Improved MPPT algorithms for rapidly changing environmental conditions

Dezso Sera[*], Tamas Kerekes[*], Remus Teodorescu[*] and Frede Blaabjerg[*]
[*] Aalborg University/Institute of Energy Technology, Aalborg, Denmark

***Abstract*—The first part of this paper intends to give an overview of the Maximum Power Point Tracking methods for Photovoltaic (PV) inverters presently reported in the literature. The most well-known and popular methods, like the Perturb and Observe (P&O), the Incremental Conductance (INC) and the Constant Voltage (CV), are presented. These methods, especially the P&O, have been treated by many works, which aim to overcome their shortcomings, either by optimizing the methods, or by combining them. In the second part of the paper an improvement for the P&O and INC method is proposed, which prevents these algorithms to get confused during rapidly changing irradiation conditions, and it considerably increases the efficiency of the MPPT.**

I. Introduction

PV solar electricity together with solar thermal has the highest potential of all the renewable energies since solar energy is a practically unlimited resource, available everywhere.

The power delivered by the PV module depends on the irradiance, temperature, and shadowing conditions. The PV panel has a nonlinear characteristic, and the power has a Maximum Power Point (MPP) at a certain working point, with coordinates VMPP voltage and IMPP current. Since the MPP depends on solar irradiation and cell temperature, it is never constant over time; thereby Maximum Power Point Tracking (MPPT) should be used to track its changes.

The penetration of PV systems as distributed power generation systems has been increased dramatically in the last years. In parallel with this, Maximum Power Point Tracking (MPPT) is becoming more and more important as the amount of energy produced by PV systems is increasing.

II. Maximum Power Point Tracking Methods

Many MPPT techniques have been reported in the literature, but there are three main methods, which are the most widely used: [1]

- Perturb and Observe (P&O)
- Incremental Conductance (INC)
- Constant Voltage (CV)

The first two are so called 'hill-climbing' methods, and they are using the fact that on the V-P characteristic, on the left of the MPP the variation of the power against voltage $dP/dV > 0$, while at the right, $dP/dV < 0$. (see Fig. 1) [14] The CV method is based on the fact that generally the ratio $V_{MPP}/V_{OC} \approx 0.76$ [1].

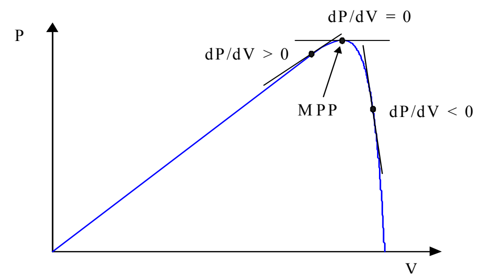

Fig. 1 Sign of the dP/dV at different positions on the power characteristic

A. The Perturb and Observe (P&O) method

The most commonly used MPPT algorithm is the Perturb and Observe (P&O), due to its ease of implementation in its basic form. In Fig. 1, if the operating voltage of the PV array is perturbed in a given direction and $dP/dV > 0$, it is known that the perturbation moved the array's operating point toward the MPP. The P&O algorithm would then continue to perturb the PV array voltage in the same direction. If $dP/dV < 0$, then the change in operating point moved the PV array away from the MPP, and the P&O algorithm reverses the direction of the perturbation. [1]

The advantage of the P&O method is that it is easy to implement. However, it has some limitations, like oscillations around the MPP in steady state operation, slow response speed, and even tracking in wrong way under rapidly changing atmospheric conditions. [1][2][3][5][6][8]

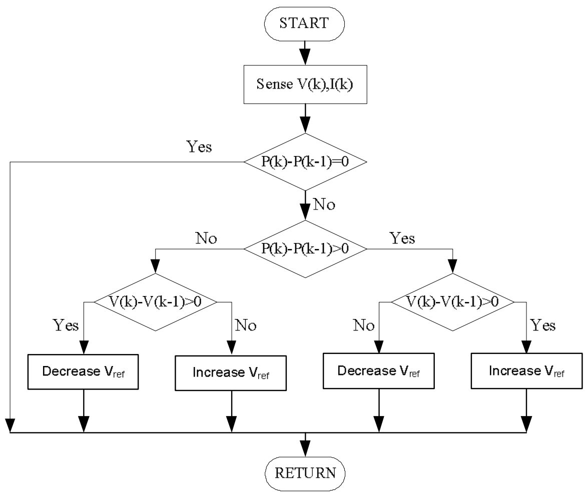

Fig. 2 The flowchart of the P&O MPPT method

B. The Incremental Conductance (INC) method

The incremental conductance uses the PV array's incremental conductance dI/dV to compute the sign of dP/dV.[1]. It does this using an expression derived from the condition that, at the MPP, dP/dV = 0. Beginning with this condition, it is possible to show that, at the MPP dI/dV = -i/v [1],[4]. Thus, incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between dI/dV and –i/v, [1],[4]. The INC method was firstly reported by the authors of [4].

The INC can track rapidly increasing and decreasing irradiance conditions with higher accuracy than P&O. [1] However, because of noise and errors due to measurement and quantization, this method also can produce oscillations around the MPP; and it also can be confused in rapidly changing atmospheric conditions.[2] Another disadvantage of this algorithm is the increased complexity when compared to perturb and observe. This increases computational time, and slows down the sampling frequency of the array voltage and current. [1]

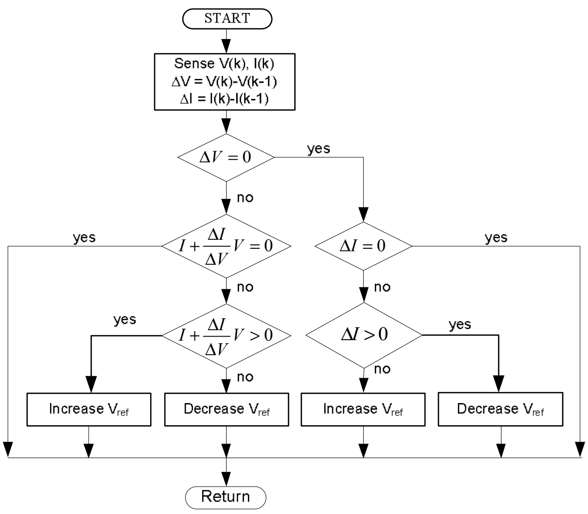

Fig. 3 The flowchart of the INC MPPT method

C. The Constant Voltage (CV) method

This algorithm makes use of the fact that the MPP voltage changes only slightly with varying irradiances. The ratio of V_{MPP}/V_{OC} depends on the solar cell parameters, but a commonly used value is 76% [1],[9]. In this algorithm, the MPPT momentarily sets the PV array current to zero to allow a measurement of the array's open circuit voltage. The array's operating voltage is then set to 76% of this measured value. This operating point is maintained for a set amount of time, and then the cycle is repeated.

A problem with this algorithm is available energy is wasted when the load is disconnected from the PV array; also the MPP is not always located at 76% of the array's open circuit voltage. [1]

D. Other MPPT methods

There are many other MPPT methods reported in the literature, and a big number of them are based on the combination of the three above presented methods.

A combination of the INC and CV method is proposed in [16], in which above 30% normalized irradiation intensity the INC method is active, while below the CV method is used. [16]

In [13] another hybrid method is proposed, where the P&O method is combined with the CV. The algorithm starts with measuring the open-circuit voltage, from which calculates the initial V_{MPP}. After setting the operating point according to the V_{MPP}, the P&O method is switched on.

A different MPPT approach is based on the power equilibrium on the DC link of the two-stage PV converter [15], where the PV array side boost chopper plays a role of keeping the link voltage constant, while the line side PWM inverter plays a role of adjusting the load level not to cause the link voltage breakdown.

In [18], an MPPT control in combination with One-cycle control for single stage photovoltaic converter is presented. A single controller is responsible for the MPPT and dc-ac conversion, and it can be implemented using basic electronic components, without DSP. The authors state that it can be a low cost and increased efficiency solution for commercial PV systems.

E. MPPT algorithms in partially shaded conditions

Although many MPPT algorithms have been reported, which are claimed to be efficient with fast response time, most of them (for example [2], [3], [4], [5], [8], [13], [15], [16]) did not consider the situation when part of the PV array is shadowed. Partial shadowing can lead to multiple MPP-s, confusing most of the common MPPT algorithms, which converge to a local MPP instead of the global one as shown on the figure below.

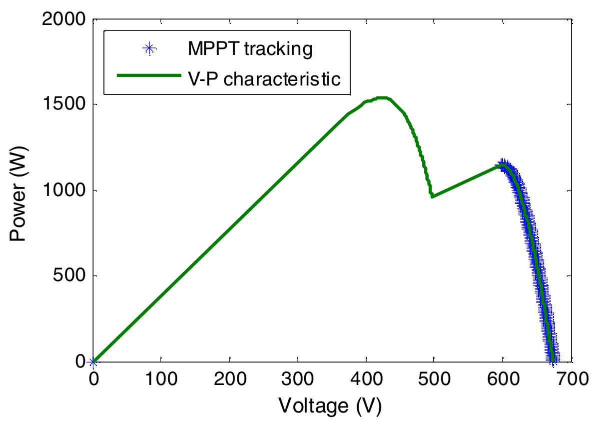

Fig. 4 Simulation of a PV array characteristic in case of partial shading

One of the most common approaches to find the MPP in partially shaded conditions is the periodical sweeping over the v-p characteristic of the solar array, like in [10] and [16]

The method proposed in [17] is based on use of a ***short-circuit current pulse*** of the PV to determine an optimum operating current for the maximum output power. This is done for 80 µs in every 80 ms. According to the experimental results presented in [17], the proportionality factor k between the optimum current I_{MPP} and short-circuit current I_{SC} from (1) keeps its value fairly constant for a wide temperature and luminance range for a given panel.

$$I_{MPP} = k \cdot I_{SC} \qquad (1)$$

As k is dependent on surface conditions, especially on partial shading, the PV characteristic is swept (in 25 ms) in every several minutes to determine the k.

The authors of [11] propose a *Fibonacci-search based MPPT method*, which gives fast response, and it is able to handle the multiple MPP-s when the PV array is partially shaded.

Equation (2) represents the Fibonacci sequence:

$$c_{n+2} = c_{n+1} + c_n, \quad c_1 = c_2 = 1, \quad n = (1, 2...) \qquad (2)$$

The searching process is visualized on Fig. 5:

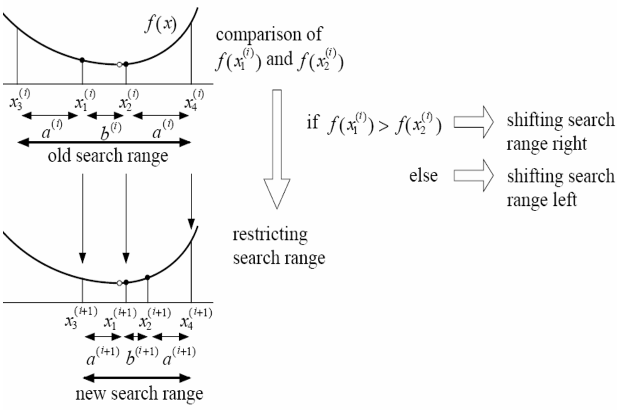

Fig. 5 Searching process of the line search technique in one operation cycle of the Fibonacci-search based MPPT [11] [12]

The variable x and the function $f(x)$ are regarded as voltage, current or duty factor and output power, respectively, when the Fibonacci-search algorithm is applied to the MPPT. [11]

In Fig. 5 the search range is changed by satisfying the following equation:

$$\begin{aligned} &a^{(i)} = a^{(i+1)} + b^{(i+1)}, \quad a^{(i+1)} = b^{(i)} \\ &and \quad a^{(i)} = a^{(i+1)} + a^{(i+2)}, \\ &a^{(i)} = c_{n+1}, \quad b^{(i)} = c_n \\ &and \quad a^{(i+1)} = c_n, \quad b^{(i+1)} = c_{n-1} \end{aligned} \qquad (3)$$

where the term c_n is an element of the Fibonacci-sequence, and the search range is narrowing according to the Fibonacci-sequence values.

To be able to find the MPP in partial shading conditions, an additional function is used with the search algorithm, which detects sudden changes in irradiation, and if the change in output power is larger than a specified threshold, it reinitializes the conditions for the search.

F. The P&O and INC methods in rapidly changing irradiance

As mentioned in section II.A, the P&O method can be confused in rapidly changing irradiation conditions. This is valid also for the INC method. If the change in the irradiation intensity causes bigger change in power than the one caused by the increment in the voltage, the MPPT can get confused, as it will interpret the change in the power as an effect of its action. This is illustrated in the figures below:

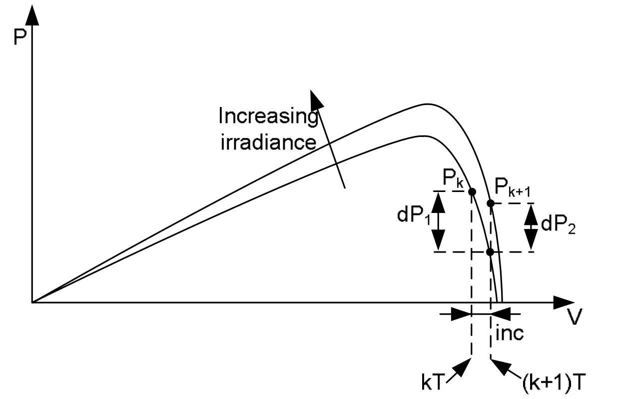

Fig. 6 In case of slow irradiation changes, the P&O and INC methods are able to determine the right tracking direction

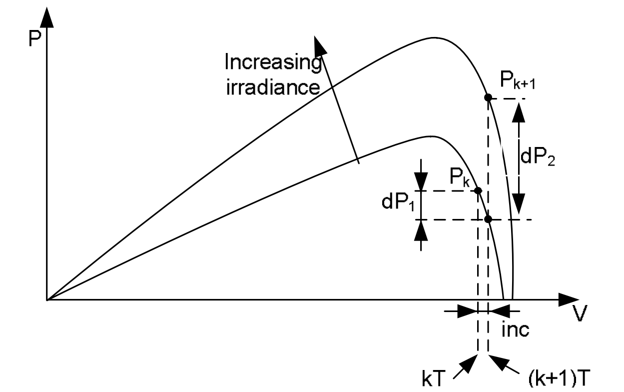

Fig. 7 In case of rapidly changing irradiation, the P&O and INC methods are unable to determine the right tracking direction

On Fig. 6 and Fig. 7:

T – the sampling period of the MPPT,

P_k, P_{k+1} – the powers measured at the k and the k+1 sampling instances

dP_1 – the change in power caused by the perturbation of the MPPT

dP_2 – the change in power caused by the increase in irradiation

inc – the voltage increment of the MPPT

If dP1 > dP2 the MPPT is able to interpret correctly the change in the power between two sampling instances. (Fig. 6), as the overall change in power will reflect the effect of the perturbation. On the other hand, if dP2 > dP1, the MPPT is unable to determine the right direction of tracking as P_{k+1}–P_k in Fig. 7 is positive regardless of the perturbation direction of the MPPT.

III. The Proposed Method

The proposed method (patent pending) performs an additional measurement of power in the middle of the MPPT sampling period without any perturbation, as illustrated in the figure below.

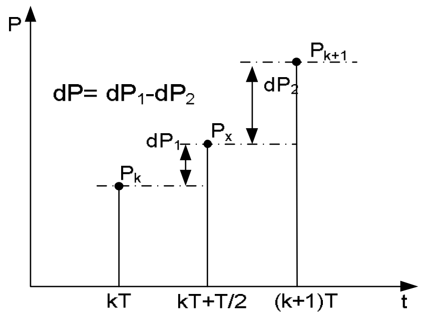

Fig. 8 Measurement of the power between two MPPT sampling instances

As it can be seen on the figure, the change in power between P_x and P_{k+1} reflects only the change in power due to the environmental changes, as no action has been made by the MPPT. The difference between P_x and P_k contains the change in power caused by the perturbation of the MPPT plus the irradiation change. Thereby, assuming that the rate of change in the irradiation is constant over one sampling period of the MPPT, the dP due to the MPPT action can be calculated as:

$$dP = dP_1 - dP_2 = \left(P_x - P_k\right) - \left(P_{k+1} - P_x\right) = \\ = 2P_x - P_{k+1} - P_k \quad (4)$$

The resulting dP, reflects the changes due to the perturbation of the MPPT method.

A. The dP-P&O MPPT

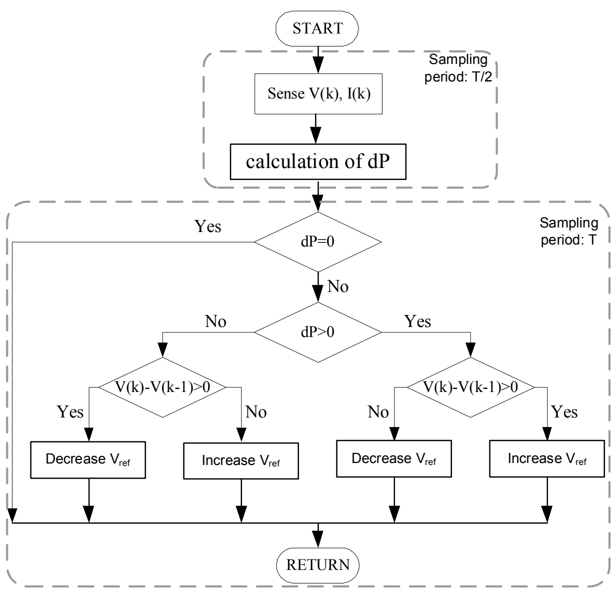

Fig. 9 The flowchart of the dP-P&O method

The flowchart of the modified method, containing the additional block to calculate the dP is shown on Fig. 9

In the dP-P&O the P_k-P_{k-1} (see

Fig. 2) is replaced by the dP calculated in (4) and thereby can be avoided the confusion of the MPPT due to the rapidly changing irradiation.

Similarly the INC method can be improved by adding (4) to the algorithm. The INC method uses the dP/dV in its algorithm (see section I.B). The $I + dI/dV$ term in the flowchart of the INC algorithm (Fig. 3) can be replaced with dP/dV, using the dP calculated in (4).

IV. Experimental Tests

In order to verify the efficiency of the dP-P&O, and compare it to the original P&O, the proposed method has been implemented on a laboratory setup, using a control system as visualized on Fig. 10. The setup consists of the following main components:

- A PV simulator, made of two programmable series connected Delta Elektronika SM300-10 DC power supplies, having Vmax = 300V, Imax = 10A. Their output voltages were controlled in real time according to a photovoltaic model of a PV array. The model is based on a series connected array of 15 BPMSX120 PV panels. The panels have the following main characteristics: maximum delivered power PM = 120W, short-circuit current ISC = 3.87A, open circuit voltage VOC = 42.1V. The model is using the following equations:

$$v = n_{ps}V_{OC} + n_{ps} \cdot n_s \cdot V_T \ln\left(1 - \frac{i}{I_{SC,1000} \cdot \frac{G}{1000}}\right) \quad (5)$$

Where:

n_{ps} – the number of panels connected in series,

n_s – the number of cells in one panel

V_T – thermal voltage (V)

$I_{SC,\,1000}$ – shortcircuit current at standard conditions (at 1000 W/m^2 irradiation) (A)

G – irradiation (W/m^2)

- A Danfoss VLT 5000 5KW 3 phase inverter. The inverter is used in single-phase mode, with unipolar PWM, having an effective switching frequency of 20 kHz. The inverter is connected to an LC filter, with the parameters L = 1.4mH, C = 2 μF. The setup is connected to the grid through a transformer, having a short-circuit inductance of 2mH.
- The control system together with the solar array model has been implemented on a DS1103 dSpace system, as also shown on Fig. 10.The control system has been implemented in Simulink, in discrete time, and using the real time workshop, and dSpace RTI toolbox, has been generated a real time code for the dSpace system.

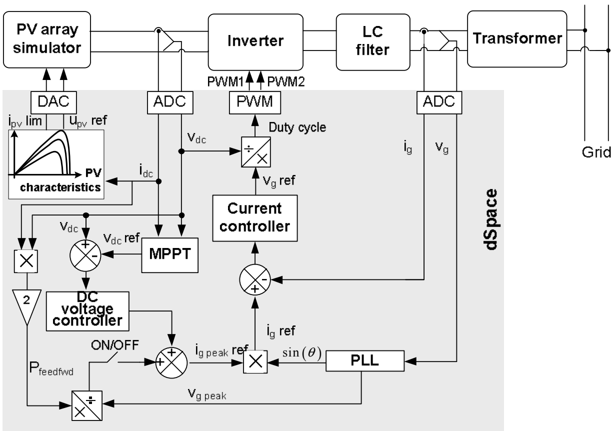

Fig. 10 Experimental laboratory setup

The tests have been made in the following conditions:

- The control system sampling frequency is 10 kHz, same as the PWM outputs frequency.
- The DC voltage controller is a proportional one, with a gain of 0.1.
- The MPPT algorithm sampling frequency is 2Hz, and the voltage increment is set to 2V.
- The current controller is a Proportional-Resonant one. The Phase Lock Loop (PLL) has a settling time of 0.02s. As the current loop has a much faster response than the MPPT, it can be considered ideal from its point of view
- In order to verify the effect of rapidly changing irradiation conditions, an irradiation ramp change was used. This irradiation change starts from 125 W/m2, stops at 800 W/m2, waits at this level for 40s, and decreases again back to 125 W/m2 with a constant slope. A 25s period for the increasing and decreasing ramp was selected. This corresponds to approximately 60 W/s slope of the output power change. The limit of 800W/m2 irradiation is due to the output current limitation of the used inverter.

In the following, the results of the experimental tests of the proposed dP-P&O method will be presented and compared to the results of the traditional P&O method.

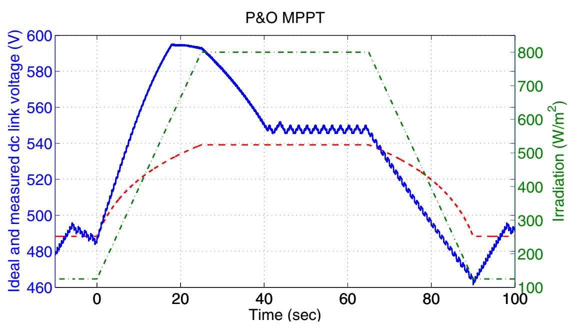

Fig. 11 Ideal and measured DC link voltage during the irradiation change. The DC link voltage (continuous line) increases far beyond the optimal value (dashed line). The actual irradiation (dash-dotted line) is represented on the right axis.

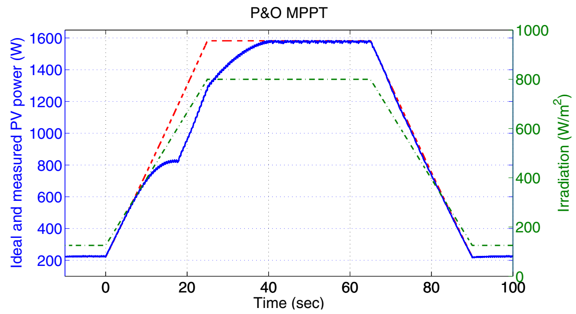

Fig. 12 Ideal and measured PV power during the irradiation change. The power drawn by the P&O MPPT (continuous line) cannot follow the maximum available (dashed line) from the PV array during rapidly increasing irradiation (dash-dotted line)

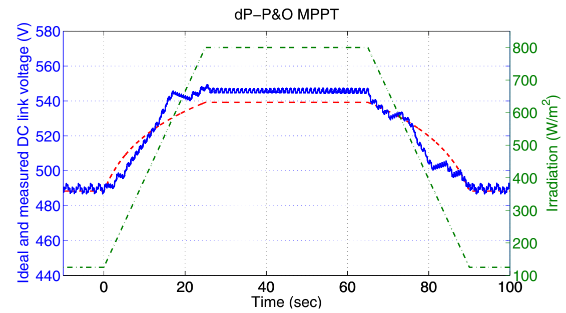

Fig. 13 In case of the dP-P&O, the DC link voltage (continuous line) tracks the optimal value (dashed line) with a fairly good precision also during irradiation change (dash-dotted line).

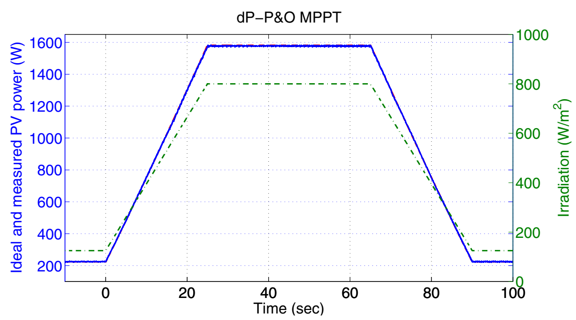

Fig. 14 The power drawn by the dP-P&O (continuous line) follows with a good precision the maximum available power (dashed line) even under rapidly changing irradiance (dash-dotted line)

On the above graphs, the curves for the ideal power and the optimal DC link voltage are calculated based on the same model used to control the DC power sources.

Based on the measured and ideal (calculated) power at the actual irradiation, the instantaneous efficiency is calculated based on the following formula:

$$\eta_{inst} = \frac{P_{PV\_meas}}{P_{MPP\_ideal}} \cdot 100 \qquad (6)$$

In order to evaluate the dynamic efficiency for the entire test interval, the following formula was used:

$$\eta_{dynamic} = \frac{P_{PV\_meas\_mean}}{P_{MPP\_ideal\_mean}} \cdot 100 \qquad (7)$$

Where: $P_{PV\_meas\_mean}$ – is the mean value of the measured power over the entire test time, and

$P_{PV\_ideal\_mean}$ – is the mean value of the maximum available power over the test time, based on the PV model.

On the next plot one can see the instantaneous efficiencies of P&O and dP-P&O, according to (6).

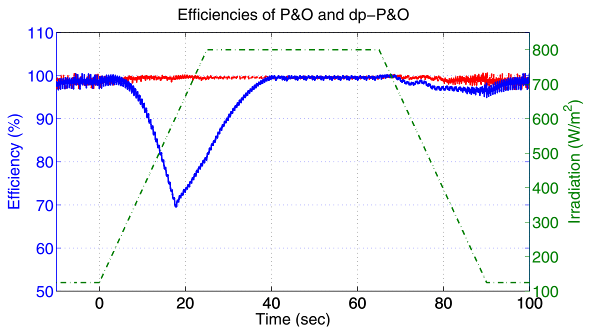

Fig. 15 The efficiency of the traditional P&O method decreases to as low as 70% during rapidly increasing irradiation, while the efficiency of dP-P&O is not affected.

As it can be seen on Fig. 15, in steady-state operation, when the irradiation is constant, the P&O and the dP-P&O are performing similarly, which was expected. On the other hand, when the irradiation increases, the traditional P&O get confused, as it cannot interpret correctly the change in power caused by the irradiation and the one caused by its own command. During the irradiation change, the instantaneous efficiency of the traditional P&O can fall about 30% (depending on the speed and duration of the irradiation change), while the dP-P&O tracks the MPP with same efficiency as in steady-state operation.

For the entire period represented on Fig. 15, the calculated dynamic efficiencies of the two methods according to (7), are 99.6% for the dP-P&O, and 94.5% for the classical P&O. This means an efficiency improvement of about 5% for the dP-P&O method.

V. Conclusions

An overview of the existing MPPT methods has been provided in the first part of the paper. Discussions about partial shadowing case were also included, showing that conventional trackers can stop at local MPP, instead of the global MPP. Furthermore, in case of rapidly changing irradiation condition the P&O and INC methods were shown to get confused. Therefore an improvement for these two methods, which can overcome their confusion during rapidly changing irradiance, was introduced in the second part.

The method is very simple and the experimental results show that it is able to considerably increase the efficiency of the MPPT method during rapidly changing irradiance.

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