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A Comparative Study of Flexible Power Point Tracking Algorithms in Photovoltaic Systems

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Abstract—The ever-increasing penetration of photovoltaic power plants (PVPPs) in the power system and the need for voltage control and frequency support services impose new requirements on PVPPs, extending the functionalities of existing maximum power point tracking (MPPT) algorithms. Accordingly, a considerable number of flexible power point tracking (FPPT) algorithms are introduced in the literature. The aim of such algorithms is to regulate the PV power to a specific value rather than continuously track the maximum power point. This power reference value is calculated based on the operation condition and grid requirements. This paper provides a short description of several available FPPT algorithms in the literature, and studies various features of each algorithm. The dynamic performance of the investigated algorithms is compared using experimental tests on a scaled-down prototype. The comparison reveals that the FPPT algorithms with direct calculation of the voltage reference, which corresponds to the required power reference, provide better performance in all aspects.

Index Terms – Active power control, constant power generation, flexible power point tracking, photovoltaic systems, power curtailment control, power reserve control.

I. INTRODUCTION

An evolution in the infrastructure associated with photovoltaic (PV) plants has occurred due to the increasing penetration of renewable energy systems, in particular, PV power plants (PVPPs). There has been a considerable boost in the installation of PV systems, as a result of advancements in PV technology, decline in the price of PV panels and increasing awareness of limited availability of conventional fossil-fuel-based energy resources as well as global warming concerns [1]. In order to confront potential challenging issues for the power system, grid codes and/or standards are continuously updated [2]–[8].

Frequency support regulations are one of new requirements of grid codes to maintain the stability and reliability of the power system under the high penetration of renewable energy resources. The frequency support requirement of four different countries is depicted in Fig. 1 [3]–[7]. In most of the grid codes, while the grid frequency is within the frequency control band (f_2 and f_3), a power reserve value of ΔP is considered between the extracted PV power and its maximum available power. This enables the PVPP to increase the output power to the maximum available power (P_{avai}), if the grid frequency drops below f_2 . For example, for 50-Hz systems,

Fig. 1. Frequency support regulations by international grid codes.

if the frequency is between 47 Hz and f_1 , the PV injects the maximum power P_{avai} to the grid. On the other hand, for frequencies larger than the upper limit of the frequency band f_3 , the PV power reduces based on the droop gain, given in the standard, which is exemplified in Fig. 1. When the grid frequency is larger than 52 Hz, the PV power reduces to zero and the PV system is disconnected from the grid. The values of f_1 , f_2 , ... are defined in various standards.

Based on the new grid codes and standards, the PVPPs should be able to inject a flexible amount of active and reactive power to the grid, depending on the grid conditions. The power limiting control (also referred as the constant power control) [9], [10], power reserve control [11], absolute active power control [12], reduced power control [13], delta power control [14] and power ramp-rate control [15], [16] requirements are some examples of these new regulations. These require a flexible and controlled active power extraction from PV panels. Accordingly, flexible power point tracking (FPPT) algorithms are implemented in PVPPs, instead of maximum power point tracking (MPPT) algorithms.

As depicted in Fig. 2, during the FPPT operation mode, the extracted power from the PV strings is adjusted to the power reference p_{fpp} , which is regulated by the grid operators. If the power reference p_{fpp} is smaller than the maximum available

Fig. 2. Maximum and flexible power point tracking in PVPPs (MPP - Maximum power point; FPP - Flexible power point).

power, the operation point of the PV string can be moved to the right- or left-side of the MPP (denoted as FPP_r and FPP_l , respectively), by implementing an FPPT algorithm. Moreover, if the power reference is larger than the available maximum power of the PV string (p_{mpp}), the FPPT algorithm moves the operation point to the MPP. Several FPPT algorithms are proposed in the literature. Some of these algorithms consider extra energy storage devices, capacitors, etc., to provide the required features [17]–[19]. However, the main focus of this paper is to review the algorithms, which can provide these features to PVPPs by changing the operation point, without adding any extra components.

In order to help researchers and engineers select the suitable FPPT algorithm for specific applications and identify the advantages/disadvantages of various FPPT algorithms, this paper provides an overview of the prior-art FPPT algorithms. The main contribution of this paper is to compare these algorithms in various aspects, e.g.: i) ability to track the MPP, ii) requirement of multi-mode transitions, iii) operation regions (right or left-side of the MPP), iv) dynamics, v) steady-state performance, vi) operation under environmental changes, and (vii) sample-based or instantaneous regulation of the power. The performance of these algorithms is also experimentally tested on a scaled-down 1-kVA two-stage PVPP and results are compared under various operating conditions.

The remainder of this paper is structured as follows: The overall control algorithm for a two-stage PVPPs is described in Section II. The details of the investigated FPPT algorithms are explained in Section III, while their performance is compared experimentally in Section IV. Finally, a comprehensive benchmarking between these FPPT algorithms is provided in Section V. Concluding remarks and future research perspectives are given in Section VI.

II. SYSTEM DESCRIPTION

The topology and overall control structure of a two-stage PVPP are illustrated in Fig. 3. It consists of a dc-dc converter to extract the power from the PV strings and a grid-connected inverter to transfer this power to the grid [20]. The controller of the inverter has the following blocks:

- Grid support: This control block provides low-voltage ride-through capability (LVRT), frequency support, power

Fig. 3. Topology and overall control structure of the two-stage PVPP system.

ramp rate control, etc. It calculates the active/reactive power reference (p_{fpp} and q_{ref}) for the inverter, according to the grid condition and grid requirements.

- Grid synchronization: It commonly includes a phase-locked-loop (PLL) to determine the grid voltage angle and synchronize the inverter current with the grid.
- DC-link voltage control: This controller adjusts the dc-link voltage v_{dc} to its reference value. It calculates the d-axis current reference i_{d-ref} of the inverter current, which corresponds to the injected active power to the grid. This controller eventually adjusts the inverter power to the extracted power of the dc-dc converter, by keeping the stored energy in the dc-link capacitor to be constant.
- Current control: Various current control strategies, like the proportional integral (PI) controller and proportional resonant (PR) controller can be implemented in this block in order to regulate the inverter current to its reference.

The following functionalities are implemented in the control of the dc-dc converter:

- FPPT control: This block calculates the PV voltage (v_{dc-ref}), related to the power reference, as illustrated in Fig. 2. It is the main focus of this paper and different algorithms are presented.
- PV voltage control: This block regulates the PV voltage to the voltage reference v_{pv-ref} , calculated by the FPPT/MPPT algorithm.

III. FLEXIBLE POWER POINT TRACKING ALGORITHMS

Various FPPT algorithms have been introduced in the literature. A short description of these algorithms is provided in this section.

Method 1 (m1): The FPPT is achieved using a multi-mode operation with the calculation of the PV voltage reference [21]–[23], as shown in Fig. 4(a). During the MPPT operation, in which $p_{pv} < p_{ref}$, the MPPT algorithm calculates the PV voltage reference v_{pv}^* , while the duty cycle is computed using a proportional controller k_{mpp} . During the power limit operation ($p_{pv} \geq p_{ref}$), the duty cycle of the

Fig. 4. Flexible power point tracking algorithms: (a) Method 1 ($m1$) - multi-mode operation with PV voltage control [21]–[23], (b) method 2 ($m2$) - PV power control with PV power-based delta-voltage control [24], (c) method 3 ($m3$) - proposed algorithm in [13], [14], [22], [25]–[27] with constant voltage-step values for MPPT and CPG, and (d) method 4 ($m4$) - proposed algorithm in [28] with general algorithm for both MPPT and FPPT operation modes.

dc-dc converter is calculated based on the error between the p_{pv} and p_{ref} . The transition between the operation modes is necessary, which increases the complexity of the design of the control parameters.

Method 2 ($m2$): This control method was proposed in [24], [29]–[31], where an extra amount of Δv_{pv} is added to the calculated voltage reference from the MPPT algorithm, during the power limit operation mode. The detail schematics of these algorithms are illustrated in Fig. 4(b). During the MPPT operation mode, the MPPT algorithm calculates the PV voltage reference, which is fed into the controller without adding Δv_{pv} . At the beginning of the power limit operation mode, the MPPT algorithm is disabled and the last calculated v_{mpp} is recorded. Accordingly, Δv_{pv} is computed based on the error between the PV power and its reference p_{fpp} .

Method 3 ($m3$): The method was introduced in [13], [14], [22], [25]–[27], which divides the operation mode into the MPPT and constant power generation (CPG) operation modes. During the MPPT operation, a conventional MPPT algorithm, e.g. the perturb and observe, incremental conductance, is implemented to calculate the PV voltage reference v_{mpp} , corresponding to the maximum power. During the CPG operation, a power control algorithm is implemented to calculate the voltage reference v_{fpp} corresponding to the PV power reference p_{fpp} . In order to achieve optimum operation in both modes, the voltage- and time-step values of the voltage reference calculation algorithm are selected as different

values, as depicted in Fig. 4(c). During the MPPT operation, $T_{step} = T_{step-mpp}$ and $V_{step} = V_{step-mpp}$, in which $T_{step-mpp}$ is relatively large (0.1 s to 1 s) and $V_{step-mpp}$ is relatively small, in order to obtain small power oscillations during the MPPT operation. On the other hand, $T_{step-cpg}$ is relatively small and $V_{step-cpg}$ is relatively large in order to obtain fast dynamics during the CPG operation.

Method 4 ($m4$): A general algorithm for the FPPT control in PVPPs was introduced in [28], as shown in Fig. 4(d). One general voltage reference calculation algorithm is implemented, which is able to calculate the voltage reference for both MPPT and FPPT operation modes. The main advantage of this algorithm, compared to the algorithm $m3$, is the use of a fixed time-step for all operation modes. This feature reduces the implementation complexity of the algorithm, in addition to a simpler design of the controller parameters. The use of a general algorithm for all operation modes eliminates the need for transition changes between the various operation modes of the controller. The voltage-step is calculated adaptively based on the operation mode of the PVPP, being *transient* or *steady-state*, identified according to the schematic shown in Fig. 4(d).

IV. EXPERIMENTAL EVALUATION

A scaled-down 1-kVA two-stage PVPP, shown in Fig. 3(b), has been implemented experimentally to compare the dynamic

Fig. 5. Experimental setup.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SYSTEM

Symbol	Parameter	Values
V_{dc}	DC-link voltage	250 V
V_g	Grid voltage (line-line)	110 V
P_{mpp}	PV maximum power*	1000 W
V_{mpp}	PV maximum power voltage	140 V
C_{pv}	PV capacitor	1.18 mF

* Irradiance = 1000 W/m² and Temperature = 25 °C.

and steady-state performance of the above-mentioned FPPT algorithms. The PV panel is simulated using a Chroma 62000H-S solar array simulator, while the grid is simulated using a Cinergia grid emulator. IMPERIX H-bridge modules are used to build the two-stage PVPP, and the controller is implemented using a BOOMBOX control platform from IMPERIX. The parameters of the experimental setup are provided in Table I.

The dynamic performance of various algorithms under a step change of the power reference from 500 W to 950 W is compared in Fig. 6. As it can be seen in Figs. 6(a) and (b), there is a step increase in the power reference p_{fpp} at $t = 0.04$ s. Observations in Fig. 6(b) indicate that both $m1$ and $m2$ adjust the power to its new reference value in less than 0.01 s, by adjusting the PV voltage. The FPPT operation in $m3$ and $m4$, depends on the calculation of the PV voltage reference. The execution time-step for the voltage reference calculation algorithm is set to 0.5 s, which requires longer time to adjust the PV power to its reference. Accordingly, Figs. 6(c) and (d) illustrate a longer period of time after the step-change in the power reference p_{fpp} . Algorithm $m3$ implements a constant voltage-step in all operation modes, which results in a slower dynamic compared to $m4$ with an adaptively calculated voltage-step. This adaptive voltage-step results in a faster dynamic, as evidenced in Fig. 6(c). It also leads to lower power oscillations in the steady-state compared to $m3$.

Fig. 6. Comparison of the performance of various FPPT algorithms under the step-change of the power reference: (a) PV power for Methods $m1$ and $m2$, (b) PV voltage for Methods $m1$ and $m2$, (c) PV power for Methods $m3$ and $m4$, and (d) PV voltage for Methods $m3$ and $m4$.

It should be noted that the dynamic performance of $m3$ and $m4$ can be improved by selecting a smaller execution time-step. However, because these algorithms are sample-based, they result in slower dynamics compared to the algorithms with instantaneous regulation of the power ($m1$ and $m2$). It is worthy mentioning that even the sample-based algorithms show slower dynamic performance, they result in other flexibility benefits for PVPPs, which will be discussed in the following section.

V. COMPARISON OF VARIOUS FPPT ALGORITHMS

This section provides a comprehensive comparison of the above-mentioned FPPT algorithms. Various features of the algorithms are investigated in Table II. The main demerits of each algorithm are also stated in the table.

The algorithms $m1$ and $m2$ require multi-mode transitions and large power oscillations occur during these operation mode

TABLE II
COMPARISON OF VARIOUS FPPT ALGORITHMS

Algorithm	<i>m1</i> - multi-mode operation with PV voltage control [21]–[23]	<i>m2</i> - PV power control with PV power-based delta-voltage control [24]	<i>m3</i> - FPPT with constant voltage-step [13], [14], [22], [25]–[27]	<i>m4</i> - General FPPT algorithm with adaptive voltage-step [28]
Ability to track MPP	Yes	No	Yes	Yes
Multi-mode transition	Yes	Yes	Yes	No
Operation region (right or left-side of MPP)	Right	Right	Both	Both
Dynamic response	Fast	Slow	Slow	Fast
Power oscillation in steady state	High	Low	High	Low
Operation under environmental changes	Yes	No	Yes	Yes
Sample-based or instantaneous regulation of the power	Instantaneous	Instantaneous	Sample-based	Sample-based
Main demerit	Large steady state power oscillations due to multi mode transitions	Not applicable for long period of FPPT operation	Slow dynamic response	Need of high computational complexity

transitions. The algorithm *m2* cannot be implemented for the FPPT operation for a long period of time. This algorithm freezes the operation of the MPPT algorithm during the FPPT operation and uses the last recorded MPP voltage during the FPPT operation. It assumes that the environmental conditions (irradiance and temperature) do not change during the FPPT operation, which makes it applicable only for a short period of the FPPT operation.

The main advantage of the FPPT algorithms with direct calculation of the voltage reference that correspond to p_{fpp} , is that the voltage and current controller of the dc-dc converter remains the same as any conventional control algorithm. Therefore, a re-design and tuning of the controller is not required to obtain the FPPT control. The only difference between the MPPT and FPPT operation is that instead of calculating v_{mpp} , shown in Fig. 2, v_{fpp} is calculated and fed into the voltage controller of the converter. Accordingly, the implementation of these algorithms requires less complexity. Another difference is that the algorithms with direct calculation of the voltage reference are sample-based, meaning that they change the voltage reference in every execution interval. This fact slows down the dynamic response of the system, compared to the algorithms with instantaneous regulation of the power (i.e., *m1* and *m2*).

The algorithm *m3* uses a constant voltage-step during the FPPT operation. In this case, the selection of a relatively large voltage-step results in high power oscillations during the steady state, while a small voltage-step on the other hand results in slow dynamics. This drawback is solved in the algorithm *m4*, which implements the adaptive voltage-step cal-

culation structure based on the operation point of the PV string and operation mode of the PVPP. This algorithm achieves fast dynamics in combination with low power oscillations during the steady state operation. Among all of the investigated algorithms, *m4* obtains a better performance in all the aspects. It has only the demerit of relatively high complexity of calculations, although it can be easily implemented on the available digital signal processors in the market.

VI. CONCLUSION AND FUTURE DIRECTIONS

An overview of several FPPT algorithms in the literature has been provided in this paper. A short description of the algorithms is provided, while their features are comprehensively compared. Experimental results are also illustrated to analyze the dynamic performance of these algorithms. Based on the results, the FPPT algorithms that directly calculate the PV voltage reference, corresponding to the PV power reference, demonstrate a better overall performance in various aspects. These algorithms do not necessitate multi-mode transitions between different operation modes, while they are flexible to move the operation point of the PV string to the right- or left-side of the MPP. Fast dynamic response and low power oscillations in steady state can also be achieved by adaptively calculating the voltage-step in these algorithms. Furthermore, they do not compel any change in the voltage control block of the PVPPs.

The following aspects can be regarded as future directions of this study:

- Investigating novel FPPT algorithms with the capability to operate under partial shading conditions, which is a practical problem in PVPPs.
- Estimation of the maximum available power during the FPPT operation to adjust the power reserve, without distorting the extracted power from the PV strings.

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