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Multiple-Power-Sample based P&O MPPT for Fast-Changing Irradiance Conditions for a Simple Implementation

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***Abstract*- This paper proposes an improved Maximum Power Point Tracking (MPPT) method that features i) a simple design , and ii) improved efficiency in fast changing irradiance conditions. The method uses three consecutive measurements and compares the power difference between each two consecutive samples, furthermore the voltage variation between the last two successive samples is observed. According to the obtained result of these comparisons, the algorithm applies the suitable action either increasing or decreasing the voltage. This simple concept allows easy implementation and reduces the implementation cost and calculation burden. Secondly, the method has a prompt tracking response during fast changes in solar irradiance (e.g., due to passing clouds). The proposed method is validated through experimental tests using solar irradiance profiles according to the EN50530 standard and is compared to the classical Perturb and Observe (P&O) method. The experimental results show that the proposed MPPT effectively identifies the change in solar irradiance, and maintains high tracking efficiency even in fast changing conditions.**

***Index terms*- Maximum Power Point Tracking, photovoltaic energy harvesting, efficiency, EN50530 standard.**

I. INTRODUCTION

The integration of photovoltaic (PV) technologies, as a main source in power plants has been one of the important subjects of research during the past few decades. However, the fundamental issue with PV technology is that its power extraction characteristic is nonlinear and its maximum power point (MPP) is highly dependent on uncontrollable environmental conditions (solar irradiation and temperature) [1]. Hence, its use remains imperfectly convenient from productivity and efficiency point of view[2]. Nevertheless, this issue is addressed by introducing the Maximum Power Point Tracking (MPPT) method.

The focus of the continuous improvement of the MPPT techniques is to improve the PV system efficiency and reduce the implementation cost[3]. MPPT is a controller that extracts the maximum power from the PV panel which gives rise to an optimal operation of the PV system[4], [5].

In literature, most of the available MPPT techniques exhibit a roughly similar behavior in steady state conditions. This behavior is observed when solar irradiance is stable and most MPPT methods can track the MPP with high accuracy[6]. However, since the location of MPP changes according to the solar irradiation and temperature conditions, the difference between the responses of the MPPT techniques lies on how they handle the erratic variation of these weather conditions.

The Perturb and Observe (P&O) algorithm is the most used and known MPPT technique. The P&O satisfies simplicity and low implementation cost criteria [6]-[8]. However, from an efficiency point of view, this method is less efficient during fast changing weather conditions. The P&O method uses a specific step size to perturb the PV voltage/current, and its performance depends mainly on the choice of the step size, i.e. a smaller or bigger one shows pros and cons during both transient and steady states leading to a possibly poor overall efficiency [6]. Apart from that, the use of the P&O algorithm is impractical during rapid variation in weather conditions since it deviates from the right tracking direction[9], [10], which creates a bottleneck for this method to associate efficiency with the aforementioned criteria. Even with these limitations, it is still attracting a widespread interest and the focus of researchers is still on improving the performance of the P&O algorithm. The authors of [11] have addressed the dilemma of the step size by introducing a variable one. This method is achieved through three steps. During the first step, the operating point moves toward the MPP by applying the conventional P&O. Afterwards, when a sudden change in solar irradiation takes place, a new operating point is set to be close to the MPP. The last step provides a variable step size based on the power variation. The disadvantage of this method is the use of the Short Circuit Current multiplied by a constant to put the operating point close to the MPP. Moreover, the method has been validated using only a sudden change of solar irradiance which doesn't reflect the real case of the variation of solar irradiance. In[12], a modified version of the P&O algorithm has been proposed. The principle of this method is to apply three consecutive perturbations (+-+) in the PV voltage prior to the final perturbation decision. The information obtained from these perturbation sequences allows excluding the effect that brings the environmental conditions on the overall power variation. The authors claim that their method

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improves the PV system efficiency and ensures a fast tracking. The demerit of this method is that its response is not immediate, due to the need of setting three perturbations to determine the correct perturbation decision which affects the convergence time in fast changing irradiance. Alternative approaches have been adopted in[9] and[13] to address the occurrence of drift phenomenon, that the conventional P&O exhibits. The authors of [9] have modified the P&O algorithm by including a new check-condition, which is the change in current ΔI, prior to the final decision. The change in current provides information about the change in solar irradiation which helps the P&O to distinguish the power variation is caused by either the solar irradiation or by the perturbation. Nevertheless, the method has not been validated under fast changes in solar irradiance to demonstrate the behavior of the method. In[13], the authors have found an approach that improves the performance of P&O method. An extra measurement is performed in the center of the MPPT sampling period where the calculated power variation dP permits identifying the effect of the change in solar irradiance. This method prevents from the drift occurrence, however it needs a longer sampling period. A modified version of the P&O MPPT have been proposed in[26] which reduces the oscillations around the MPP and deals with the drift issue by limiting the PV voltage in a defined interval. These limits are a constant-based, therefore, by relying the PV voltage on these boundaries could be inaccurate and effective in some cases. Another popular MPPT algorithm, which is frequently used in the literature is the Incremental Conductance (INC) method. Several publications have been done to improve the algorithm's performance as in[14], [15]. However, in[16], it has been concluded that P&O and INC are equivalent since they share the same principle and exhibit identical tracking performance during both static and dynamic conditions. Fractional Open Circuit Voltage (FOCV) and Fractional Short Circuit Current (FSCC) are a part of the classical MPPT methods and widely recognized in this area. They estimate the region where the MPP lies in the P-V curve based on the measurement of the open circuit voltage or short circuit current of the PV panel [17]. These methods could exhibit a good performance in some cases, although they may be inefficient due to the power losses resulting from open circuit voltage and short current circuit measurements. In addition, their concept is estimation-based. Some interesting approaches for MPPT techniques use artificial intelligence [17], [18], such as Fuzzy Logic Controller (FLC), and Artificial Neural Network (ANN). A limited number of improvements on these methods have been found in the literature. Some authors use the combination of FLC and ANN, also known as the Adaptive Neural-Fuzzy Inference System (ANFIS), in order to harness the effectiveness of each method[19]. Others combine artificial intelligence methods with the classical MPPT techniques [20]. Despite the improvement that these methods show, they require a large database and a considerable computation time. In this case, achieving a good efficiency is guaranteed to the detriment of the computation burden and implementation cost.

Quite recently, Model Predictive Control (MPC) has been gaining a considerable attention for controlling the power converters. MPC has many features and advantages which made it an attractive solution that fulfills challenging control requirements [21]. Currently, there is ongoing interest and research investigating the application of MPC on MPPT for PV systems. The authors in [22] have presented a review of MPC-MPPT applied to different converter topologies and discussed various key points of the difference between MPC and the conventional P&O. The authors demonstrate that the reviewed MPC-MPPTs do not offer considerable improvement over P&O, since the prediction consider only the converter model. In [10], an improved MPC-MPPT, in which the predictions are also performed according the PV characteristic, has been proposed, showing a reasonable improvement. However, the advantages of MPC come at the cost of the computation effort since a powerful control platform is needed [21].

Based on the literature survey, researchers tend to improve and propose MPPT methods. Despite their effectiveness, most of them suffer from limitations, like the presence of thresholds in the algorithm that are hard to define properly, the response time of the algorithm to follow the MPP during dynamic conditions, high computational complexity and/or burden or the algorithm conception is parameter-dependent which limits its accuracy. The present paper proposes an improved version of the classical P&O algorithm. The proposed approach is i) a simple yet effective method that tackles the deviation phenomenon exhibited by P&O method, and ii) ensures a very good efficiency.

The article contains five sections. The second section provides an insight into the limitations of P&O. The third section is dedicated mainly to a description of the operating principle of the proposed MPPT method. Then, the experimental results are presented and discussed in Section IV. Finally, the conclusion summarizes the proposed approach and the results of this work.

II. Limitations of the Perturb and Observe MPPT Algorithm

The classical P&O suffers from several limitations in its performance. As reported previously, a bigger step size guarantees fast convergence to the MPP, but excessive oscillations are produced. Whereas, a smaller step size increases the transient state operation but limits the generation of excessive oscillations [6].

During a realistic case when the solar irradiance is changing rapidly, the P&O may not be able to track the MPP. This is attributed to the lack of information that P&O needs to identify the reason of the increase in power. In fact, there are two major causes leading to the increase in power, which are: 1) the rise in solar irradiance. 2) The perturbation applied by the method itself, which means that an increment or a decrement in the PV voltage (V) drives the power to increase. For instance, as long as the solar irradiation rises, the MPP location changes, almost, proportionally and since this algorithm does not define a dedicated decision of whether the power variation is due to a change in solar irradiance or caused by the perturbation, the algorithm gets confused. Therefore, the calculation method

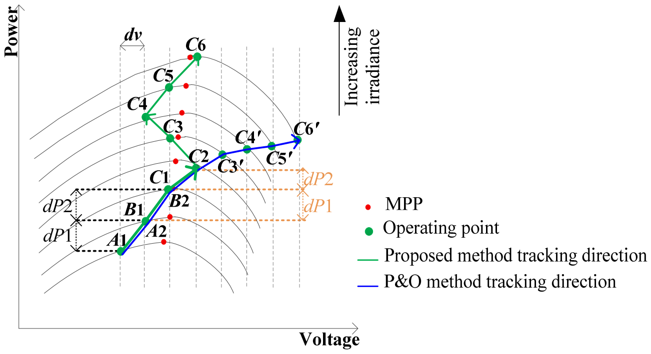

Fig. 1 Difference between the tracking directions using the P&O and the proposed method.

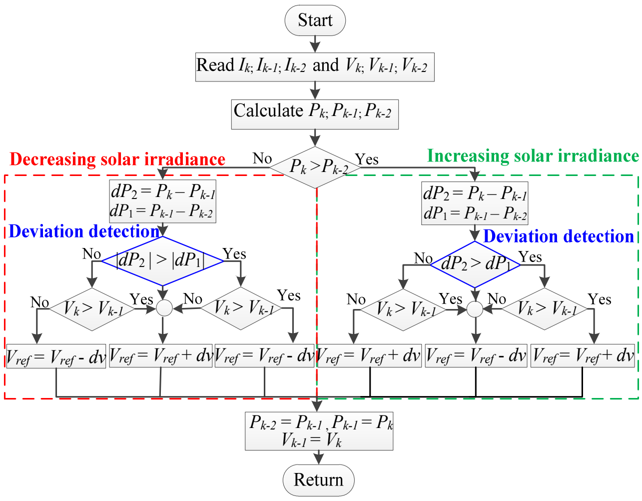

Fig. 2 Flowchart of the proposed MPPT method.

could be ill-defined to track the MPP during fast changing weather conditions [9], [10]. As an example, in Fig.1, it is assumed that: the solar irradiance is increasing rapidly, which is accompanied by a rise in PV power (P) and the actual operating point is C_2. The P&O algorithm evaluates $P(k)$-$P(k$-1)>0 and same for V, in this case V is incremented and the operating point is displaced to C_3'and continues in this direction until it reaches C_6'. Hence, the P&O is confused, and the operating point starts to get away from the right tracking direction of the MPP. The observed phenomenon is referred as a Drift.

III. Proposed MPPT Method

As depicted in Fig.1, considering the PV curve shape, it is noticeable that when the operating point deviates from the right tracking direction (MPP direction in Fig.1), the power difference between these points becomes smaller. This observation gives rise to a novel and simple approach that inhibits the deviation phenomenon under fast dynamic conditions. Considering this, the key of the proposed method is to use three consecutive operating points and observe the PV power variation between each two consecutive operating points. This provides a knowledge about the direction of the operating point whether it is following the MPP or moving away from it.

Fig. 1 illustrates the concept of the proposed method and Fig. 2 summarizes the steps of the algorithm. In addition, it should be noted that in the following explanation, an increasing irradiance is assumed, and the first perturbation is positive. For the purpose of ensuring proper operation of this approach, three consecutive operating points are measured at time instances t_{k-2}=(k-2)T_p, t_{k-1}=(k-1)T_p and t_k=(k)T_p where T_p denotes the MPPT sampling time and k is the sample of the current operating point. In Fig. 1, it is supposed that the three samples have the following reference: $A_1(P_{k-2}, V_{k-2})$, $B_1(P_{k-1}, V_{k-1})$ and $C_1(P_k, V_k)$ where C_1 is the current operating point sample, P_k and V_k are the corresponding PV power and voltage. Also, the position of these samples A_1, B_1 and C_1 in Fig. 2 has been randomly chosen to explain the proposed method's operating principle.

A. Concept

1) Dynamic conditions case: The flowchart in Fig. 2 depicts that the first step of the proposed method is to introduce a check condition, which allows the algorithm to be able to differentiate between an increasing and decreasing change in solar irradiance. This is achieved by comparing P_k and $P_{k-2.}$ The reason behind choosing P_k and P_{k-2} is that those points guarantee the knowledge of the direction of solar irradiance. Subsequently, the power variation between each two of the three operating point samples is calculated as: dP_2 and dP_1. The proposed method is built upon the calculation of dP_2 and dP_1 because during dynamic conditions, the power difference (dP) is the result of the power variation caused by the perturbation of the MPPT rules (dP_{per}) plus the power variation derived from the change in solar irradiance (dP_G)[2][16].

$$dP = dP_{per} + dP_G . \tag{1}$$

Accordingly

$$dP_2 = dP_{per2} + dP_{G2} \tag{2}$$

$$dP_1 = dP_{per1} + dP_{G1} \tag{3}$$

If it is assumed that the solar irradiance change is approximately linear over two MPPT perturbations. Therefore, dP_{G2}=dP_{G1}. Subtracting (3) from (2), yields to:

$$dP_2 - dP_1 = dP_{per2} - dP_{per1} \tag{4}$$

As a consequence

$$\text{If } dP_{per2} - dP_{per1} > 0 \text{ leads to } dP_2 - dP_1 > 0 \tag{5}$$

$$\text{If } dP_{per2} - dP_{per1} < 0 \text{ leads to } dP_2 - dP_1 < 0 \ . \tag{6}$$

It follows from (5) and (6) that the effect of solar irradiance is eliminated and the only variable that indicates whether dP_2 is bigger or smaller than dP_1 is the perturbation introduced by the MPPT (dP_{per1} and dP_{per2}).

A graphical explanation is provided in Fig. 3, where the solar irradiance is increasing and three operating points are

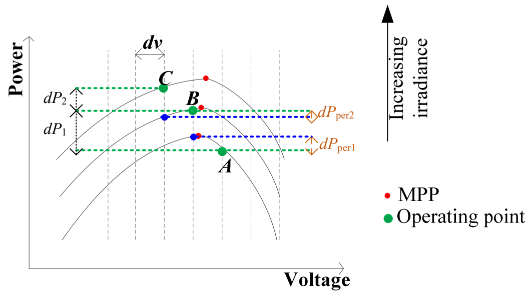

Fig. 3 Movement of the operating point when the solar irradiance changes

considered (A, B and C). The position assumed for these operating points shows that dP_2 is smaller than dP_1. Applying the explanation of how dP_{per} is obtained, it appears that dP_{per2} is also smaller than dP_{per1}. Consequently, the used approach is not sensitive to the variation of solar irradiation and it takes into account only the power variation resulted from the MPPT perturbation. Hence, in the algorithm, a comparison between dP_2 and dP_1 should be done. The case illustrated in Fig.1 shows that $dP_2 > dP_1$ which means that, in this situation, the operating point direction was moving toward the MPP (from A_1 to B_1 to C_1), where in this case, C_1 is located at the MPP. With the intention of defining the operating point position, a comparison of the PV voltage of C_1 and B_1 is included. As $V_k > V_{k-1},$ the proposed method suggests that the PV voltage should be incremented to keep the operating point moving towards the MPP. In this case, the applied perturbation is: $V_{ref} = V_{ref} + dv$. V_{ref} is the reference voltage that the PV voltage must follow, and dv corresponds to the voltage increment. This perturbation settles the operating point at a new position C_2. After updating the voltage reference, the algorithm shifts the sampled voltage and power values one step back, i.e. V_k to be V_{k-1} and V_{k-1} to be V_{k-2}, and does similarly for the power.

A second case is presented in Fig.1 where similar steps of the algorithm will be applied when the next sampling time $(k+1)T_p$ arrives. The new operating points become A_2, B_2 and C_2. Note that C_2 position is resulted from the perturbation applied during the previous sampling time $(k)Tp$. The coordinates of B_2 and A_2 correspond to C_1 and B_1, respectively, due the aforementioned shift. Now, considering the new position of the operating point, the algorithm starts its process. In this example, Fig.1 shows that $dP_2<dP_1$. It is reasonable to interpret this result by the following: when the operating point does not follow the MPP direction, the power difference between the operating points decreases due the shape of the PV curve. Consequently, it could be concluded that when the operating point is around the MPP and $dP_2 < dP_1$, this result is associated to the Drift phenomenon. As $dP_2 < dP_1$ and $V_k > V_{k-1},$ the proposed method is designed to apply the adequate decision of perturbation that will settle the actual operating point C_2 to the right position..

2) Static conditions case: The algorithm checks first P_k and P_{k-2}, which its result varies along the static PV curve. For instance, considering the position of the operating point in the PV curve, the result of P_k -P_{k-2} could be positive as it could be negative. According to this, and by following the flowchart of the method, logically the algorithm will execute the rules of the two branches (increasing and decreasing solar irradiance). As a consequence, the perturbation of the PV voltage could be positive as it could be negative. This case will be highlighted in the experimental results section.

It is worth to mention that the proposed method differs from dP-P&O method [13]. The method of this work relies on three successive power measurements prior to the final decision, as explained previously. Whereas, the dP-P&O method measures the power in the middle of the MPPT sampling period to observe its variation before the sampling period has elapsed in such a way to prevent from the wrong tracking.

B. Highlight of simulation results

This part provides a comparison between the proposed MPPT method and existing MPPT algorithms which are: the conventional P&O, the MS-MPPT [12], dI-MPPT[9] and dP-P&O [13]. The reasons behind choosing these methods are: 1) The P&O is considered as a test benchmark for the MPPT methods. 2) The MS-MPPT, dI-MPPT and dP-P&O are an enhanced version of the P&O method and a comparison in terms of performance between simple-modified P&O methods could be more relevant.

These methods have been tested using a constant solar irradiance, fixed at 1000W/m² and a dynamic profile where the solar irradiance varies between 300W/m² and 1000 W/m². The latter has a trapezoidal form with an ascending and descending slope of 100W/m²/s. It should be noted that the simulation results are issued using the same parameters for all the MPPT methods. The following Table I sums up the performance of the MPPT methods.

TABLE I
COMPARAISON OF THE PROPOSED MPPT AND EXISTING MPPTs

Parameters	**P&O**	**Proposed MPPT**	**MS-MPPT**	**dI-MPPT**	**dP-P&O**
Speed of tracking(s)	0.2	0.6	1	0.2	0.4
Static efficiency(%)	99.91	99.95	99.28	99.87	99.89
Dynamic efficiency(%)	94.72	99.81	99.14	92.46	99.33

From the simulation results, it can be visualized that the proposed method has a slower convergence time compared to the P&O, dI-MPPT and dP-P&O. This limitation will be discussed in the next section. However, it outperforms the P&O and the modified P&O methods in terms of efficiency.

IV. Experimental Results

The assessment of MPPT methods is achieved through testing the solar irradiance profiles proposed by the European standard EN50530 under static and dynamic changing conditions [23].

A. Experimental test conditions

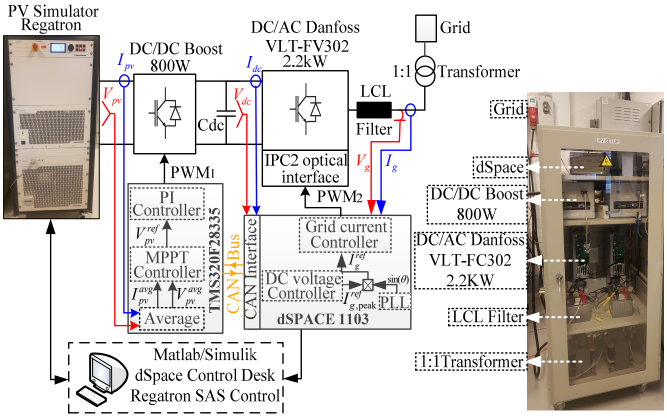

Fig. 4 The experimental setup used to test the MPPT methods

1) Static conditions according to EN50530: Different levels of solar irradiance are defined to calculate the static efficiency of the MPPT controller. The static efficiency is calculated using the European and California Energy Commission (CEC) weighting factors. Their expressions are provided in [23].

2) Dynamic conditions according to EN50530: The EN50530 has proposed a specific test pattern of the solar irradiance[23]. The test pattern is a set of repetitive trapezoidal irradiance profiles with different and well-defined slopes. The EN50530 requires to respect the defined slopes described in [23], as well as the dynamic efficiency expression. In this paper, a shortened version of the EN50530 test is used which is detailed in Table II and Table III. It should be noted that the wait time is 10s as in [23].

B. Description of the experimental setup

Fig. 4 depicts the PV test platform used in this paper which comprises a 1000V/40A high bandwidth PV simulator with a linear post processing unit. The simulator is connected to a custom-built 800W DC/DC boost converter. The described DC unit is interfaced to the grid via a 2.2kW Danfoss VLT-FC302 inverter, LCL filter and a 1:1 transformer. The PV array is replaced by the PV simulator in which the I-V and P-V curves are uploaded and emulated. The characteristics of the PV array and LCL filter are indicated in Table IV. The proposed MPPT method and P&O have been programmed in C and implemented on the TMS320F28335 DSP from Texas Instruments, along with the PV voltage and current control loops. An average over half of the MPPT period is applied to the measured PV current and voltage since the noise accompanies the measurement and this limits the proper operation of the MPPT methods. The averaged values are used by the algorithms to compute the voltage reference then the Proportional Integral (PI) controller sets the PV voltage according to the provided reference. For the grid current controller, a Proportional Resonant (PR) controller with a harmonic compensator have been used and designed according to [24]. As, the system is operating at a sampling frequency of 8 kHz, a high bandwidth of the overall system needs to be

TABLE II
RAMPS OF THE IRRADIANCE PROFILE FROM LOW TO MEDIUM OF THE SHORTENED VERSION OF EN50530

No.of.rep.	2	2	2	2	2	5	5	5
Slope (W/m²/s)	3	5	7	10	14	20	30	50
Rise & Fall (s)	133	80	57	40	29	20	13	8

TABLE III
RAMPS OF THE IRRADIANCE PROFILE FROM MEDIUM TO HIGH OF THE SHORTENED VERSION OF EN50530

No.of.rep.	2	2	2	5	5	5
Slope (W/m²/s)	10	14	20	30	50	100
Rise & Fall (s)	70	50	35	23	14	7

TABLE IV
PV CHARACTERISTICS AND IMPLEMENTATION PARAMETERS

Element	Parameters
PV array	P_{mpp}=584W, V_{mpp}=288V, I_{scc}=2.2A, V_{oc}=310V
LCL filter	L_i=2.6mH; C=2.2µF; L_g=0.41mH
MPPT	f_{mppt}=10Hz; dv=2V
Switching frequencies	$f_{sDC/DC}$= 20kHz; $f_{sDC/AC}$ = 8kHz
PI Parameters	PV voltage loop: Kp=0.05; Ki=0.0001 PV current loop: Kp=0.02; Ki=0.0005

guaranteed which explain the choice of the MPPT frequency. The value of *dv* is set according to[25]. The sampling frequencies of dSpace and DSP are equal to the switching frequencies of each converter that they are controlling.

C. Results and discussion

1) Analysis of the dynamic condition cases: Fig.5 and Fig.6 depict the PV voltage using P&O method and the proposed MPPT method, respectively, when the solar irradiance changes according to the shortened version of the EN50530 test. It can be seen from these plots that when using the P&O method, an

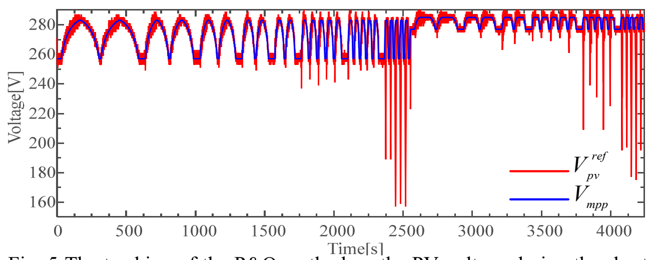

Fig. 5 The tracking of the P&O method on the PV voltage during the shortened EN50530 test.

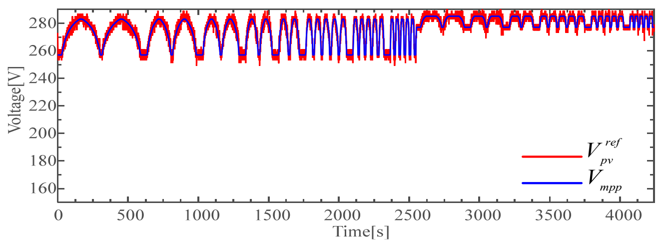

Fig. 6 The tracking of the proposed method on the PV voltage during the shortened EN50530 test.

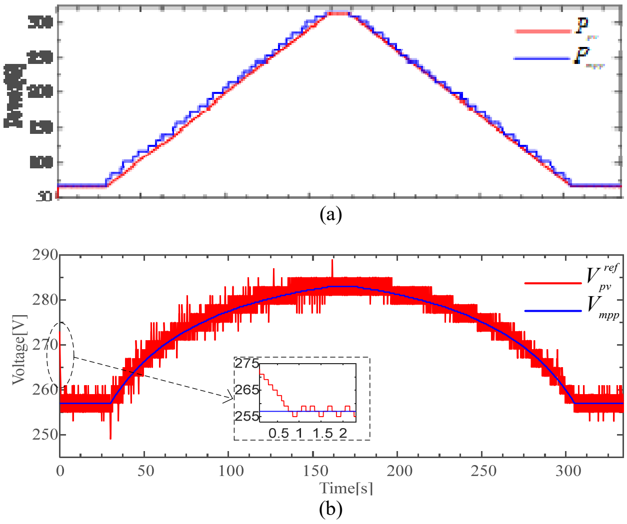

Fig. 7 The tracking of the P&O method during a slow change of irradiance from low to medium (100 W/m² to 500W/m²) in the EN50530 test, at a slope of 3W/m²/s, on: (a) the PV power, (b) the PV voltage

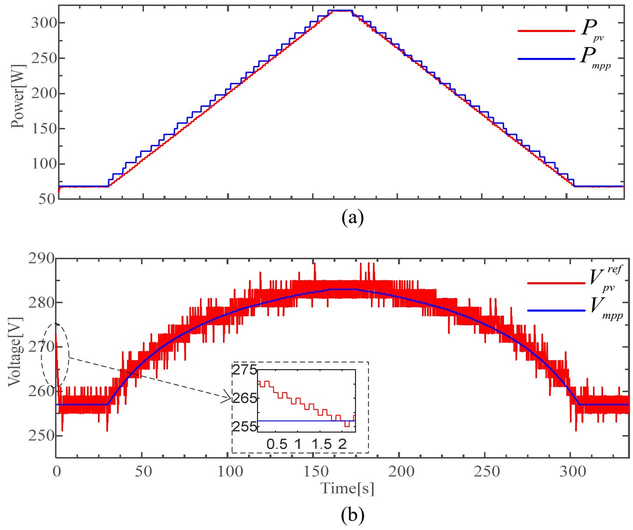

Fig. 9 The tracking of the proposed method during a slow change of irradiance from low to medium (100 W/m² to 500W/m²) in the EN50530 test at a slope of 3W/m²/s, on: (a) the PV power, (b) the PV voltage

existing difference between its tracking direction and the MPP direction is observed, where the operating point deviates completely from the right tracking direction and this is, obviously, accompanied by losses of the extracted PV power. However, the proposed method maintains the PV voltage operating around the MPP, therefore the harvested power is in line with the available power of the PV array. Because this description is barely noticeable in Fig. 5 and Fig. 6, close up views of an individual trapezoidal profile is presented in Fig. 7, 8, 9, 10, 11, 12 when solar irradiance is changing at a different rate. Fig.7 and Fig. 9 reveal the effect of the conventional P&O method and the proposed MPPT method, respectively, on the behavior of the PV power and voltage during a slow change of solar irradiance, while Fig.8, 10, 11, 12 are corresponding, respectively, to a medium and fast variation of solar irradiance. During a slow change in the solar irradiance, it is apparent from Fig. 7 that the PV voltage increases and decreases compared to the MPP voltage. However, it could be considered as an acceptable operation because, in this case, the power variation due the perturbation is larger than the power variation caused by the change in irradiance. This results almost a correct tracking of the MPP. Fig. 9 shows the tracking behavior of the proposed method during a slow variation of solar irradiance, as it can be seen, the PV voltage operation is similar to the P&O method.

One striking contradiction in the performance of the P&O method is shown in Fig.8 and Fig. 11 where solar irradiance is

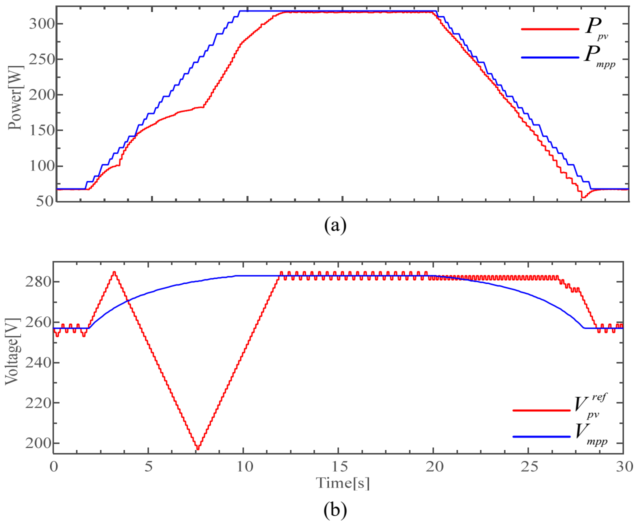

Fig. 8 The tracking of the P&O method during a medium change of irradiance from low to medium (100 W/m² to 500W/m²) in the EN50530 test at a slope of 50 W/m²/s, on: (a) the PV power, (b) the PV voltage

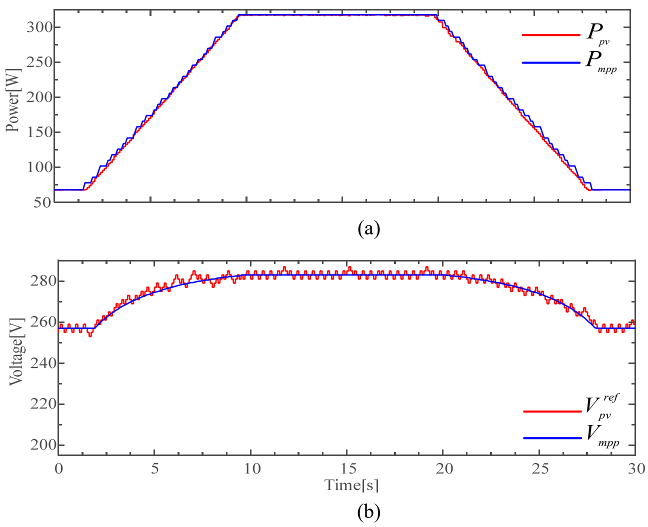

Fig. 10 The tracking of the proposed method during a medium change of irradiance from low to medium (100 W/m² to 500W/m²) in the EN50530 test at a slope of 50 W/m²/s, on: (a) the PV power, (b) the PV voltage

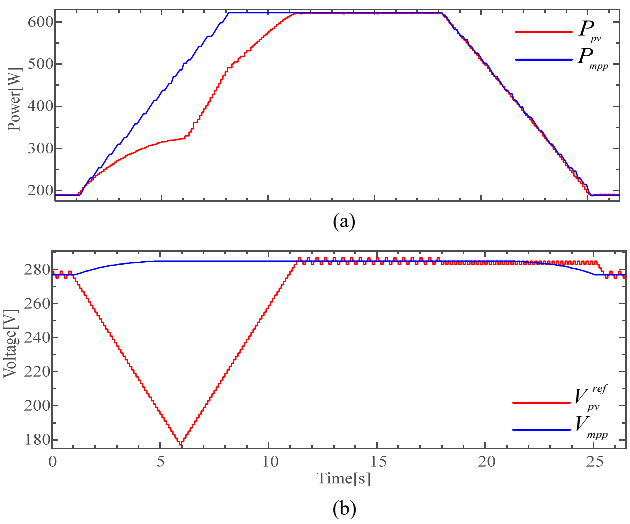

Fig. 11 The tracking of the P&O method during a fast change of irradiance from medium to fast (300 W/m² to 1000 W/m²) in the EN50530 test at a slope of 100 W/m²/s, on: (a) the PV power, (b) the PV voltage

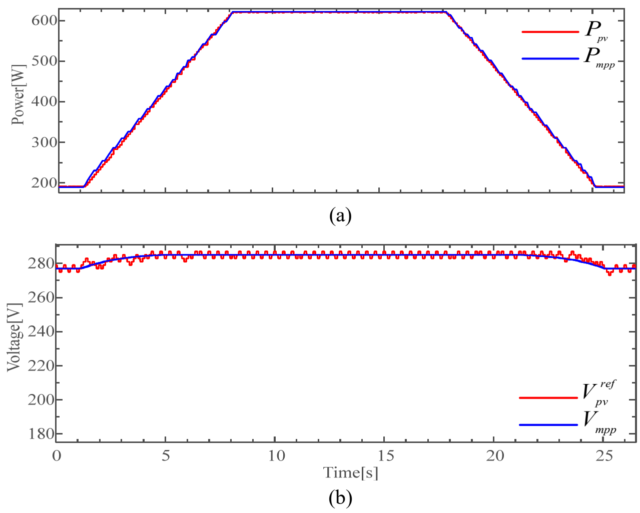

Fig. 12 The tracking of the proposed method during a fast change of irradiance from medium to fast (300 W/m² to 1000 W/m²) in the EN50530 test at a slope of 100 W/m²/s, on: (a) the PV power, (b)

changing fast, at a slope of 50W/m²/s and 100W/m²/s, respectively. In Fig. 8, when the ascending slope of solar irradiance takes place, the P&O algorithm starts by increasing the PV voltage. The applied action relies upon the action that has been set by the algorithm during the previous sampling time (before the solar irradiance changes). In other words, following the P&O algorithm rules, the PV voltage increases when the PV slope is positive which goes with the exhibited scenario in Fig.8. It can be observed that the PV voltage rises further and goes beyond the MPP which is attributed to the lack of knowledge of the source of power increase. However, when the operating point reaches the linear part of the P-V curve, the algorithm senses a variation in the PV power which makes the PV voltage decreases continuously once again until another variation in the PV power is received. In this circumstance, an opposite perturbation to the previous one is set, leading to an increase in the PV voltage. Note that, the sign of the PV voltage is reversed due to the presence of a power variation that could come only from the algorithm's actions, since the power variation caused by the perturbation is smaller than the power variation due to the change in irradiance. The subsequent case is when solar irradiance is decreasing which contributes to a power decrease. In this case, the perturbation's sign is alternately reversed because: 1) The power variation is negative; 2) Taking into account the first reason and setting a positive perturbation leads to an increase in the PV voltage, according to this result, the PV voltage will decrease for the next sampling time. This explanation holds for the second scenario presented in Fig. 11 as well. It may be reasonable to assume that the difference between the two scenarios (Fig. 8 and Fig. 11) lies on the rate by which solar irradiance is varying which triggers a drastic decrease in the PV voltage. As a consequence, during fast changing solar irradiance, the PV voltage is moving beyond the MPP direction. This undesirable operation is translated into a Drift in the PV power as illustrated in Fig.8 and Fig. 11 which yields in power loss. Fig.10 and Fig.12 provide a clear distinction between the tracking behavior of the proposed method and the P&O method. As evident from the figures, the proposed method tracks the MPP with good accuracy and moves the PV voltage in the right direction as expected. There is, therefore, no likelihood of Drift occurrence.

2) Analysis of the start-up condition: At the beginning of the test, it is clear that both of the methods successfully reach the MPP, also it is worth to mention that their convergence time is different as shown in the enlarged figures of Fig. 7 and Fig. 9. The P&O reaches the MPP in 1s, however the proposed method takes 2s to achieve it. The behavior that the proposed method exhibits during the transient state is attributed to the position of the operating point, it is located far from the MPP vicinity, therefore the convergence time is long. The given result is not considered as a critical point owing to the following reasons: First, the operating point ends up reaching the MPP. Secondly, in a real situation of a PV power plant, the MPPT is executed at the start of the day where solar irradiance is low as well as is equivalent PV power. In this case, the proposed algorithm makes the operating point move towards the MPP and it succeeds in achieving it. The amount of the extracted power could be negligible or not important as the solar irradiance level is low. Thirdly, this situation happens once a day during the startup of the MPP tracker. This start-up issue could be solved by using the FOCV method. The latter estimates the voltage at the MPP with the help of the open circuit voltage of the PV used, in this way, the start point of the algorithm is positioned roughly, near the MPPT which will reduce the convergence time. Moreover, the behavior of the MPPT algorithm is more important and must be evaluated when solar irradiance is changing throughout the day where a considerable amount of power is produced.

3) MPPT efficiency analysis: Table V summarizes the static and dynamic efficiencies according to the EN50530 test. As expected, a slight difference exists between the efficiency of both methods during static conditions, therefore, the methods have almost similar performance in static conditions. In dynamic conditions, Table V and Fig. 13 show the efficiency of the shortened version of the EN5530 test using P&O and the proposed method. It can be observed that the efficiency of the P&O method is different and depends mainly on the solar irradiance slopes. During the slow ramps, the P&O efficiency is almost similar to the proposed method because the P&O is able to handle the slow variation of solar irradiance. Whereas, when a rapid ramp takes place, the efficiency drops until 92.52% (Fig.13.(a)) and 94.15% (Fig.13.(b)) due to the inability of the P&O method to track correctly the MPP in such conditions. However, this limitation is eliminated by the proposed MPPT method, it results in an efficiency in a range between 99.67% and 99.60% from a low to medium rate of change of solar irradiance and between 99.72% and 99.70% from a medium to high rate of change of solar irradiance. This efficiency improvement demonstrates the ability of the proposed method to retrieve all the produced power regardless how fast or slow the solar irradiance changes.

TABLE V
STATIC AND DYNAMIC EFFICIENCIES OF THE P&O AND THE PROPOSED METHOD ISSUED FROM THE EXPERIMENTAL RESULTS

MPPT methods	Static efficiency		Dynamic efficiency	
	η_{EUR}	η_{CEC}	Slope: 50W/m²/s	Slope:100W/m²/s
P&O	99.59%	99.68%	92.52%	94.15%
Proposed method	99.64%	99.72%	99.60%	99.70%

V. CONCLUSION

The proposed MPPT in this work is i) a simple, and ii) efficient method in a way that drives the operating point towards the right tracking direction, even under fast varying atmospheric conditions. Experimental tests were performed to support the theoretical analysis of the proposed method according to the EN50530 standard. The presented results strongly confirm the effectiveness of the proposed method. In steady state conditions, the proposed method shows similar behavior to P&O method, however in dynamic conditions, it is able to handle the rapid variation, and track correctly the MPP which leads to an increased efficiency. The efficiency of P&O according to the shortened EN50530 test is 98.6%, whereas the proposed method reached 99.66%. These findings are compelling evidence that the proposed maximum point tracker is a simple, effective and promising, therefore, the proposal is envisaged to be employed in future industrial applications.

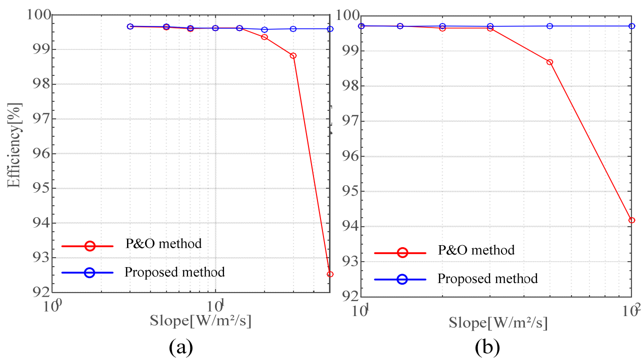

Fig. 13 The MPPT efficiency of both method during the shortened EN50530 test as a function of the solar irradiance slope. (a) from low to medium variation of irradiance range (b) from medium to high variation of irradiance

REFERENCES

[1] O. Lopez-Santos et al., "Analysis, Design, and Implementation of a Static Conductance-Based MPPT Method," *IEEE Trans. Power Electron*., vol. 34, no. 2, pp. 1960–1979, Feb. 2019.

[2] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, *Power Electronics and Control Techniques for Maximum Energy Harvesting in Photovoltaic Systems*. Boca Raton, FL, USA: CRD Press, 2013.

[3] R. Teodorescu, M. Liserre, P. Rodríguez, *Grid Converters for Photovoltaic and Wind Systems*. Chichester, U.K.: John Wiley & Sons,Ltd, 2011.

[4] S. L. Brunton, C. W. Rowley, S. R. Kulkarni, and C.Clarkson, "Maximum Power Point Tracking for Photovoltaic Optimization Using Ripple-Based Extremum Seeking Control," *IEEE Trans. Power Electron*. ,vol. 21, no. 6, pp. 2315–2322, 2013.

[5] L. V. Hartmann, "Combining Model-Based and Heuristic Techniques for Fast Tracking the Maximum-Power Point of Photovoltaic Systems," *IEEE Trans. Power Electron.*,vol. 28, no. 6, pp. 2875–2885, 2013.

[6] M. Aureliano *et al.*, "Evaluation of the Main MPPT Techniques for Photovoltaic Applications," *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 1156–1167, 2013.

[7] A. K. Abdelsalam, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "High-Performance Adaptive Perturb and Observe MPPT Technique for Photovoltaic-Based Microgrids," *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1010–1021, 2011.

[8] A. R. Reisi, M. H. Moradi, and S. Jamasb, "Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 433–443, 2013.

[9] M. Killi and S. Samanta, "Modified Perturb and Observe MPPT Algorithm for Drift Avoidance in Photovoltaic Systems," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5549–5559, 2015.

[10] A. Lashab, D. Sera, and J. M. Guerrero, "A Dual-Discrete Model Predictive Control-based MPPT for PV systems," *IEEE Trans. Power Electron.*, no. January, pp. 1–1, 2019.

[11] S. K. Kollimalla and M. K. Mishra, "Variable perturbation size adaptive P&O MPPT algorithm for sudden changes in irradiance," *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 718–728, 2014.

[12] G. Escobar, S. Pettersson, C. N. M. Ho, and R. Rico-Camacho, "Multisampling Maximum Power Point Tracker (MS-MPPT) to Compensate Irradiance and Temperature Changes," *IEEE Trans. Sustain. Energy*, vol. 8, no. 3, pp. 1096–1105, 2017.

[13] D. Sera, R. Teodorescu, J. Hantschel, and M. Knoll, "Optimized maximum power point tracker for fast-changing environmental conditions," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2629–2637, 2008.

[14] K. S. Tey and S. Mekhilef, "Modified incremental conductance MPPT algorithm to mitigate inaccurate responses under fast-changing solar irradiation level," *Sol. ENERGY*, vol. 101, pp. 333–342, 2014.

[15] N. Kumar, I. Hussain, B. Singh, and B. Ketan, "Self-Adaptive Incremental Conductance Algorithm for Swift and Ripple Free Maximum Power Harvesting from PV Array," *IEEE Trans. Ind. Informat.,* vol. 3203, no. c, pp. 1–10, 2017.

[16] D. Sera, L. Mathe, T. Kerekes, S. V. Spataru, and R. Teodorescu, "On the Perturb-and-Observe and Incremental Conductance MPPT Methods for PV Systems," *IEEE Journal of Photov*. vol. 3, no. 3, pp. 1070–1078, 2013.

[17] B. Subudhi and R. Pradhan, "A comparative study on maximum power point tracking techniques for photovoltaic power systems," *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 89–98, 2013.

[18] N. Karami, N. Moubayed, and R. Outbib, "General review and classification of different MPPT Techniques," *Renew. Sustain. Energy Rev.*, vol. 68, no. July 2016, pp. 1–18, 2017

[19] H. Abu-rub, S. Member, A. Iqbal, S. Member, and S. M. Ahmed, "Quasi-Z-Source Inverter-Based Photovoltaic Generation System With Maximum Power Tracking Control Using ANFIS," *IEEE Trans. Sustain. Energy*, vol.4, no.1, pp. 11–20, 2013.

[20] B. N. Alajmi, K. H. Ahmed, S. J. Finney, and B. W. Williams, "Fuzzy-Logic-Control Approach of a Modified Hill-Climbing Method for Maximum Power Point in Microgrid Standalone Photovoltaic System," *IEEE Trans. Power Electron*., vol. 26, no. 4, pp. 1022–1030, 2011.

[21] J. Rodriguez, P. Cortes, *Predictive control of power converters and electrical drives.* Chichester, U.K.: John Wiley & Sons,Ltd, 2012.

[22] A. Lashab, S. Member, D. Sera, and S. Member, "Discrete Model-Predictive-Control-Based Maximum Power Point Tracking for PV Systems : Overview and Evaluation," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 7273–7287, 2018.

[23] H. Häberlin, P. Schärf, "New procedure for Measuring Dynamic MPP Tracking Efficiency at Grid connected PV inverters", 24th European Photovoltaic Solar Energy Conf., Germany, Sep 2009, pp. 3631-3637.

[24] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "Control of single-stage single-phase PV inverter," *EPE J. (European Power Electron. Drives Journal)*, vol. 16, no. 3, pp. 20–26, 2006.

[25] H. Schmidt, B. Burger, U. Bussemas, and S. Elies, "How Fast Does an MPP Tracker Really Need To Be?," 24th European Photovoltaic Solar Energy Conference, Jan 2009,pp. 3273–3276.

[26] J. Ahmed and Z. Salam, "A Modified P and O Maximum Power Point Tracking Method with Reduced Steady-State Oscillation and Improved Tracking Efficiency," *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1506–1515, 2016.