 23]

$$\begin{cases} \frac{di_L}{dt} = \frac{V_{pv} - V_o}{L} + \frac{V_o}{L} \cdot u \\ \frac{dV_o}{dt} = \left(-\frac{V_o}{RC_2} + \frac{i_L}{C_2} \right) - \frac{i_L}{C_2} \cdot u \end{cases} \quad (4)$$

where V_o and i_L are the output capacitor voltage and inductor current, respectively. The control input u is the switch position; it is set to 0 when the switch is open and it is set to 1 when the switch is closed.

The expression (4) can be rewritten in the general form of the non-linear time system as

$$\dot{x} = \frac{dx}{dt} = f(x, t) + g(x, t) \cdot u + h \quad (5)$$

It is assumed that the boost converter is working in continuous conduction mode, in which the average value of the inductance current never drops to zero due to load variations.

4 MPPT techniques

4.1 Classical and modified IncCond technique

The classical IncCond tracks the MPP by comparing the instantaneous conductance (I_{pv}/V_{pv}) with the IncCond (dI_{pv}/dV_{pv}) of the PV panel [24]. The modified IncCond uses the principle of the PV panel I - V curve to avoid divergence in the case of rapidly changing atmospheric conditions [3]. On the I - V curve for a given fixed climatic condition, the changes in current and in voltage have opposite signs. If not, the PV array is in rapidly changing atmospheric conditions. Therefore, it is mandatory to change the direction of the perturbation to avoid divergence. This principle is explained in Fig. 2 considering two levels of irradiance ($G_1 < G_2$). If the operating point (OP) moves from A to A' or from C to C', the

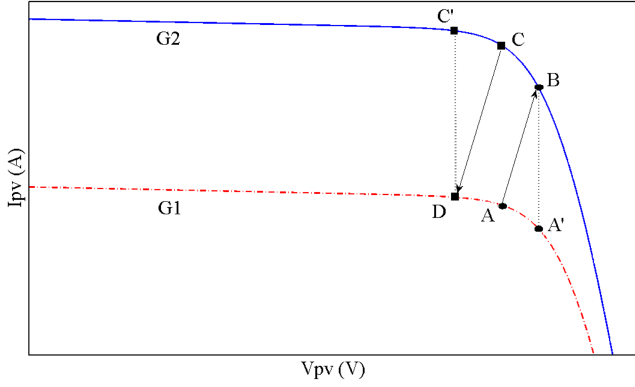


Fig. 2 Principle of the modified IncCond MPPT

$$\frac{dP_{pv}}{dV_{pv}} = \frac{dV_{pv}}{dV_{pv}} I_{pv} = I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}} = 0 \quad (6)$$

Then, the switching surface can be chosen as

$$S = \frac{dP_{pv}}{dV_{pv}} \quad (7)$$

The control law u of the converter is based on the fact that $S > 0$ on the left of the MPP and $S < 0$ on the right

$$u = \begin{cases} 0 & \text{if } S > 0 \\ 1 & \text{if } S < 0 \end{cases} \quad (8)$$

When the sliding mode exists, the switching surface and its

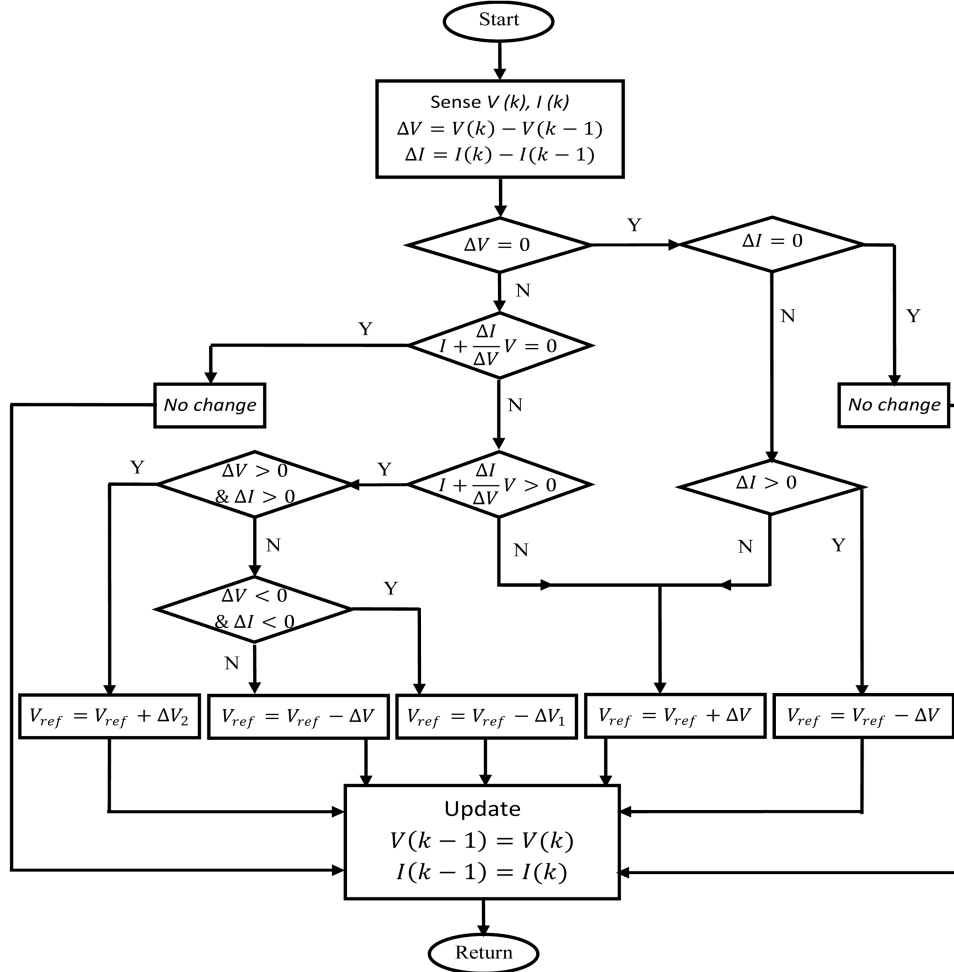


Fig. 3 Flowchart of the modified IncCond method

system is under normal conditions. Therefore, the modified method is to act as the conventional method. However, if the OP displaces from A to B or from C toward D, the system is under rapidly changing conditions. In this case, the modified method must act contrary to the conventional method. Fig. 3 gives the flowchart of the modified IncCond.

4.2 Basic and improved SMC technique

The objective of the SMC is first to design the switching surface. The second stage then consists of conceiving a control law which is responsible for forcing the system trajectories toward this area of state space and will maintain them in it [16]. On a sliding surface, the system shows the desired behaviour and is insensitive to parameter variations and external disturbances.

When the PV panel is operating in its MPP, the slope of P - V characteristics is null

derivative will be null. The general control law u combines two terms, a non-linear component u_n and an equivalent control u_{eq}

$$u = u_n + u_{eq} \quad (9)$$

To determine these components, we consider the Lyapunov function L which satisfies the control objective either in attractivity mode or sliding mode

$$L = \frac{1}{2}S(x)^2 \quad (10)$$

To ensure the attractiveness of the control variable to the switching surface, the time derivative of L must be negative definite

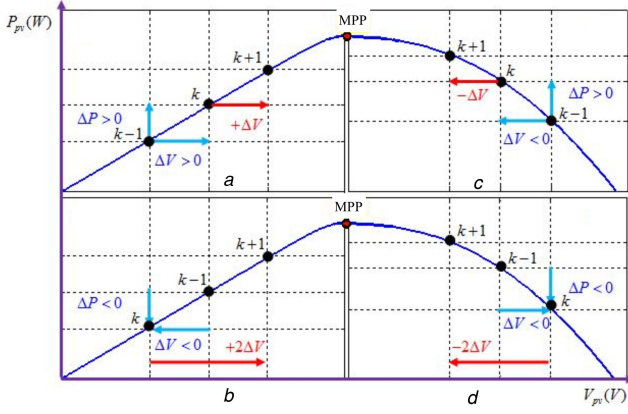


Fig. 4 Different cases of OP locations in P - V characteristics
(a) Zone1, case1, (b) Zone1, case2, (c) Zone2, case1, (d) Zone2, case2

$$\dot{L} = S(x) \cdot \dot{S}(x) < 0, \quad \forall S(x) \neq 0 \quad (11)$$

The latest expression is known as the reaching condition or the stability condition.

To prove the existence of sliding mode (11), we made some assumptions:

- In an ideal case, the series resistance is neglected and the parallel resistance approaches infinity

$$\exp\left(\frac{V_{pv}}{n_s a v_t}\right) \gg 1.$$

By application of the first assumption, the expression (1) becomes

$$I_{pv} = N_p I_{ph} - N_p I_s \left[\exp\left(\frac{V_{pv}}{n_s a v_t}\right) - 1 \right] \quad (12)$$

In the case where the panel is in a short circuit $I_{pv} = N_p I_{sc}$ and $V_{pv} = 0$, we can write

$$I_{ph} = I_{sc} \quad (13)$$

Moreover, with second assumption, we can write

$$I_{pv} = N_p I_{sc} - N_p I_s \cdot \exp\left(\frac{V_{pv}}{n_s a v_t}\right) \quad (14)$$

In the case where the panel is in an open circuit $I_{pv} = 0$ and $V_{pv} = N_s V_{oc}$, we can write

$$I_{sc} = I_s \exp\left(\frac{N_s V_{oc}}{n_s a v_t}\right) \Rightarrow I_s = I_{sc} \exp\left(\frac{-N_s V_{oc}}{n_s a v_t}\right) \quad (15)$$

Replacing (15) in (14)

$$I_{pv} = N_p I_{sc} - N_p I_{sc} \exp\left(\frac{V_{pv} - N_s V_{oc}}{n_s a v_t}\right) \quad (16)$$

Moreover thus

$$\begin{aligned} S(x) &= I_{pv} + \frac{dI_{pv}}{dV_{pv}} V_{pv} \\ &= N_p I_{sc} - \left(N_p I_{sc} + \frac{N_p I_{sc}}{n_s a v_t} V_{pv} \right) \exp\left(\frac{V_{pv} - N_s V_{oc}}{n_s a v_t}\right) \end{aligned} \quad (17)$$

The derivative is given by

$$\dot{S}(x) = - \left(2 + \frac{V_{pv}}{n_s a v_t} \right) \frac{N_p I_{sc}}{n_s a v_t} \exp\left(\frac{V_{pv} - N_s V_{oc}}{n_s a v_t}\right) \frac{dV_{pv}}{dt} \quad (18)$$

When $S(x) > 0$, the system operates on the left of the MPP, the voltage must be increased to attain the MPP ($dV_{pv}/dt > 0$), replacing in (18) it follows that $\dot{S}(x) < 0$, and hence $\dot{S}(x)S(x) < 0$.

When $S(x) < 0$, the system functions on the right, the voltage must be decreased ($dV_{pv}/dt < 0$), which implies that $\dot{S}(x) > 0$; therefore, $\dot{S}(x)S(x) < 0$.

Thus, the sliding mode exists and the system could reach global stability, regardless of the OP location on the left or on the right of the MPP.

To satisfy the reaching condition (11), a constant rate reaching law can be selected for the non-linear component

$$u_n = -k_n \operatorname{sgn}(S(x)) \quad (19)$$

where k_n (positive constant), is the scaling factor which is tuned at the time of design to adjust the step size.

The equivalent control u_{eq} proposed by Filippov characterises the system dynamics on the sliding surface [25], and is determined by using the invariance conditions [26]

$$S(x) = 0 \text{ and } \dot{S}(x) = 0 \quad (20)$$

$$\dot{S}(x) = \frac{dS(x)}{dt} = \left[\frac{\partial S}{\partial x} \right]^T \cdot \dot{x} = \frac{\partial S}{\partial i_L} \dot{i}_L + \frac{\partial S}{\partial V_o} \dot{V}_o \quad (21)$$

The expression (17) is a function of V_{pv} which depends on i_L and it never depends on V_o . That it means

$$\frac{\partial S}{\partial V_o} = 0 \text{ and } \frac{\partial S}{\partial i_L} \neq 0 \quad (22)$$

A combination of formulas (20)–(22) implies that the first expression of (5) should be null $\dot{i}_L = 0$, thus we obtain

$$u_{eq} = 1 - \frac{V_{pv}}{V_o} \quad (23)$$

After designing the sliding mode via the design of the switching function and the reaching mode, it is then possible to express the overall control law by combining (19) and (23)

$$u = u_{eq} - k_n \cdot \operatorname{sgn}(S) \quad (24)$$

The new SMC uses two different step sizes for incrementing or decrementing the PV output voltage or the converter duty cycle. From the P - V characteristics, the OP can be located in two zones on both sides of the MPP on each side two cases are distinguished.

Zone 1, case 1: Fig. 4a: The OP is located in zone 1, displaces from $(k-1)$ to (k) , it moves close to the MPP, it should continue in the same direction to reach $(k+1)$ by increasing the voltage by ΔV , i.e.

$$V(k+1) = V(k) + \Delta V \quad \text{or} \quad d(k+1) = d(k) - \Delta d$$

Zone 1, case 2: Fig. 4b: The OP still displaces in zone 1, from $(k-1)$ to (k) , it moves away from the sliding surface. In this case, we must change direction and in order to not return to the same starting point $(k-1)$, the step size should be doubled as

$$V(k+1) = V(k) + 2\Delta V \quad \text{or} \quad d(k+1) = d(k) - 2\Delta d$$

Zone 2, case 1: Fig. 4c: The OP is situated on the right of the sliding surface, it moves from $(k-1)$ to (k) in the direction of the MPP, it should continue in the same direction to reach $(k+1)$ by decreasing the voltage by ΔV , i.e.

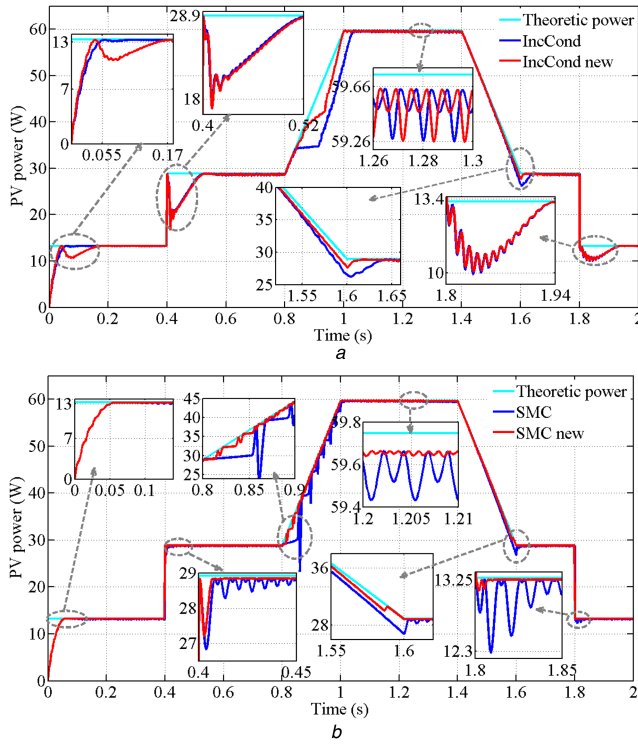


Fig. 5 Comparison of tracking MPP under varying irradiances of (a) Modified and classical IncCond, (b) New and basic SMCs

$$V(k+1) = V(k) - \Delta V \quad \text{or} \quad d(k+1) = d(k) + \Delta d$$

Zone 2, case 2: Fig. 4d: The OP still displaces in zone 2, from $(k-1)$ to (k) , it moves far from the sliding surface. In this case, it must change direction and double the step size as

$$V(k+1) = V(k) - 2\Delta V \quad \text{or} \quad d(k+1) = d(k) + 2\Delta d$$

It is concluded that the increment or decrement step size should be doubled when $\Delta P < 0$ i.e. $P(k) < P(k-1)$.

5 Simulation results

The PV system is composed of the Megamodule Solar X 60 module connected to a boost converter. The scheme of the overall PV system is shown in Fig. 1. The converter has been designed. Its main switch is the insulated-gate bipolar transistor (IGBT) controllable by the gate signal with a switching frequency of $f = 10$ kHz. Input and output capacitors and inductors are used as filters: $L = 5$ mH, $C_1 = 1000$ μ F, $C_2 = 470$ μ F. The converter is designed according to the prototype which is available at the Laboratory of Information Technology and Automatic Control for Systems (LIAS) laboratory, University of Poitiers, France. The system feeds a load $R = 30$ Ω . The proposed MPPT algorithm is then implemented with three others in a MATLAB/Simulink environment using the following parameters $R_s = 0.357$ Ω , $R_p = 151$ Ω , $n_s = 36$, $a = 1$, $I_{sc} = 3.8$ A, $V_{oc} = 21.1$ V, $k_v = -0.08$ V/ $^\circ$ C and $k_i = 0.003$ mA/ $^\circ$ C.

In fact, the work aims to demonstrate and compare the performance and effectiveness of the proposed new SMC MPPT controller, in both steady-state and dynamic responses with the classical SMC and both the conventional and modified IncCond. So, to achieve those objectives, a stringent profile which contains consecutively the step-up, the trapezoidal and the step-down shapes was selected for changing irradiation. Indeed the simulation results have illustrated roughly the good performance of the proposed MPPT system under fast-changing solar radiation.

In simulations, the temperature is kept fixed at constant value of 25° C, the irradiation change is set at a constant value of 250 W/ m^2 from 0 to 0.4 s, suddenly jumps up to 500 W/ m^2 , at 0.8 s starts increasing with a constant slope to achieve 1000 W/ m^2 at 1 s, is

still at that level until 1.4 s, and then it descends with a slope to reach 500 W/ m^2 at 1.6 s, it ends with step-down shape between 500 and 250 W/ m^2 where the change is at the medium. From 1 to 1.4 s the PV system operates in STC conditions; there, the MSX 60 module provides 60 W at an optimal voltage value of 17.1 V and an optimal current value of 3.5 A.

Fig. 5a with enlarged images in many locations shows the comparison of tracking the MPP of the modified and classical IncCond to the theoretical power. It can be seen that the two methods present similar performance in static and when the irradiance change is as a step. If the change follows a ramp, both MPPTs lose their tracking direction, the amount of losing is greatest for the ramp-up. At start-up, the basic IncCond exhibits good time response in comparison with the new IncCond. However, the modified IncCond exhibits slightly better performance than the classical one, especially in dynamic response. The same comparison is made for conventional and modified SMC techniques; the results are shown in Fig. 5b. From this figure, we can see that the traditional SMC shows a poorer performance than the new SMC under decreasing solar radiation and an even lower performance when solar radiation is increasing. For the new SMC, the oscillation has very weak amplitude and it does not lose its tracking direction. On the other hand, the conventional SMC exhibits big oscillation at steady state as shown by the zoom in this figure. Also, through the gradual ascending of the irradiance, the conventional SMC has lost its tracking direction many times. However, during descends of the irradiance, no loss of tracking is observed. It demonstrates that the classical methods (IncCond and SMC) present divergence from the MPP under fast-varying irradiance levels. This problem is resolved by adopting the modified IncCond and the new SMC. We conclude that the modified methods improve the performance of the classical ones.

In Fig. 6a, the behaviour of the modified IncCond and the new SMC under the selected profile change are compared with the ideal MPP power. The latest results demonstrate clearly the good dynamic response and best performance at steady state of the new SMC compared with the modified IncCond. At start-up of the irradiance profile, the proposed controller tracks the MPP in 55 ms by against the modified IncCond approach tracks the MPP in 170 ms. When a step is applied, the difference of tracking time is about 10 ms. If the gradual irradiance has occurred, the new IncCond loses its tracking direction. At steady state, the MPP (59.65 W) tracked by new SMC is close to theoretical power (59.75 W) and it has very low undulation. However, the MPP attained by new IncCond exhibits the oscillations around 0.38 W. Fig. 6b depicts the behaviour of the tracking accuracy for these modified algorithms and gives their average values. Finally, two tables summarise the results. Table 1 lists a comprehensive comparison between the four MPPT algorithms. The details include three indicators:

- The tracking accuracy T_{acc} or the instantaneous MPPT efficiency is defined as the ratio of the power obtained by a given MPPT method P_{MPP} to the theoretically available power P_{pv} , it is calculated as [18, 27]

$$T_{acc} = \frac{P_{MPP}}{P_{pv}} \cdot 100\% \quad (25)$$

- The tracking efficiency T_{eff} is the average MPPT efficiency, it is evaluated as [18, 27]

$$T_{eff} = \frac{\int_0^t P_{MPP}}{\int_0^t P_{pv}} \cdot 100\% \quad (26)$$

- The tracking time t_r which is considered here is the time necessary to achieve the new MPP when the irradiance changes.

It concludes that the proposed MPPT system offers good conversion performance (tracking speed, tracking efficiency) under rapidly changing solar radiation.

Table 2 presents a comparative analysis between the modified IncCond and the new SMC using the transitory and stationary

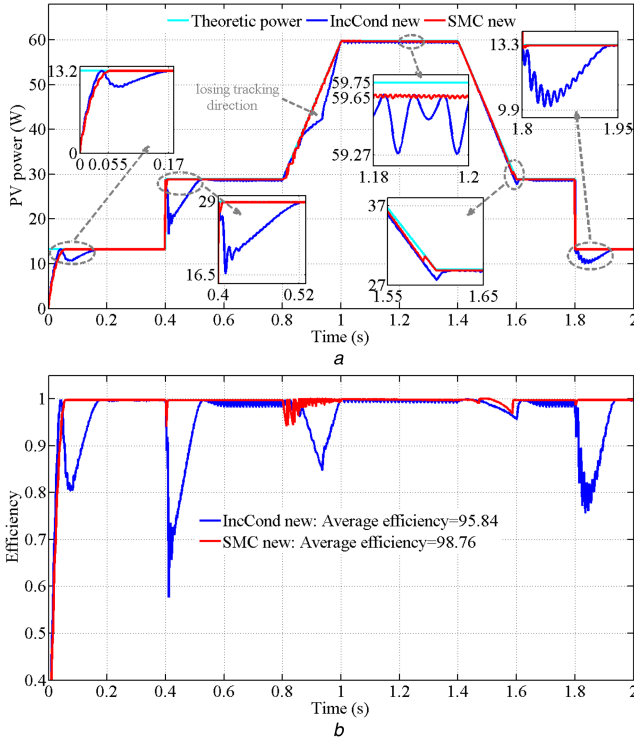


Fig. 6 During a trapezoidal irradiation profile
(a) Comparison of tracking MPP of new SMC and modified IncCond, (b) Conversion efficiency of the proposed MPPT compared with modified IncCond

tracking accuracies. The transitory tracking accuracy $T_{t,acc}$ can be defined as the MPPT performance in dynamic conditions, i.e. how the MPPT method reacts to changes in MPP. The stationary tracking accuracy $T_{s,acc}$ can be defined as the MPPT performance in static conditions, i.e. how the MPPT method approaches the true MPP in fixed conditions.

It can be shown that $T_{s,acc}$ for both methods has a value $>99\%$ with a slight superiority for new SMC. However, the IncCond new technique exhibits a limited value of $T_{t,acc}$ inferior to that obtained by the proposed SMC.

6 Hardware implementation and experimental results

An experimental model has been designed and built on a test bench in the research laboratory. The prototype which was built consists of a programmable DC voltage source (TDK-Lambda Americas Inc. Genesys 300-11) as an emulator which replaces the PV array, a diode in order to block reverse currents in the PV source and a boost converter to step-up the voltage level and resistance load. This real-time emulator of PV array output characteristics is based on the closed-loop reference model. The programmable power supply is controlled by a Digital Signal Processor for Applied and Control Engineering DS1104 board through a MATLAB/Simulink

environment. The control software uses feedback from the output voltage, current and reference model to regulate, through the proportional–integral regulator, the actual OP for the connected load to the characteristics of the PV panel.

The MPPT algorithms have been implemented to generate the pulse-width modulation signal for acting the IGBT gate of the boost converter. The sampling time of the system is chosen with performance of controller board at $T_s = 10^{-4}$ s, and the MPPT sampling rate is taken as a multiple of the system sampling time as $T_{MPPT} = 0.03$ s. The Company for Electrical Measurements Probe30 current probe is used in conjunction with a Tektronix oscilloscope to monitor the PV output current. The differential sensor Sensor Tektronix 1000 two-way is used to measure the input and output voltages of the converter. Operational amplifiers are used to match the voltage levels of the variables being measured through the Digital Signal Processor analogue/digital converter, which goes from 0 to 5 V. Control Desk software is used to supervise the displacement of the MPP on the P – V characteristics under constant or changing climatic conditions.

In experiments, tests were done with a PV emulator which is programmed to replace three real MSX 60 modules connected in series to feed a resistance of 72Ω , the temperature is fixed at 25°C and the irradiance is changed with a trapezoidal profile. The duty cycle step size used for the proposed algorithm is about $\Delta d = 0.04$, and the steps for the modified IncCond are $\Delta d = 0.004$, $\Delta d_1 = 0.005$ and $\Delta d_2 = 0.0008$. Figs. 7a and b show the waveforms of PV current I_{pv} (A), voltage V_{pv} (V), power P_{pv} (W) and output voltage V_o (V) for the modified IncCond and the new SMC respectively. They confirm that the current of MPP is dramatically affected by fast-varying irradiance, unlike the MPP voltage which is only slightly affected. It can also be clearly seen that the results for the new SMC present a better performance in time response or in conversion efficiency than the results of the modified IncCond. However, in Fig. 7b we can see small oscillations around the average value of the output current and voltage. The ratio of their width to the average value is around 5%, thus the effect of these oscillations can be ignored.

Experimental measurement of the converter duty cycle corresponding under a trapezoidal irradiance using the proposed algorithm has been depicted in Fig. 8.

To illustrate the response time well, we test the proposed MPPT system with a step profile, from 500 to 1000 W/m^2 . Figs. 9a and b present the results over the new profile for the modified IncCond and the new SMC, respectively. From the results, it can be concluded that the new SMC is about four times faster than the modified IncCond.

It ends with Fig. 10 which was obtained by using the Control Desk software. This figure presents the practical behaviour of tracking MPP under a trapezoidal profile by using the proposed SMC algorithm.

7 Conclusion

This paper has presented a cost-efficient MPPT system of low complexity and based on an improved SMC applied to a simple boost converter. The new SMC, when compared with three other

Table 1 Comparison of the simulated results

Method	t_r , s start-up	t_r , s step-up	t_r , s step-down	T_{acc} , % minimum	T_{acc} , % maximum	T_{eff} , %
IncCond	0.055	0.12	0.14	63.17	99.94	95.27
IncCond new	0.17	0.12	0.14	58.07	99.96	95.84
SMC	0.05	0.008	0.0055	60.92	99.99	97.84
SMC new	0.05	0.0067	0.0035	94.07	99.99	98.76

Table 2 Comparison by means of the transitory and stationary tracking accuracies

$G, \text{W/m}^2$	250	500	1000	250 $\rightarrow$ 500	500 $\rightarrow$ 1000
SMC new, %	$T_{s,acc} = 99.8$	$T_{s,acc} = 99.74$	$T_{s,acc} = 99.8$	$T_{t,acc} = 96.9$	$T_{t,acc} = 97.0$
IncCond new, %	$T_{s,acc} = 99.7$	$T_{s,acc} = 99.15$	$T_{s,acc} = 99.6$	$T_{t,acc} = 78.4$	$T_{t,acc} = 92.5$

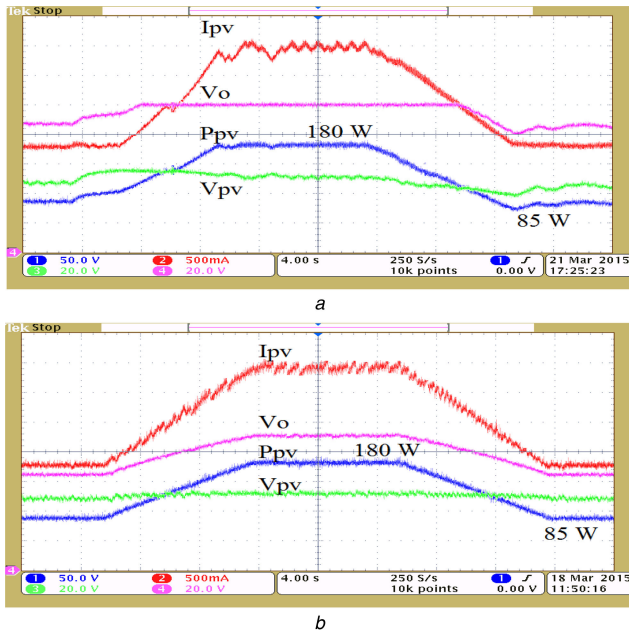


Fig. 7 Experimental measurement of the PV power, voltage, current and output voltage during a trapezoidal irradiation profile using (a) Modified IncCond (50 W/div, 500 mA/div, 20 V/div), (b) Proposed algorithm (50 W/div, 500 mA/div, 20 V/div)

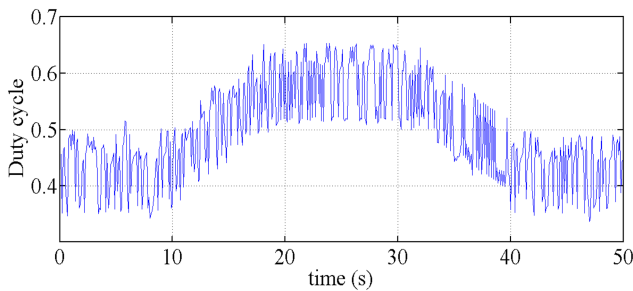


Fig. 8 Experimental measurement of the converter duty cycle during a trapezoidal irradiation profile using the proposed algorithm

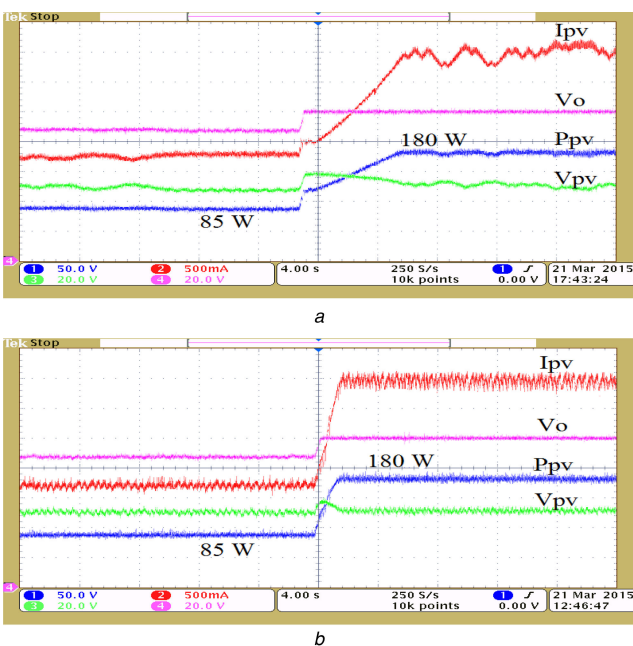


Fig. 9 Experimental measurement of the PV power, voltage, current and output voltage during a step irradiation profile using (a) Modified IncCond (20 W/div, 500 mA/div, 20 V/div), (b) Proposed algorithm (20 W/div, 500 mA/div, 20 V/div)

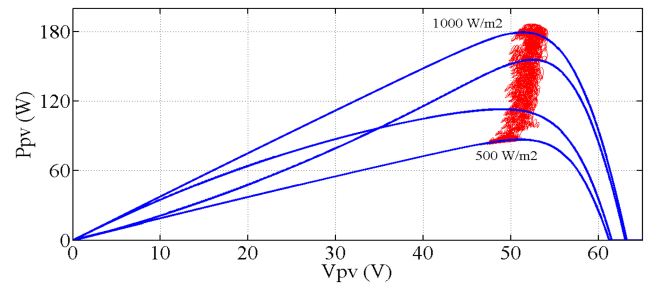


Fig. 10 Tracking of the PV peak power during a trapezoidal irradiation profile using the proposed MPPT method

MPPT techniques, demonstrated that it has the capability to follow the MPP under fast-changing solar radiation conditions with a high performance in both steady and dynamic states. The proposed MPPT tracker has been designed and verified by simulation within a MATLAB/Simulink environment and digitally implemented using a DS1104 R&D controller board. Therefore, the objective of this paper is achieved and it can say that the proposed control strategy may be considered as an interesting solution in the PV systems control area.

8 Acknowledgments

The work reported in this paper has been developed within the Laboratory of Information Technology and Automatic Control for Systems (LIAS), Poitiers University, France. Additionally, it has been supported by the Comité National d'Evaluation et de Programmation de la Recherche Universitaire research project no. J0201220110016, conducted at the Department of Electrical Engineering, University of Setif, Algeria. This support is gratefully acknowledged.

9 References

- [1] Taleb, M.: 'Performance of a maximum power point tracker (MPPT) photovoltaic generator (PVG)', *Electr. Power Compon. Syst.*, 2007, **35**, (4), pp. 367–375
- [2] Pallavee Bhatnagar, A., Nema, B.R.K.: 'Conventional and global maximum power point tracking techniques in photovoltaic applications: a review', *J. Renew. Sustain. Energy*, 2013, **5**, (3), 032701; 10.1063/1.4803524
- [3] Ghassami, A.A., Sadehghzadeh, S.M., Soleimani, A.: 'A high performance maximum power point tracker for PV systems', *Int. J. Electr. Power Energy Syst.*, 2013, **53**, (1), pp. 237–243
- [4] Dhar, S., Sridhar, R., Mathew, G.: 'Implementation of PV cell based standalone solar power system employing incremental conductance MPPT algorithm', *IEEE Int. Conf. on Circuits, Power and Computing Technologies (ICCPCT)*, Nagercoil, India, March 2013, pp. 356–361
- [5] Tey, K.S., Mekhilef, S.: 'Modified incremental conductance MPPT algorithm to mitigate inaccurate responses under fast-changing solar irradiation level', *Sol. Energy*, 2014, **101**, pp. 333–342
- [6] Kollimala, S.K., Mishra, M.K.: 'A new adaptive P&O MPPT algorithm based on FSCC method for photovoltaic system', *Int. Conf. on Circuits, Power and Computing Technologies, ICCPCT*, Nagercoil, India, March 2013, pp. 406–411
- [7] Yuvarajan, S., Xu, S.: 'Photo-voltaic power converter with a simple maximum-power-point-tracker', *Int. Symp. on Circuits Systems*, May 2003, vol. 3, pp. III-399–III-402
- [8] Murtaza, A.F., Sher, H.A., Chiaberge, M., *et al.*: 'A novel hybrid MPPT technique for solar PV applications using perturb & observe and fractional open circuit voltage techniques', *15th Int. Symp. on Mechatronika*, Prague, Czech, December 2012, pp. 1–8
- [9] Schoeman, J.J., VanWyk, J.D.: 'A simplified maximal power controller for terrestrial photovoltaic panel arrays', *Proc. 13th Annual IEEE Power Electron Specialists Conf.*, 1982, pp. 361–367
- [10] Ben Salah, C., Ouali, M.: 'Comparison of fuzzy logic and neural network in maximum power point tracker for PV systems', *Electr. Power Syst. Res.*, 2011, **81**, (1), pp. 43–50
- [11] Ishaque, K., Salam, Z., Amjad, M., *et al.*: 'An improved particle swarm optimization (PSO) based MPPT for PV with reduced steady state oscillation', *IEEE Trans. Power Electron.*, 2012, **27**, (8), pp. 3627–3638
- [12] Chu, C.C., Chen, C.L.: 'Robust maximum power point tracking method for photovoltaic cells: a sliding mode control approach', *Sol. Energy*, 2009, **83**, (8), pp. 1370–1378
- [13] Mamarelis, E., Petrone, G., Spagnuolo, G.: 'An hybrid digital–analog sliding mode controller for photovoltaic applications', *IEEE Trans. Ind. Inf.*, 2012, **9**, (2), pp. 1094–1103
- [14] Costabeber, A., Carraro, M., Zigliotto, M.: 'Convergence analysis and tuning of a sliding-mode ripple-correlation MPPT', *IEEE Trans. Energy Convers.*, 2015, **30**, (2), pp. 696–706

- [15] Bianconi, E., Calvente, J., Giral, R., *et al.*: 'Perturb and observe MPPT algorithm with a current controller based on the sliding mode', *Int. J. Electr. Power Energy Syst.*, 2013, **44**, (1), pp. 346–356
- [16] Bianconi, E., Calvente, J., Giral, R., *et al.*: 'A fast current-based MPPT technique based on sliding mode control'. IEEE Int. Symp. on Industrial Electronics (ISIE), Gdansk, Poland, June 2011, pp. 59–64
- [17] Guldemir, H.: 'Sliding mode control of DC–DC boost converter', *J. Appl. Sci.*, 2005, **5**, (3), pp. 588–592
- [18] Bizon, N.: 'Global extremum seeking control of the power generated by a photovoltaic array under partially shaded conditions', *Energy Convers. Manage.*, 2016, **109**, pp. 71–85
- [19] Ishaque, K., Salam, Z., Lauss, G.: 'The performance of perturb and observe and incremental conductance maximum power point tracking method under dynamic weather conditions', *Appl. Energy*, 2014, **119**, pp. 228–236
- [20] Besheer, A.H., Kassem, A.M., Abdelaziz, A.Y.: 'Single-diode model based photovoltaic module: analysis and comparison approach', *Electr. Power Compon. Syst.*, 2014, **42**, (12), pp. 1289–1300
- [21] Nanou, S.I., Papathanassiou, S.A.: 'Modeling of a PV system with grid code compatibility', *Electr. Power Syst. Res.*, 2014, **116**, pp. 301–310
- [22] Yu, G.J., Jung, Y.S., Choi, J.Y., *et al.*: 'A novel two-mode MPPT control algorithm based on comparative study of existing algorithms', *Sol. Energy*, 2004, **76**, (4), pp. 455–463
- [23] Keshri, R., Bertoluzzo, M., Buja, G.: 'Integration of a photovoltaic panel with an electric city car', *Electr. Power Compon. Syst.*, 2014, **42**, (5), pp. 481–495
- [24] Radjai, T., Rahmani, L., Mekhilef, S., *et al.*: 'Implementation of a modified incremental conductance MPPT algorithm with direct control based on a fuzzy duty cycle change estimator using dSPACE', *Sol. Energy*, 2014, **110**, pp. 325–337
- [25] Slotine, J.J.E., Li, W.: '*Applied nonlinear control*' (Prentice-Hall, Englewood Cliffs, NJ 07632, 1991), p. 459
- [26] Komurcugil, H.: 'Adaptive terminal sliding-mode control strategy for DC–DC buck converters', *ISA Trans.*, 2012, **51**, (6), pp. 673–681
- [27] Jubaer, A., Zainal, S.: 'An improved perturb and observe (P&O) maximum power point tracking (MPPT) algorithm for higher efficiency', *Appl. Energy*, 2015, **150**, pp. 97–108