Innovative Decision Reference Based Algorithm for Photovoltaic Maximum Power Point Tracking

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Abstract

A novel decision reference based method for the maximum power point tracking (MPPT) of PV arrays is presented in this paper. The proposed decision reference was derived from a simplified solar cell model. This method solves the problems of conventional MPPT algorithms, such as oscillation of the operating point at the steady state and confusion under rapidly changing insolation. It is shown by simulation and experimental results that the method properly tracks a rapidly changing insolation profile. The signal to noise ratio (SNR) of the new decision reference is also higher than those of conventional P&O and INC methods. An updating subroutine was included in the proposed MPPT algorithm to compensate for temperature and aging effects.

Key Words: Maximum power point tracker, Photovoltaic systems, Renewable energy, Solar cells

I. INTRODUCTION

Due to the growing demand for energy and the limitations of fossil fuels, renewable energies are attracting increasing attention in many countries. Among the different renewable energies, photovoltaics (PV) are the most promising.

Due to the high cost of the solar modules, there is a trend to extract as much energy as possible from PV modules. To extract the maximum power, impedance matching between the solar array and the load is mandatory. The voltage and the current at which the maximum power is obtained (V_m and I_m) depends on the insolation and operating temperature. Generally, this goal is achieved by using a dc/dc converter between the load and the PV array.

Various MPPT techniques have been proposed so far, with different advantages and drawbacks that make them appropriate for specific applications. A review of these methods has been done in [1] and [2]. Among the different approaches, the hill climbing, perturb and observe (P&O) and incremental conductance (INC) [3] methods are the most popular ones due to their simple implementation. The operating principle of these methods is based on trial and error. They alter the duty cycle of a dc/dc converter even at steady insolation, which leads to further power loss and oscillation of the dc bus [4] and [5]. On the other hand, there is a trade-off between the accuracy and the tracking speed by adjusting the perturbation step size. Another problem encountered with the above methods is their confusion under rapidly changing climate conditions [4]–[6]. Several studies [7]–[9] have modified these methods by finding solutions for the oscillation and promptness trade-

off, whereas others [6] and [9] have found solutions for the confusion problem. Studies [10] and [11] used open circuit voltage or the short circuit current of PV arrays to find the MPP. However these are not favorable in practice. References [5] and [12] used mathematical solutions to find the MPP and improve the speed and accuracy. However, they added system complexity without finding any solution for the confusion problem. Reference [13] proposed a good method to increase the promptness but did not solve the oscillation problem. There are some other schemes that focus on partially shaded conditions [14].

The limited accuracy of ADC, the finite resolution of digital PWM and the converter EMI affect the accuracy and speed of the MPPT methods, but have rarely been mentioned in the literature [5]. Many of the MPPT algorithms such as P&O and INC employ the differential of the sampled signals, which significantly deteriorates the signal to noise ratio (SNR) of the decision reference and hence reduces the accuracy and speed.

The proposed method in this paper improves the SNR and completely removes the steady state oscillation and confusion under rapidly changing insolation. The new method adds some complexity to the algorithm but can still be performed with low cost microcontrollers.

II. PRINCIPLE OF THE NEW MPPT METHOD

A. Concept of the Decision Reference in MPPT Methods

Almost all of the algorithms introduced so far agree on one point: they calculate one parameter called the “decision reference”, which accordingly decides how to change the duty cycle to move closer to the MPP. Among all of the decision references introduced thus far, the most practical ones are the hill climbing and P&O algorithms, which determine the new

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operating point based on $(\Delta P/\Delta D)$ and $I + V(\Delta I/\Delta V)$, respectively.

The use of differential terms leads to the following major problems:

1- Confusion of INC and P&O under rapidly changing environmental conditions [8]. In fact, the output power of the PV array (P) is a multivariable function of the temperature (T), insolation level (G) and the operating point. The total derivative of the output power with respect to the operating point variable is:

$$\frac{\Delta P}{\Delta X} \approx \frac{dP}{dX} = \frac{\partial P}{\partial X} + \frac{\partial P}{\partial G} \frac{dG}{dX} + \frac{\partial P}{\partial T} \frac{dT}{dX} \quad (1)$$

where X is the symbols for the operating point variable, which can be one of V_{PV} , I_{PV} or D . I_{PV} and V_{PV} are the array output current and the voltage, respectively. D represents the duty cycle of the dc-dc converter. The common MPP algorithms search for an operating point to fulfill the following condition:

$$\frac{\Delta P}{\Delta X} \approx \frac{\partial P}{\partial X} \Big|_{MPP} = 0. \quad (2)$$

They are successful only when the other variables, i.e., G and T , are constant. Under varying climate conditions, the partial derivative of the power with respect to the operating point variable leads to the real MPP. Therefore, in this paper (3) has been used as the decision reference:

$$\partial P / \partial i_{PV} \Big|_{MPP} = 0. \quad (3)$$

2- The output oscillation problem of the P&O, hill climbing and INC methods around the MPP under stationary conditions was indicated by [4]. The INC method can detect the MPP when $I + V(\Delta I/\Delta V) = 0$. However, due to non idealities, this condition rarely occurs in practice, and a proper threshold should be considered around zero ($I + V(\Delta I/\Delta V) < \epsilon$) [3].

3- The SNR reduction of the decision references due to taking the derivative of the output power with respect to the operating point variables.

B. Developing a New Decision Reference

To avoid the above mentioned problems, a novel decision reference is introduced (DI or decision index) based on equation (3). The proposed index is calculated based on the instantaneous PV voltage and current.

In this paper, the simplified model of a solar array as illustrated in Fig. 1 is used. I_{ph} is the photo-generated current. It can approximate a short circuit current I_{sc} and has a linear relation with the insolation level [15]. The diode represents the charge recombination of the solar cell. R_s represents the solar cell internal resistance plus the wiring resistance. A solar array composed of n series and m parallel cells is modeled as the solar cell by the substitution of (4)-(6):

$$I_{ph} = m \times I_{ph}(\text{cell}) \quad (4)$$

$$V_D = n \times V_D(\text{cell}) \quad (5)$$

$$R_s = R_s(\text{cell}) \times n/m. \quad (6)$$

Fig. 1. Simplified solar array model.

The relation between the diode voltage (V_D) and diode current (I_D) of the solar array model is expressed in (7). The diode current can also be approximated as (8) when it is in forward conduction mode:

$$I_D = m \times I_0 \left(e^{\frac{V_D}{n\eta V_T}} - 1 \right) \quad (7)$$

$$I_D = m \times I_0 \left(e^{\frac{V_D}{n\eta V_T}} \right) \quad (8)$$

where I_0 is the reverse saturation current of the diode in each cell, V_T is the thermal voltage and η is the technology coefficient. These parameters can be derived according to the solar module manufacturer's data [15]. The effective power delivered to the load is derived from (9).

$$P = V_{PV} \times I_{PV} = V_D \times I_{PV} - R_s I_{PV}^2. \quad (9)$$

The maximum available output power at each instant occurs when (3) is satisfied. Equation (10) takes the partial derivative of the output power with respect to I_{pv} as the operating point variable:

$$\frac{\partial P}{\partial I_{PV}} = V_D + I_{PV} \frac{\partial V_D}{\partial I_{PV}} - 2R_s I_{PV}. \quad (10)$$

V_D can be derived from (8), considering $I_D = I_{sc} - I_{PV}$:

$$V_D = n\eta V_T \ln \left(\frac{I_{sc} - I_{PV}}{mI_0} \right). \quad (11)$$

The partial derivative of (11) with respect to I_{PV} is:

$$\frac{\partial V_D}{\partial I_{PV}} = -\frac{n\eta V_T}{I_{sc} - I_{PV}} = -\frac{n\eta V_T}{mI_0} e^{-\frac{V_D}{n\eta V_T}}. \quad (12)$$

Finally, substituting equation (12) into equation (10) yields:

$$\frac{\partial P}{\partial I_{PV}} = V_{PV} - R_s I_{PV} - I_{PV} \left(\frac{n\eta V_T}{mI_0} \right) e^{-\frac{V_{PV} + I_{PV} R_s}{n\eta V_T}} \quad (13)$$

From (13), one can conclude that the value of depends on the instantaneous values of the array voltage (V_{PV}) and the array current (I_{PV}). Additionally, $\partial P / \partial I_{PV}$ approaches zero at around the MPP, and its magnitude represents the deviation from the MPP (see Figs. 2 and 3). Therefore, $DI = \partial P / \partial I_{PV}$ is defined as the decision index for the MPPT algorithm. Using low cost microcontrollers, (13) can be calculated in less

TABLE I
SYSTEM PARAMETERS USED IN SIMULATIONS

Cell type	A-300 SUNPOWER	
Number of series cells	n	70
Technology coefficient	η	1.2
Saturation current	I_o	$4.25 \times 10^{-8} A$
Series resistance	R_s	0.5Ω
dc bus voltage	V_{dc}	150V

Fig. 2. DI versus D and I_{SC} (as a representative of insolation). MPPs are shown as squares on the surface intersection with the plane $DI = 0$.

than 1 ms. In normal situations, an update time of 50 ms is sufficient to follow the insolation changes. This time interval is usually sufficient for the system to settle down after any disturbance. The settling time of the implemented prototype is approximately 7 ms, according to the formula given in [8].

C. Investigations of the New Decision Reference

To develop a proper control strategy for the MPPT algorithm based on the new index (defined in (13)), the DI behavior under various insolation and load values was closely studied. Usually, a dc/dc converter is used between the PV array and the load to process the maximum power (see Fig. 4). Equation (14) describes the relation between the load parameters and the front end array when the intermediate converter is a boost type:

$$V_{PV} = (1 - D)E + (1 - D)^2 R_L I_{PV} \quad (14)$$

where the end load is modeled with a constant voltage source E and a series resistance R_L .

Fig. 2 and 3 demonstrate the calculated decision index (DI) under the different insolation and duty cycle values derived by (13) and (14). The simulations are carried out based on the system data given in Table I. All of the values are in accordance with our test bench, which uses the A-300 cells of SUNPOWER.

Fig. 2 illustrates a three-dimensional view of the DI versus both I_{SC} (representative of insolation) and the duty cycle. The MPPs are a cross section of the DI surface with the horizontal plane at $DI = 0$ (indicated by squares). There is

Fig. 3. DI versus duty cycle with the short circuit current taken as the parameter; MPPs are indicated by squares.

Fig. 4. Simplified circuit configuration of PV system and equivalent load.

Fig. 5. Block diagram of a PV control system.

no linear relation between the duty cycle and the DI value. Furthermore, the sensitivity of DI increases with respect to the duty cycle as the insolation increases. Additionally, from (13) one can conclude that the decision index DI tends towards V_{PV} in the array voltage source region, and it tends to infinity in the current source region.

Fig. 3 shows a focused two-dimensional view of DI versus the duty cycle for various I_{SC} . The MPPs are marked with squares on the surface. Some of these points are not placed exactly at $DI = 0$. Its reason is the finite accuracy of the digitized duty cycle, deliberately inserted into the simulation to show the finite resolution of the experimental 8-bit PWM. However, all of the points marked as the actual MPPs are the points nearest to the ideal MPPs.

III. CONTROL STRATEGY

The closed loop MPPT control system is proposed with the block diagram illustrated in Fig. 5. The PV system consists of a PV array, a power converter and a load, which may be an inverter or a battery. The DI value is calculated and fed back into the controller. The input reference is set to zero to satisfy the condition $DI = 0$. The system open loop transfer function has a highly nonlinear relation between the duty cycle and DI , as illustrated in Fig. 2 and 3. It also varies with the insolation level and the temperature, so it is a time variant system. Additionally, due to the time delays in the calculation of DI , the data conversion and the converter dynamic response, a fuzzy controller or a lookup table should be used for such a nonlinear system. A lookup table was used in this paper due to its simplicity, speed, ease of implementation, and insensitivity to parameters.

The controller determines the duty cycle deviation based on the DI value. The DI value is divided into several segments similar to the fuzzy logic method. More segments lead to more precise results but increase the size of the program. Practical experiences show that selecting 15 to 30 segments is sufficient and results in an acceptable speed. In our implementation, the DI span is divided into 17 segments. Table II illustrates the lookup table used for the hardware prototype. Because the digitized duty cycle was implemented with 8-bit accuracy, the ΔD values are given as a fraction of 255.

The lookup table is organized based on the relationship between DI and ΔD in Fig. 3. The dependency of DI on ΔD is time variant because the insolation level may vary with time. To avoid oscillations, the worst case scenario is considered in the organization of this table. In this scenario, the insolation level is set to maximum because the sensitivity of DI to the duty cycle increases with a higher insolation. Additionally, any typical value for the PV parameters can be used for the table organization because, like fuzzy controllers, this controller is inherently insensitive to small variations in the segments. Choosing zero for ΔD in the first segment freezes the duty cycle in the steady state condition. The width of the first segment (W_1) was selected with more attention to maximizing the PWM accuracy. Choosing a small value may cause unwanted oscillations, and selecting a large value reduces the tracking accuracy. An appropriate value for W_1 is the DI difference of two points above and below the zero axis (Fig. 3) on the DI curve associated with the maximum insolation ($DI_{I_{sc}(max)}$). Therefore, equation (15) was used to determine W_1 :

$$W_1 = |DI_{I_{sc}(max)}|_{D_M + \Delta D_{min}} - |DI_{I_{sc}(max)}|_{D_M} \quad (15)$$

where D_M is the duty cycle of the actual MPP and ΔD_{min} is the resolution of the k-bits PWM ($\Delta D_{min} = 1/2^k$).

IV. PRACTICAL CONSIDERATIONS

A. Determination of Constants

Successful performance of the proposed method depends on a true evaluation of (13). It is worth noting that I_0 strongly depends on temperature, aging and the fabrication technology.

TABLE II
LOOKUP TABLE FOR DUTY CYCLE CONTROL

DI	ΔD	DI	ΔD
$-5 < DI < 5$	0	$5 < DI < 10$	1/255
$-15 < DI < -5$	-1/255	$10 < DI < 15$	2/255
$-30 < DI < -15$	-2/255	$15 < DI < 20$	3/255
$-85 < DI < -30$	-3/255	$20 < DI < 25$	4/255
$-180 < DI < -85$	-5/255	$25 < DI < 30$	6/255
$-360 < DI < -180$	-8/255	$30 < DI < 35$	8/255
$-680 < DI < -360$	-12/255	$35 < DI < 45$	11/255
$-1300 < DI < -680$	-15/255	$DI < 45$	20/255
$DI < -1300$	-20/255		

Additionally, the thermal voltage V_T depends on the ambient temperature. Hence, the compensation of thermal change and I_0 variations are mandatory.

Equations (16) and (17) describe the dependency of I_0 and V_T on temperature, respectively.

$$I_0 = I_{0N}(T/T_N)^3 \exp\left(\frac{E_g}{\eta k/q} \left(\frac{1}{T_N} - \frac{1}{T}\right)\right) \quad (16)$$

$$V_T = \frac{kT_N}{q} \times \frac{T}{T_N} = V_{TN} \times \frac{T}{T_N} \quad (17)$$

where I_{0N} and V_{TN} are the saturation current and thermal voltage at standard temperature, $T_N = 300K$, respectively. E_g is the band gap energy of the material used in the cells, which is 1.2 eV for silicon. k is the Boltzmann constant, and q is the electric charge of an electron.

Substituting (16) and (17) into (13), DI can be derived as:

$$DI \frac{\partial P}{\partial I_{PV}} = V_{PV} - R_s I_{PV} - n\eta V_{TN} \times I_{PV} \exp\left(-\frac{V_{PV} + R_s I_{PV}}{n\eta V_{TN}}\right) \times C \quad (18)$$

where C is a the compensating factor defined by:

$$C = 1/(mI_{0N}) \times 1/\left[\left(\frac{T}{T_N}\right)^2 \times \exp\left(\frac{\Delta T}{T} \left(\frac{E_g}{\eta V_{TN}} - \frac{V_{PV} + R_s I_{PV}}{n\eta V_{TN}}\right)\right)\right]. \quad (19)$$

In (19), ΔT is the thermal change, which is supposed to be $|\Delta T| < 30^\circ C$ in standard conditions. Substituting (16) and (17) into (11) results in:

$$I_D = I_{sc} - I_{PV} = [mI_{0N} \exp\left(\frac{V_{PV} + R_s I_{PV}}{n\eta V_{TN}}\right)] \times \left(\frac{T}{T_N}\right)^3 \exp\left[\frac{\Delta T}{T} \left(\frac{E_g}{\eta V_{TN}} - \frac{V_{PV} + R_s I_{PV}}{n\eta V_{TN}}\right)\right]. \quad (20)$$

The parameter B is defined as follows:

$$B = [\exp\left(\frac{V_{PV} + R_s I_{PV}}{n\eta V_{TN}}\right)] / (I_{sc} - I_{PV}). \quad (21)$$

Using (20) and (21), B can be rewritten as follows:

TABLE III
NOMINAL SPECIFICATIONS OF A-300 CELLS

Open-circuit voltage	0.67 V
Short-circuit current	5.9 A
Typical MPP current	5.54 A
Nominal output power	3.1 W
Voltage deviation with temperature @ 25°C	-1.9 mV /°C
Power deviation with temperature @ 25°C	-0.38% /°C

$$B = \frac{1}{mI_{0N}} \times \frac{1}{\left(\frac{T}{T_N}\right)^3 \exp\left[\frac{\Delta T}{T} \left(\frac{E_g}{\eta V_{TN}} - \frac{V_{PV} + R_s I_{PV}}{n\eta V_{TN}}\right)\right]} \quad (22)$$

Comparing (19) and (22), C can approximate B as:

$$C = \left(1 + \frac{\Delta T}{T_N}\right) B \cong B. \quad (23)$$

It is possible to install a temperature sensor on the PV cells to compensate the temperature effect precisely. However, $\Delta T/T_N$ is usually less than 0.1, and the compensation factor C can be approximated by B . B can be calculated from (21) by turning on the boost switch for a short time and measuring I_{sc} . Then, the duty cycle is restored to measure V_{PV} and I_{PV} again. These measurements should be done under steady conditions. To guarantee steady conditions, the output power should be compared before and after the short circuit test. By executing this subroutine the temperature and aging effects are compensated.

Using (18) instead of (13) and estimating C by (21) and (23) periodically, the proposed algorithm will depend only on $n\eta V_{TN}$ and R_s . The thermal voltage at the standard condition ($V_{TN} = 0.0258$ V) is independent of the rest of the variables. n is the number of the series cells in a PV array and does not change in the algorithm. The technology coefficient (η) depends only on the PV technology and is set to 1.2 for Si-mono and 1.3 for Si-poly technologies [16]. The series resistance R_s can be approximated in an easy and straightforward way addressed in [11]. Because R_s has a small value, the sensitivity of DI to R_s can be ignored. Therefore, using the compensating subroutine, the dependency of the MPPT algorithm on temperature, array parameters and aging is suppressed.

B. Updating Constants

Updating of the compensating factor (C) can be done automatically during specified intervals. Usually 15-minute intervals are sufficient due to the high thermal inertia of the solar cells [17]. It is worth noting that there is an inherent difference between the proposed method and those that perform I_{sc} sampling. These methods sample I_{sc} more frequently because their objective is to follow the insolation changes. However, the proposed method samples I_{sc} to follow the temperature variation, which has slower rate than the insolation. Fig. 6 shows the flowchart of the main algorithm and the subroutine that updates C .

Fig. 6. Flowchart of proposed algorithm and update of compensation factor (C).

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation Results

The configuration that was chosen to verify the proposed approach is depicted in Figs. 4 and 5. The computer simulations were carried out using the MATLAB program. The PV array consisted of 70 A-300 cells with the specifications listed in Table III. The accuracy and speed of the proposed method under varying insolation condition were compared with the “variable step size INC” method proposed by [7]. Reference

Fig. 7. Simulation results for proposed method, variable step size INC method, and ideal performance under a trapezoidal insolation profile: (a) duty cycle. (b) output power.

[7] used $N(dP/dV)$ as the duty cycle step (ΔD) to track the MPP:

$$N \frac{dP}{dV} = N \left(\frac{V(k)I(k) - V(k-1)I(k-1)}{V(k) - V(k-1)} \right) \quad (24)$$

where N is a scaling factor and is set to 0.2 in the simulations. Fig. 7(a) and (b) compare the derived duty cycle and the output power under a trapezoidal insolation profile for both methods. The profile for an ideal MPPT is also shown. The insolation level increases from 330 W/m^2 to 1000 W/m^2 within 1 s linearly and then decrease to 330 W/m^2 .

The results show that during a change in insolation, the “variable step size INC” method fails to track the MPP. In fact, there is rather large fluctuation in the duty cycle due to the varying insolation. This results in a large ΔP and affects the decision reference (NdP/dV). The details surrounding this issue were discussed in [8]. The simple INC method has the same problem. However, the amplitude of the fluctuation is lower due to the independence of ΔD and the magnitude of ΔP . The simple INC method, however, has a slower dynamic

Fig. 8. DI versus duty cycle for different insolation levels after temperature compensation: (a) $T_p = 330 \text{ K}$ (b) $T_p = 300 \text{ K}$ (c) $T_p = 270 \text{ K}$.

when compared to the variable step size INC method.

The proposed method tracks the change of insolation closely

(a)

(b)

(c)

Fig. 9. Experimental setup: (a) boost converter with controller. (b) A-300 solar arrays installed on structure with variable tilt angle. (c) Li-ion battery box.

because (33) is valid under variable insolation. Both methods have a quick start up, and the steady state responses are almost identical. However, the proposed method provides 1.37% more output power under the same insolation profile. In practice, the performances of the alternative methods are even worse than the proposed method due to presence of measurement noise.

Ambient temperature may vary up to 25°C within a day and 35°C during a year. However, these values are not absolute and depend on the installation site. Therefore, considering 60°C variation in temperature should be enough to investigate the effect of temperature and its compensation factor on the performance of the proposed method.

Assuming the parameters of Table I, equation (18) is simulated at different insolation and temperatures in Fig. 8. Fig.

Fig. 10. Decision references comparison: (a) DI and $\Delta P/\Delta V$ values during the duty cycle scan with minimum step size, (b) power, (c) duty cycle.

Fig. 11. Investigation of the approach at a steady state insolation level of 500 W/m² and operating point scan between 5 s and 55 s: (a) output power in watts, (b) duty cycle.

8(a), (b) and (c) show DI versus D at a PV temperature of 330 K, 300 K and 270 K, respectively. This simulation verifies the approximation made by (23). The real MPPs (indicated by squares) do not coincide with the zero axis, but the actual MPPs obtained with the algorithm (indicated by dots inside the W_1 span) are almost as near as possible to the real MPPs at different temperatures. These results show that C effectively compensates the temperature effect.

B. Experimental Results

The validity of the proposed method was verified by experimental results on a laboratory prototype. The configuration was similar to the system shown in Figs. 4 and 5. The tests were carried out on a 300-W boost converter with the specifications listed in Table IV. Fig. 9(a) shows the implemented boost converter and its controller. The PV array is shown in Fig. 9(b), which was composed of 70 series connected A-300

Fig. 12. Investigation of the method at a steady state insolation level of 750 W/m^2 and operating point scan between 5 s and 55 s: (a) output power in watts, (b) duty cycle.

Fig. 13. Performance of the proposed method under a trapezoidal insolation profile and real MPP.

Fig. 14. Performance of the variable step size INC under a trapezoidal insolation profile and real MPP.

cells mounted on a variable tilt angle structure. The system load was made up of Li-ion batteries with a nominal voltage

Fig. 15. Performance of a simple INC under a trapezoidal insolation profile and real MPP.

TABLE IV
SPECIFICATIONS OF THE EXPERIMENTAL SET-UP

Boost inductor	Output filter capacitor	Microcontroller	Switching frequency	Algorithm updating rate
1 mH	220 μF	Atmel's 8-bit-Mega16	33 kHz	Up to 50 Hz

of 144 V (Fig. 9(c)).

Fig. 10 illustrates a comparison between the proposed and the “variable step size INC” decision references. To investigate both DI and dP/dV under the same conditions at all operating points, the duty cycle was increased continually with the minimum step size under constant insolation.

In Fig. 10(a), both decision references approach zero at the MPP (which is the maximum point of Fig. 10(b)). Fig. 10(a) also shows the noise effect on both methods. Although both values are calculated according to identical data, the DI profile shows smooth behavior, which implies a higher noise immunity. Thus, the proposed approach has better performance in practice. The other interesting fact from Fig. 10(a) is the higher noise of dP/dV in the constant voltage region (left hand side of MPP). In fact, the lower SNR of dP/dV is due to the lower amplitude of the differential values (ΔV , ΔI) when compared with the absolute values of the voltage and current samples (V_{PV} , I_{PV}). This fact affects the performance of these methods in the discontinuous current mode region, where the ΔV and ΔI values are very small, and sometimes cause the duty cycle to stick in this region when the MPPT load is a battery. The analytical investigation of SNR also proves the higher SNR value of the proposed decision reference under typical operating conditions (refer to Appendix I).

Figs. 11 and 12 evaluate the performance of the proposed scheme under two different insolation levels. In both figures, the system operates at the steady state conditions and tracks the MPP (between 0 and $t=5$ s). At $t=5$ s, the duty cycle is reset and then increases gradually to sweep the different operating points (with an open loop system).

The results show that the real MPP in both cases are identical to the power obtained by the closed loop system. Similar

$$SNR_{INC} = 12\gamma \times \frac{1}{\left(\frac{\Delta_2}{I_D}\right)^2 + \left(\frac{\Delta_1}{n\eta V_T}\right)^2 + 2\left(\frac{V_{PV}}{I_D}\right)^2 \left[\frac{\Delta_2^2}{\Delta_1^2} + \left(\frac{\Delta I_{PV}}{\Delta V_{PV}}\right)^2\right] \left(\frac{\Delta V_{PV}^2}{\Delta V_{PV}^2 - \Delta_1^2}\right)} \quad (32)$$

tests were carried out to investigate the system performance at different hours and at different temperatures. The experiments confirm the effectiveness of the proposed method.

To evaluate the proposed method under dynamic insolation, a trapezoidal insolation profile was imposed on the system by changing the exposure angle at a constant insolation (Figs. 13-15). Auxiliary cells were installed beside the main cells to measure the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}) during the test conditions. These values were used to estimate the real MPP at each instant by (25).

$$P_{MPP} = I_{sc} \times V_{oc} \times FF. \quad (25)$$

FF in (25) represents the fill factor. FF depends on the V_{oc} and V_T values as indicated by (26). Under varying insolation, V_{oc} shows a minor change, except at very low insolation levels. Thus, FF is almost constant and varies between 0.778 and 0.784 during the experiments. These values are in good agreement with the data sheet value and the measurements.

$$FF = \frac{V_{oc} - nV_T \ln\left(\frac{V_{oc}}{nV_T} - 0.72\right)}{V_{oc} + nV_T}. \quad (26)$$

Fig. 13 confirms the fast response of the proposed method under rapidly changing insolation without confusion. Furthermore, oscillations at the steady state condition were not observed.

Fig. 14 illustrates the performance of the “variable step size INC” method under a trapezoidal insolation profile with $N = 0.1$. As predicted from the high noise content of $\Delta P/\Delta V$ in Fig. 10, the steady state and the dynamic performances are poor, which leads to a greater power loss (compared with the simulation results). In addition, the duty cycle sticking problem in the discontinuous current mode region is observed before the increment of insolation.

Fig. 15 illustrates the test results for the simple INC method with a 1/255 step size. The oscillation at steady state and the confusion in the slope area can be seen. The proposed method shows about 1.8% and 9.8% better efficiency than the simple INC and VSINC methods under the assumed insolation profile, respectively.

VI. CONCLUSION

In this paper, a novel MPPT algorithm was introduced, which guarantees tracking of the real MPP under changing insolation conditions with the highest accuracy and fast speed. In the proposed method, the oscillation problem around the MPP was completely solved. An updating subroutine was provided in the algorithm, which compensates for the temperature and aging effects. It can be implemented with low cost microcontrollers. The simulation and experimental results confirmed the validity and effectiveness of the new method.

APPENDIX

A. SNR Analysis of the Decision References

The measured PV voltage and current introduces noise into the decision reference. To compare the noise sensitivity of the different methods, the boost converter with a constant load voltage is considered for analysis. Here, the quantization noise of the ADC channel (with j -bits) is the main source of noise. Therefore, the PV voltage and current can be written as follows:

$$V_{pv} = V_Q + e_v \quad \text{Where} \quad -0.5\Delta_1 < e_v < 0.5\Delta_1 \quad (27)$$

$$V_{pv} = I_Q + e_I \quad \text{Where} \quad -0.5\Delta_2 < e_I < 0.5\Delta_2 \quad (28)$$

where V_Q and I_Q are the digitized samples of the PV voltage and current, and the voltage and current quantization errors are e_v and e_I , respectively. Additionally, Δ_1 and Δ_2 define the resolution of the ADC channels calculated in (29) and (30). Now, the quantization noise power can be derived from (29) and (30).

$$\sigma_{e_v}^2 = \frac{\Delta_1^2}{12} \quad \text{Where} \quad \Delta_1 = \frac{V_{max}}{2^j} \quad (29)$$

$$\sigma_{e_I}^2 = \frac{\Delta_2^2}{12} \quad \text{Where} \quad \Delta_2 = \frac{I_{max}}{2^j} \quad (30)$$

where V_{max} and I_{max} represent the full scale of the voltage and current in the ADC channels. The quantization noises can be assumed to be uncorrelated white noises. Thus, using stochastic analysis, the noise power of the different decision references (P&O, INC and the proposed method) are calculated and demonstrated in (31)-(33), with some logical simplification. The parameter γ is also defined in (34):

$$SNR_{\Delta P} = 12\gamma \left[0.5 \frac{\left(\frac{I_D}{I_{PV}} \frac{\Delta D}{1-D}\right)^2}{\left(\frac{\Delta_1}{V_{PV}}\right)^2 + \left(\frac{\Delta_2}{I_{PV}}\right)^2} \right] \quad (31)$$

$$SNR_{DI} = 12\gamma \left[\frac{(n\eta V_T)^2}{\Delta_1^2 (1 + (I_{PV}/I_D)^2) + R_s^2 \Delta_2^2} \right] \quad (33)$$

$$\gamma = \left[\frac{V_{PV}}{R_s I_D + n\eta V_T} - \frac{I_{PV}}{I_D} \right]^2. \quad (34)$$

The calculated terms for SNR are complicated. To compare the different SNRs at typical operating points, the following relations are used. According to [1], (35) and (36) provide an operating point close to MPP.

$$\frac{V_{oc}}{V_{pv}} = \frac{4}{3} \quad (35)$$

$$\frac{I_{sc}}{I_{pv}} = 1.18. \quad (36)$$

According to (35) and (36), and considering a 10-bit resolution for the ADC and an 8-bit resolution for the PWM generator, the SNR values of the P&O and INC decision references are 25 dB and 46 dB lower than that of the proposed method, respectively. These results confirm the effectiveness and superiority of the proposed method when compared with the conventional methods.

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