Employing dual scaling mode for adaptive hill climbing method on buck converter

Chin Yew Tan1,3✉, Nasrudin Abd Rahim2,3, Jeyraj Selvaraj2

1Department of Electrical Engineering, Faculty of Engineering, University of Malaya
2Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
3University of Malaya Power Energy Dedicated Advanced Centre (UMPEDAC), Wisma R&D, University of Malaya, Kuala Lumpur 59990, Malaysia
✉E-mail: hayview@gmail.com

Abstract: For adaptive hill climbing method, variable stepping is achieved by sizing the change of power over the change of voltage (dP/V) and change of power over change of D (dPv/D) to appropriate step size using a properly tuned scaling factor. However, the photovoltaic (PV) power versus voltage curve has two different slopes which are the left-hand side of the maximum power point (MPP), and right-hand side of MPP (ROM). The fine-tuned scaling factor for the left-hand side PV slope has good performance at left-hand side of MPP (LOM) but can cause overshoot when system operates at the ROM; while scaling factor properly tuned for the right-hand side PV slope has good performance at ROM but slow voltage response when the system operates at LOM. Dual scaling factor technique is proposed to achieve good performance at LOM and ROM. Besides that, the drawback of implementing hill climbing method on buck converter is discussed, where using constant step size, the hill climbing method has small voltage response at point far from MPP but large voltage response at point near MPP. Based on the results obtained from a lab-scale prototype, it is proven that the proposed method is simple and effective.

1 Introduction

Solar energy is an increasingly popular source of energy due to the abundant supply, ease of installation in remote area, and the elimination of rotating parts (as in electrical generator/dynamo). The simpler construction structure and the withdrawal of dynamo in photovoltaic (PV) power system make it favourable for installation at residential and industrial areas. Nevertheless, solar PV faces a few problems such as low efficiency, high initial cost, and weather depended. A MPPT controller with fast dynamic response is preferred for solar power system, as it increases the system efficiency with relatively low cost. Several techniques such as perturb and observe (P&O) method, hill climbing method, incremental conductance (INC) method [1] and fractional open circuit voltage method are very common in practice and research. While some researchers consider both P&O method and hill climbing method to be the same [2, 3], some others [4–6] suggest that the two can be differentiated based on the controlled variable: P&O method varies the voltage, while hill climbing method varies the duty cycle (D). Since power converters are controlled by the D, hill climbing method is simpler and more direct. P&O method, on the other hand, requires an additional controller to allow voltage control. According to Liu et al. [6], hill climbing method has simpler control structure and exhibits slower dynamic response compared with P&O method. Nevertheless, hill climbing method possesses similar efficiency as P&O method. Previously, INC method is believed to be better than P&O method because INC method reduces the oscillation at steady-state and does not give wrong direction of perturbation under sudden change of irradiance [7]. However, recent literature stated that P&O method and INC method are both perturbative approaches [8–10] that are mathematically equivalent and the efficiencies under static and dynamic irradiance are identical [11–13]. Even though non-perturbative works [8, 10, 14] have been proposed, hill climbing method still remain as one of the most widely used method due to simplicity. In this paper, the concept from [4–6] are adopted, where hill climbing method refers to the method where D perturbation is controlled.

The common problem of hill climbing method is the trade-off between dynamic response and the magnitude of steady-state oscillation. To overcome this problem, various works have been dedicated to the development of adaptive step size where fast convergence is achieved and steady-state error is reduced [5, 15–23]. For example, a derivation of INC method exploits increment and instantaneous resistance to realise good transient; where at MPP, increment resistance is equal to instantaneous resistance but to fulfil this condition is hard in implementation [24]. Moreover, there is adaptive frequency and varying step size method which are based on load current to achieve variable stepping. Nonetheless, the system parameters need be carefully modelled and designed [25]. The simplest and most common way to achieve adaptive stepping is by utilising dPv/dPV and (dPv/D) as adaptive terms to decide the appropriate step size [16, 19, 26]. Scaling factor is required to adjust these terms to obtain the best MPPT performance. An optimum tuning technique for the scaling factor is suggested in [19]. The suggested method is a ‘one-off’ tuning technique, which is done during system initialisation. The ‘PI P&O’ method is proposed in [18] where a proportional integral (PI) controller is utilised to create suitable voltage step. However, the complexity in designing the controller gains makes it difficult for actual implementation. In [17], an online tuning variable scaling technique using third order polynomial PV curve is suggested. For each point on the PV curve, a corresponding scaling factor is used to maintain the desirable dynamic response throughout the entire operating region. Fuzzy logic based P&O method is proposed in [27] to achieve adaptive stepping and robust performance under noisy environment. Computation based P&O method is suggested in [28] to ensure faster dynamic response by adopting exponential function, where the problem of gradient mismatch between left-hand side PV slope and right-hand side PV slope is solved. Another predictive technique is proposed in [23] where parabolic equation is adopted to approximate PV power variation to predict the next operating point. Nevertheless, prior knowledge of PV array and PV panel material constants are required for this technique. A sliding mode current control is
suggested in [15] to measure the input current of capacitor. Using the linear relation between PV current and irradiance, fast irradiance variation can be detected and fast correction can be applied. However an additional high-bandwidth current sensor is required and microcontroller with fast ADC sampling rate is crucial in this method. Optimised delta P&O method accomplishes adaptive stepping by changing the voltage reference at every changing irradiance and reducing the voltage reference upon reaching the MPP [20, 22]. However, additional measurement between every MPPT sampling period is required to detect the irradiance changes. Furthermore, the threshold value must be carefully chosen and calculated to avoid unnecessary oscillation at MPP [22].

In this paper, \( \frac{dP_{PV}}{dV_{PV}} \) is chosen as the adaptive term for its low computation requirement, simple mathematical derivation and ease of implementation. Proposed method improves the \( \frac{dP_{PV}}{dV_{PV}} \) term by further adding a derivative term based on the analysis of PV characteristic using buck converter. Even though adding an extra derivative term increases the computation burden, the computation power required is still low compared with polynomial estimation technique [17], predictive control [21, 23], exponential computation method [28], and sliding mode control [15].

This paper is structured in the following manner: First, the issues of implementing hill climbing method on buck converter are described in Section 2, where slow convergence and large steady-state error using constant step size is explained. Then, analysis on the convergence speed of hill climbing method is given in Section 3. Subsequently in Section 4, the setbacks of hill climbing method using \( \frac{dP_{PV}}{dV_{PV}} \) as its adaptive term are discussed, followed by the proposed improved adaptive method in Section 5. To validate the effectiveness of the proposed method compared with conventional adaptive hill climbing (CAHC) method, tests under different irradiance changes are conducted on a lab scale prototype. The experimental results and discussion are presented in Section 6. Finally, conclusions are stated in Section 7.

2 Issues of implementing hill climbing method on buck converter

As mentioned earlier, P&O method and hill climbing method have the same fundamental operating principles, with the only difference being the controlled variable. As a result, both P&O and hill climbing methods have the common problem: their performance is a trade-off between dynamic response and steady state error. For hill climbing method, this problem is worse. Since voltage is controlled directly in P&O method, the steady-state error varies linearly with the step size (in voltage reference). On the other hand, since hill climbing method controls \( D \) instead of voltage, a fixed step size (in \( D \)) does not guarantee a fixed voltage change. For the case of PV system with buck converter, fixed step size (in \( D \)) give small voltage step at operating points far from MPP but large voltage step at operating points near the MPP (large steady-state) and it is shown at Fig. 1, where, the \( P_{PV} \) convergence and \( V_{PV} \) step response (\( dV_{PV} \)) are presented.

The result shows that \( dV_{PV} \) is small at the starting point where the \( P_{PV} \) is low (segment 1) and slowly increases toward MPP. At the MPP, the \( dV_{PV} \) value is the highest, indicating the steady-state error is high (segment 2).

To illustrate this problem better, a PV I–V curve is swept using buck converter under constant step size of \( AD = 0.025 \) as shown in Fig. 2. The PV current curve and PV voltage curve are plotted separately to better visualise their responses with respect to \( D \). For each perturbed step, the corresponding \( V_{PV} \) points are apportioned with straight line to show the \( dV_{PV} \) at different \( D \). From Fig. 2, at \( D \) value near to one, \( V_{PV} \) response is small while the \( I_{PV} \) is almost constant due to its location at constant current source region. Nevertheless the \( V_{PV} \) response is slowly increasing when approaching MPP. However, the \( V_{PV} \) response starts to slow down when reaching low \( D \) region.

3 Analysis of hill climbing method voltage response on buck converter

A typical PV system with buck converter and a resistive load (\( R \)), as shown in Fig. 3, is considered in this paper. The effective input resistance (\( R_{PV} \)) seen by PV source is as follow

\[
R_{PV} = \frac{V_{PV}}{I_{PV}} = \frac{R}{D^2}
\]  

Since the resistance along the PV curve is different from point to point [29], by controlling \( D \), the buck converter actually vary \( R_{PV} \) which in turn changes \( V_{PV} \) in search for MPP. When \( D \) equal to one, \( R_{PV} \) is same as load \( R \), which is the smallest possible value for \( R_{PV} \). Hence, to track MPP using buck converter, it is preferable to have low \( R \) value or low voltage battery load on the output of the buck converter. The buck converter only increase the input resistance as shown in (1). If the \( R > R_{MPP} \), and assuming \( D \) is slowly decreasing, \( R_{PV} \) is actually increasing, thus the operating point is perturbing further away from MPP to ROM, hence the MPP is unable to be reached. If output of buck converter is connected to a battery load such that a constant output voltage (\( V_{BATTERY} \)) can be assumed. Under the condition \( V_{BATTERY} > V_{MPP} \), and \( D \) is reducing from unity, the operating point is perturbing further away from MPP to ROM which causes the power harvested is reducing, consequently output current is also reducing.

As aforementioned, at low \( D \) region and high \( D \) region, hill climbing method has small voltage response (slow convergence);

![Fig. 1 Voltage response of hill climbing method on buck converter](image1)

![Fig. 2 I–V curve swept under 1000 W/m²](image2)
but at point near MPP region, the voltage response is large which cause large steady state error. Therefore, the discussion of hill climbing method on buck converter is divided into three parts for analysis.

3.1 \( V_{PV} \) Response at high D region (constant current source region)

The high D region is where the D value is near or equivalent to one. At \( D = 1 \), \( V_{PV} \) is equal to \( V_{OUT} \). If the R value is small, \( V_{PV} \) is located at constant current source region. At this region, the \( I_{PV} \) is equal to short circuit current \( (I_{SC}) \) which can be assumed constant, and R is constant as well, hence the multiplication of \( I_{SC} \) and \( R \) will give constant value. Equation (1) can be modified into (2) where \( R^{*}I_{SC} \) equals to a constant parameter \( k \)

\[
V_{PV} = \frac{R*I_{SC}}{D^2} = \frac{k}{D^2} \tag{2}
\]

The control of buck converter in pursuance of MPP voltage \( (V_{MPP}) \) is inversely proportional to the square of \( D \).

The convergence rate of \( V_{PV} \) with respect to \( D \) can be obtained by differentiating (2) with respect to \( D \) as given by

\[
\frac{dV_{PV}}{dD} = \frac{2k}{D^3} \tag{3}
\]

From (3), the response of \( V_{PV} \) with respect of \( D \) is inversely proportional to \( D^3 \). In addition, the convergence direction of \( V_{PV} \) and \( D \) are opposite, whereby \( V_{PV} \) increases with decreasing \( D \), and vice versa. As \( D \) is slightly reduced from unity, \( D>1, D^3 \) is still approximately 1. Consequently, \( dV_{PV}/dD \) is small when the \( D \) is near to 1. Nevertheless, \( dV_{PV}/dD \) starts to increase at a faster rate as \( D \) continues to decrease. Due to the inverse effect of \( D^3 \), and \( D<1 \), the \( dV_{PV}/dD \) increases. This causes voltage step to get larger even with same step size. The magnitude of \( dV_{PV}/dD \) will continue to increase until the operating point exits constant current source region. At this stage, (3) is no longer applicable, and the discussion moves to ‘near MPP region’.

3.2 \( V_{PV} \) response at near MPP region

Since hill climbing method controls \( D \), the \( P_{PV} \) change \( (dP_{PV}) \) is varied with respect to \( D \) (d\( D \)). By derivation, the response of \( I_{PV} \) and \( V_{PV} \) with respect to \( D \) are as shown

\[
\frac{dP_{PV}}{dD} = V_{PV} \frac{dP_{PV}}{dV_{PV}} + I_{PV} \frac{dV_{PV}}{dD} \tag{4}
\]

At MPP, \( dP_{PV}/dD = 0 \). To fulfil this condition, the \( V_{PV} \frac{dP_{PV}}{dV_{PV}} \) and \( I_{PV} \frac{dV_{PV}}{dD} \) terms need to be either zero or both terms cancel off each other into zero. However, it is known that the \( dD \) term is not zero because hill climbing method perturbs \( D \) all the time. Furthermore, for each perturbation, the \( V_{PV} \) and \( I_{PV} \) are changed. Hence, to obtain \( dP_{PV}/dD=0 \) at MPP, the \( V_{PV} \frac{dP_{PV}}{dV_{PV}} \) and \( I_{PV} \frac{dV_{PV}}{dD} \) terms need to cancel off each other.

As the operating point approaches MPP, \( dP_{PV}/dD \) value approximate closely to zero; when the MPP is reached, \( dP_{PV}/dD \) is equal to zero. Hence within the near MPP region, \( dP_{PV}/dD \) can be assumed zero.

From (1), \( I_{PV} \) can be obtained as follow

\[
I_{PV} = \frac{1}{R} D^2 V_{PV} \tag{5}
\]

By differentiating (5) with respect of \( D \), the response of \( I_{PV} \) with respect of \( D \) is attained

\[
\frac{dI_{PV}}{dD} = \frac{2D^2 V_{PV}}{R} \tag{6}
\]

By substituting (6) into (4) and assuming \( dP_{PV}/dD=0 \), the overall equation becomes as follow

\[
V_{PV} \left( \frac{1}{R} \left[ 2DV_{PV} + D^2 \frac{dV_{PV}}{dD} \right] + I_{PV} \frac{dV_{PV}}{dD} \right) = 0 \tag{7}
\]

From (7), the dynamic response of \( V_{PV} \) can be attained as

\[
\frac{dV_{PV}}{dD} = - \frac{2DV_{PV}}{D^2 R V_{MPP} + R I_{PV}} = \frac{2DV_{MPP}}{D^2 R V_{MPP} + R I_{MPP}} \tag{8}
\]

In this region, the operating point is near MPP, hence \( I_{PV} \) can be represented as \( I_{MPP} \) and \( V_{PV} \) can be presented as \( V_{MPP} \).

From (1), after some modifications

\[
\frac{I_{MPP}}{D^2} = \frac{V_{MPP}}{R} \tag{9}
\]

By substituting (9) into (8), and the overall equation is simplified into

\[
\frac{dV_{PV}}{dD} = \frac{2}{D} \frac{V_{MPP}}{R} \tag{10}
\]

For buck converter, the load \( R \) used is small. At MPP, \( D \) is definitely <1, and \( V_{MPP} \) is likely to be large. Therefore, \( dV_{PV}/dD \) is expected to be large. Considering the fact that the direction of \( dP_{PV}/dD \) and \( dV_{PV}/dD \) are opposite, the value of \( dV_{PV}/dD \) is expected to be the highest when \( dP_{PV}/dD \) is zero. Thus, at MPP where the \( dP_{PV}/dD=0 \), the response of \( V_{PV} \) with respect of \( D \) is fast.

3.3 \( V_{PV} \) response at low D region (voltage source region)

As \( D \) approaches zero, the \( V_{PV} \) response is slow because in this region, the \( I_{PV} \) is not constant. From (1), the \( V_{PV} \) can be presented as follow

\[
V_{PV} = \frac{1}{D} R I_{PV} \tag{11}
\]
Differentiating (11) with respect to $D$ gives

$$\frac{dV_{PV}}{dD} = R \frac{d}{dD} \left( \frac{I_{PV}}{D}\right) = R \frac{dI_{PV}}{D^2} - \frac{2R}{d} \frac{d}{dD} \frac{2D}{D^3}$$ \hspace{1cm} (12)

Equation (11) is substituted into (12), and it is simplified into

$$\frac{dV_{PV}}{dD} = R \frac{dI_{PV}}{D^2} - \frac{2R}{D} \frac{d}{dD} V_{PV}$$ \hspace{1cm} (13)

As aforementioned, the directions of $V_{PV}$ and $D$ are opposite. This implies that the $dV_{PV}/dD$ term must be negative. Therefore, $V_{PV}*(2/D)$ must be larger than $(R/D^2)\cdot(dI_{PV}/dD)$. In this region, when $D$ is approaching zero, the $(R/D^2)\cdot(dI_{PV}/dD)$ term is large due to inverse of $D^2$. However, the $(R/D^2)\cdot(dI_{PV}/dD)$ term is meant to be eliminated, hence after the cancelling between $V_{PV}*(2/D)$ term and $V_{PV}*(2/D)$ term, the $dV_{PV}/dD$ becomes smaller. Hence, the voltage step is small at low $D$ region.

### 4 Setbacks of conventional adaptive hill climbing

To solve the problem mentioned in Section 2, adaptive stepping is preferred to achieve fast $V_{PV}$ response and small steady-state error. Adaptive stepping is achieved by utilising the $dP_{PV}/dV_{PV}$ and $dP_{PV}/dD$ term. The selection of $dP_{PV}/dV_{PV}$ and $dP_{PV}/dD$ term for adaptive stepping has been discussed in [16, 19]. The $dP_{PV}/dV_{PV}$ term is proven to be better than $dP_{PV}/dD$ because $dP_{PV}/dV_{PV}$ monotonically decreases as operating point approaches MPP while $dP_{PV}/dD$ does not behave linearly with the distance between operating point and MPP [19]. As a result, the $dP_{PV}/dV_{PV}$ term is preferred for adaptive stepping. However, the $dP_{PV}/dV_{PV}$ term has several drawbacks such as propriety of scaling factor and constant $V_{PV}$ response at constant current source region. The discussion is divided into two sections to describe each of these issues:

#### 4.1 Propriety of scaling factor

Since $D$ is the controlled variable in hill climbing method, the adaptive term $dP_{PV}/dV_{PV}$ needs to be multiplied with a scaling factor ($m$) to scale it to a proper step size ($\Delta D$):

$$\Delta D = m \frac{dP_{PV}}{dV_{PV}}$$ \hspace{1cm} (14)

Due to the different gradient of PV curve, a scaling factor fine-tuned for left-hand side PV slope is not suitable for operation at ROM, as it will cause overshoot problem (Fig. 4a). On the other hand, a scaling factor fine-tuned for right-hand side PV slope has slow voltage response when operating on the LOM (Fig. 4b). To verify this statement, two arbitrary scaling factors are chosen for comparison here, that is, $m = 0.01$ and $m = 0.02$. Based on the results, it can be concluded that scaling factor of 0.01 is the suitable value for the right-hand side PV slope; while the 0.02 is the more appropriate scaling factor for left-hand side PV slope. Fig. 4a shows the $V_{PV}$ response over time when both scaling factor operate at ROM. It is shown that the CAHC method with ($m=0.02$) has voltage overshoots before settling down on the $V_{MPP}$. On the other hand, the CAHC ($m=0.01$) reaches MPP nicely without any overshoot. At Fig. 4b, the CAHC ($m=0.01$) is compared with CAHC ($m=0.02$) and CAHC ($m=0.02$) shows faster $V_{PV}$ response than CAHC ($m=0.01$) when operating at LOM.

Even though CAHC ($m=0.01$) has better performance on ROM, it shows slow voltage response when operating at LOM. On the other hand, CAHC ($m=0.02$) which has overshoot problem at the ROM, exhibits good dynamic performance at the LOM. Hence, it is proven that the scaling factor which is fine tuned for right-hand side PV slope is not suitable for the left-hand side PV slope and vice versa. A dual scaling factor technique is proposed in this paper by assigning different scaling factor for left-hand side PV slope and right-hand side PV slope of PV curve.

#### 4.2 Constant $V_{PV}$ response at constant current source region

The $dP_{PV}/dV_{PV}$ term cannot achieve adaptive stepping at constant current source region and it is mathematically proven in this section, with the experimental result shown in Fig. 5.

The $dP_{PV}/dV_{PV}$ term can be expanded into (15)

$$\frac{dP_{PV}}{dV_{PV}} = I_{PV} + \frac{dI_{PV}}{dV_{PV}}$$ \hspace{1cm} (15)

In the constant current source region, $I_{PV}$ approximately equal to $I_{SC}$, which is a constant. Consecutively the $dP_{PV}/dV_{PV}$ term becomes zero, and (15) can simplified into (16)

$$\frac{dP_{PV}}{dV_{PV}} \approx I_{SC}$$ \hspace{1cm} (16)
The advantage of $dP_{pv}/dV_{pv}$ term is a constant at constant current source region, and hence is unable to achieve adaptive stepping. As a result, the performance of the MPPT deteriorates. It is further validated using experiment with the result shown in Fig. 5.

In Fig. 5, operation in region 1 shows that $I_{pv}$ is constant over time which indicates that the operating point is at constant current source region. Response in region 2 shows the $V_{pv}$ increases linearly over time, hence the $V_{pv}$ changes over time changes is considered constant. This indicates that the $dP_{pv}/dV_{pv}$ term cannot achieve adaptive stepping in constant current source region.

5 Proposed adaptive hill climbing method

In the light of the problems faced by CAHC methods, this paper proposes an improved adaptive hill climbing method using two separate adaptive terms for different slopes of the PV curve. To achieve adaptive stepping at constant current source region, new adaptive term is proposed. Compared with existing methods which rely heavily on transfer function [21], complex equations [28] and separate adaptive terms for different slopes of the PV curve. To propose an improved adaptive hill climbing method using two

5.1 Proposed adaptive term

Previously, it is mentioned that the $dP_{pv}/dV_{pv}$ term cannot achieve adaptive stepping at constant current source region. To overcome this issue, a $dP_{pv}/dD$ term is added to aid the performance of $dP_{pv}/dV_{pv}$. After combining two terms together the overall equation become

$$
\frac{dP_{pv}}{dV_{pv}} \frac{dV_{pv}}{dD} = \frac{dP_{pv}}{dD} (17)
$$

The advantage of $dP_{pv}/dD$ term over $dP_{pv}/dV_{pv}$ term is that the former allows adaptive stepping at constant current source region. This can be shown using (18), where the adaptive stepping is due to the $dP_{pv}/dD$ term

$$
\frac{dP_{pv}}{dD} = \frac{dV_{pv}}{dD} (18)
$$

At the near MPP region and voltage source region, the normal $dP_{pv}/dV_{pv}$ is applied for its fast dynamic and good accuracy. Hence, two separate adaptive terms are used: a combination of $dP_{pv}/dV_{pv}$ and $dP_{pv}/dD$ term as in (19), is used for constant current source region; while only the $dP_{pv}/dV_{pv}$ term, as in (20), is used for non-constant current source region. Two separate scaling factors, that is, $m_1$ and $m_2$, are used for the two different adaptive terms as well

$$
\Delta D_1 = m_1 \frac{dP_{pv}}{dV_{pv}} \frac{dV_{pv}}{dD} (19)
$$

$$
\Delta D_2 = m_2 \frac{dP_{pv}}{dV_{pv}} (20)
$$

5.2 Tuning of scaling factor

For the tuning of scaling factor, solar emulator is not necessary and it can be achieved using solar panel and LCD $(16 \times 2)$ display. The LCD $(16 \times 2)$ is used to display $V_{pv}$, $I_{pv}$, and $P_{pv}$ value at each step perturbed. At the initial setup, a slow MPPT sampling rate should be used for the monitoring purpose. The tuning of the adaptive coefficient $m_1$ and $m_2$ are based on trial and error method which can be tedious. Nevertheless, the initial coefficient value for $m_1$ and $m_2$ can be calculated using equation suggested by [19] to speed up the tuning process. According to Pandey et al. [19], the initial coefficient $(m)$ should not exceed the predefined maximum $D(D_{MAX})$ as shown

$$
m \leq \frac{dP_{pv}}{dV_{pv}} (D_{MAX}) (21)
$$

For $m_1$’s initial coefficient calculation, one step is perturbed from $D = 1$ to $D = (1 - \Delta D)$. After that, the change of $P_{pv}$, the change of $V_{pv}$ and predefined $D_{MAX}$ are substituted into (21), and a preliminary coefficient for $m_1$ is attained. While, the initial coefficient for $m_2$ can be obtained by perturbing one step from open circuit voltage $(D = 0)$. After that, by calculating $dP_{pv}$, $dV_{pv}$ and then substituting both values along with predefined $D_{MAX}$ into the (21), the first coefficient for $m_2$ can be calculated.

The subsequent steps required to assign proper values for both $m_1$ and $m_2$ are summarised as below

(i) Monitor the change in $P_{pv}$.
(ii) If overshoot occurs, reduce $m$; else increase $m$.
(iii) Repeat step 1 and step 2 until slightly increment of $m$ will cause overshoot.

By using two separate scaling factors, the proposed MPPT method is expected to achieve fast dynamic response at both LOM and ROM, and reduce the overshoot problem.

5.3 Detection of constant current source region

The assignment of adaptive term is based on constant current source region and non-constant current source region, hence effective detection of the regions is important. This is done by detecting the change of $I_{pv}$ ($\Delta I_{pv}$). Since the variation in current is negligible in constant current source region, if the $\Delta I_{pv}$ is small enough, the operating point can be assumed at constant current source region. This condition is satisfied when $\Delta I_{pv}$ is smaller than a tolerance error ($e$)

$$
\Delta I_{pv} < e (22)
$$

In adaptive stepping method, the perturbed step at MPP is usually the smallest, thus change of $I_{pv}$ near MPP is also the smallest ($\Delta I_{pv}$). Hence, the selection for $e$ needs to be larger than zero but smaller than the current changes due to the smallest perturbation step size at MPP, $\Delta I_P$

$$
0 < |e| < \Delta I_P (23)
$$

Fig. 5 Performance of CAHC at constant current source region
5.4 Algorithm flow chart

Fig. 6 shows the algorithm flow chart for the proposed method. The variables for present, previous and next iteration are denoted with symbols \((k)\), \((k - 1)\), and \((k + 1)\) respectively. The algorithm starts by measuring \(V_{PV}\) and \(I_{PV}\), then calculating \(P_{PV}\). After that, the \(\Delta P\), \(\Delta V\), \(\Delta I\), and \(\Delta D\) are calculated by subtracting present values \((k)\) with the previous values \((k - 1)\). Subsequently \(\Delta I\) is compared with \(e\), if \(\Delta I\) is less than \(e\), the first adaptive term \((19)\) is assigned, and otherwise the second adaptive term \((20)\) is assigned. The required step size \((D_{STEP})\) is then computed. Next, \(P_{PV}(k)\) is compared with \(P_{PV}(k - 1)\), and the \(D(k)\) is compared with \(D(k - 1)\) to decide the direction of perturbation. Later on, the present variables are stored as ‘previous variables’ for the next iteration. The assignment of variable \(D(k - 1)\) and \(D(k)\) is slight difference, where \(D(k - 1) = D(k)\) must be assigned first before \(D(k) = D(k + 1)\), to obtain one step delay between \(D(k - 1)\) and \(D(k)\).

6 Experimental result and discussion

To verify the analysis and discussion presented in this paper, experimental tests are performed on a lab-scale setup shown in Fig. 7. All controls are implemented on a low cost MSP430G2452 microcontroller (MSP430 launchpad) with 16 bits timer PWM and 10 bits ADC, which is sufficient to implement the MPPT control with adequate performance. Chroma PV solar simulator 62150H-1000S is used to emulate a Sanyo HIT210 solar panel. To allow clear evaluation of the MPPT performance, Tektronix TBS 1120 oscilloscope is used to log the \(V_{PV}\) and \(I_{PV}\) of the PV emulator. High voltage differential probe P5200 is used to capture \(V_{PV}\) and current probe 80i-110s is used to measure \(I_{PV}\).

The data obtained is further processed in Matlab for better viewing. The system parameters used are given in Table 1.

To validate the performance of the proposed method with two scaling modes, it is compared with the previous two CAHC methods with single scaling factor, that is, CAHC \((m = 0.02)\) and CAHC \((m = 0.01)\). As mentioned in Section 4.1, CAHC \((m = 0.02)\) is optimally tuned for LOM operation while CAHC \((m = 0.01)\) is optimally tuned for ROM operation. To ensure fair comparison, the scaling factors for the proposed method have been tuned using the same approach (as mentioned in Section 5.2), which gives \(m_1 = 0.02\) and \(m_2 = 0.01\).

The perturbation period for the hill climbing method is selected to the 1 s. This relatively slow perturbation period is chosen mainly due to the limitation of experimental setup. To achieve same testing conditions for all three methods (proposed method, CAHC \((m = 0.01)\) and CAHC \((m = 0.02)\)), the sampling rate is chosen to be slow enough for the authors to observe each perturbation point and select the nearest common point when changing the irradiance. It
is worth noting that in practical implementation, the perturbation period should be reduced to improve the MPPT performance. Nevertheless, care should be taken to ensure that the perturbation period is much longer than the system settling time to avoid stability problem, as pointed out in [13].

6.1 Comparison of proposed method and CAHC under sudden irradiance change

In this section, the proposed method is compared with CAHC \( m = 0.01 \) and CAHC \( m = 0.02 \) under sudden irradiance increase and sudden irradiance drop. The problems presented in CAHC are solved by the proposed method where faster dynamic response is achieved at both LOM and ROM without overshooting problem. In addition, the proposed method is able to achieve adaptive stepping at constant current source region whereas CAHC method performs poorly. Furthermore, the PV power analysis and settling time analysis assessment are made between proposed method and CAHC to quantise the performance.

6.1.1 Performance comparison under sudden irradiance increase: First, the CAHC \( m = 0.01 \), CAHC \( m = 0.02 \), and proposed method are tested under sudden increases of irradiance, and the results are plotted in Fig. 8 for comparison. Fig. 8a shows the PV power response while Fig. 8b shows the PV voltage response.

Note that \( V_{\text{SPP}} \) has been shown in Fig. 8b to clearly distinguish between ROM and LOM: operation at the ROM will be appeared above the \( V_{\text{SPP}} \) line, whereas the operating point below the \( V_{\text{SPP}} \) line is referred as at LOM. Under sudden increase of irradiance, the operating point is drifted from the MPP to ROM (Fig. 8b). The CAHC \( m = 0.02 \), which has faster dynamic response, perturbs with larger voltage step but overshooot to LOM. Longer settling time is needed by CAHC \( m = 0.02 \), where correction steps are required before MPP can be reached. On the other hand, CAHC \( m = 0.01 \) which is properly tuned for right-hand side side slope has good performance at ROM. The result shows that CAHC \( m = 0.01 \) can reach MPP very fast without overshoot problem.

Proposed method uses the same adaptive term as CAHC \( m = 0.01 \) at MPP. When there is a sudden irradiance increase, the proposed method perturbs with second adaptive term \( \Delta D_2 \), and, when the constant current source region is not detected, the proposed method continue the perturbation using \( \Delta D_2 \). Hence proposed method has equivalent performance with CAHC \( m = 0.01 \) where there is no overshoot problem. In contrast, CAHC \( m = 0.02 \) has deteriorated performance where the operating point is strayed further to LOM and longer time is taken to settle at MPP.

The settling time needed for proposed method and CAHC \( m = 0.01 \) is 1.4 s, but the CAHC \( m = 0.02 \) needs 4.4 s to reach steady-state. Extra 3 s are needed which is equivalent to three correction steps are required after the overshoot occurred.

For the energy comparison, it is divided into two parts which are ‘before overshoot’ and ‘after overshoot’. The period taken for comparison before overshoot is from the point right-hand side after sudden irradiance change until CAHC \( m = 0.02 \) reaches the nearest MPP point. It is found that CAHC \( m = 0.02 \) has better performance and it harvests 8% more energy compare with CAHC \( m = 0.01 \) and proposed method. In term of the energy gained after overshoot, CAHC \( m = 0.02 \) is used as the guideline for comparison. The energy comparison start from the instant where CAHC \( m = 0.02 \) is overshot to LOM until the instant CAHC \( m = 0.02 \) settles down at steady-state. At this point, the proposed method and CAHC \( m = 0.01 \) has 6% more energy harvest. Nevertheless, for the period from the instant the irradiance change until the instant CAHC \( m = 0.02 \) settles at steady-state, the proposed method and CAHC \( m = 0.01 \) have more energy harvested.

6.1.2 Performance comparison under sudden irradiance drop: Under sudden irradiance drop, the operating point is drifted from MPP to LOM where the operating point moves to the constant current source region. From Fig. 9, CAHC \( m = 0.02 \) shows faster dynamic response than CAHC \( m = 0.01 \), however both CAHC methods demonstrate linear power response (Fig. 9a) and linear voltage response (Fig. 9b) over time at constant current source region. These indicate that both suffer from non-adaptive stepping problem mentioned in Section 4.2.

On the contrary, the proposed method has faster power response compared with the two CAHC methods where the proposed method uses the first adaptive term \( \Delta D_1 \) to achieve adaptive stepping. The significant power increase indicates that voltage step

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<th>Table 1 System parameters</th>
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Fig. 8 Comparison between proposed method, CAHC ($m = 0.01$), and CAHC ($m = 0.02$) at sudden irradiance increase from $300 \text{ W/m}^2$ to $1000 \text{ W/m}^2$

a PV power

b PV voltage

Fig. 9 Comparison between proposed method, CAHC ($m = 0.01$), and CAHC ($m = 0.02$) under sudden irradiance drop from $1000 \text{ W/m}^2$ to $300 \text{ W/m}^2$

a PV power

b PV voltage

Fig. 10 Comparison between proposed method, CAHC ($m = 0.01$), and CAHC ($m = 0.02$) at sudden irradiance drop from $1000 \text{ W/m}^2$ to $500 \text{ W/m}^2$

a PV power

b PV voltage
is larger compared with CHAC method. Hence, the proposed method is better than both CAHC ($m=0.02$) and $m=0.01$). The improvements are attained by only using two adaptive stepping when operating in constant current region. Subsequently, an improved adaptive hill climbing MPPT method is proposed to improve the performance of the proposed method.

### 9 References

4. Power electronics and control techniques for maximum energy harvesting in photovoltaic systems (Femia, N. et al., 2013) [Book News], vol. 7, no. 3, 2013

### 7 Conclusion

This paper presents an analysis on the performance of CAHC method and highlights its shortcomings, namely the propensity of scaling factor and non-adaptive stepping on constant current region. Subsequently, an improved adaptive hill climbing MPPT method is presented to mitigate these shortfalls. Apart from avoiding overshooting during MPPT, proposed method is able to achieve adaptive stepping when operating in constant current source region, giving more superior performance than CAHC method. The improvements are attained by only using two different adaptive terms for different regions of operation. Experimental tests are conducted to validate the analysis, as well as to confirm the performance of the proposed method.

### 8 Acknowledgments

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