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A General Algorithm for Flexible Active Power Control of Photovoltaic Systems

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Abstract—The maximum power point tracking (*MPPT*) is generally implemented in grid-connected photovoltaic (PV) power plants to maximize the energy yield. However, as the penetration level increases, challenging issues such as overloading and overvoltage arise in PV applications. Accordingly, a constant power generation (*CPG*) operation, in which the PV output power is limited to a specific value, has been imposed by some grid regulators to alleviate the integration challenges. In that case, the combined operation of *MPPT* and *CPG* is required, which increases the complexity of the controller design. To generalize the two control objectives, a flexible active power control algorithm that combines both *MPPT* and *CPG* operating modes is proposed. The proposed algorithm can optimize the performance in both modes (i.e., *MPPT* and *CPG*). By adjusting the voltage-step between two consecutive operating points, fast dynamics and low-power oscillations can be obtained. The performance of the proposed strategy is evaluated through simulations and experiments under different irradiance and power reference profiles.

I. INTRODUCTION

Conventionally, the maximum power point tracking (*MPPT*) operation is required for grid-connected photovoltaic power plants (GCPVPPs) system. Various *MPPT* algorithms have been introduced in the literature [1]–[3] for photovoltaic (PV) systems. The key requirements of *MPPT* algorithms include: i) Computational efficiency, ii) speed of tracking the maximum power point, iii) operation under partial shading and iv) low power oscillations during steady-state. However, the active power from PV systems in the *MPPT* operation is dependent on the solar irradiance and ambient temperature. In other word, a flexible power control, which is required in various scenarios (e.g., overvoltage, low-voltage ride-through) is not achievable if *MPPT* is enabled. Therefore, a constant power generation (*CPG*) control, as illustrated in Fig. 1, can be adopted to enable more flexible power injection. This requirement is currently adopted in Germany, where the maximum feed-in power of the PV system is limited at 70% of the rated power [4].

Several algorithms are introduced in the literature to achieve *CPG* for single-stage GCPVPPs [5]–[7] with the focus on stability issues. In two-stage GCPVPPs, the *CPG* control is implemented by modifying the control of dc-dc converters [8]–[10]. These methods require controller state transitions in the case of operational mode changes, resulting in slow dynamics. An alternative *CPG* approach by modifying the voltage reference of the PV panel according to its power-

Fig. 1. Constant power generation from GCPVPPs.

voltage (P-V) characteristics has been investigated with two-stage GCPVPPs in [11]–[13]. Furthermore, a flexible *CPG* algorithm which can be implemented in both single- and two-stage GCPVPPs is introduced in [14], [15], offering a more generic control solution. During the *CPG* operation, the typical *MPPT* algorithm is replaced with the proposed algorithm to calculate the voltage reference based on the required power reference. As a result, no modification is required to control of the dc-dc converter. Nevertheless, this method still requires implementing two separate voltage reference calculation algorithms for the *CPG* and *MPPT* operation, which increases the computational complexity.

Motivated by the above, this paper proposes a flexible active power control algorithm, where the PV voltage reference is generalized for both *MPPT* and *CPG* operations. The proposed strategy is an adaptation of a perturb and observe (P&O) algorithm, based on the P-V characteristics, where two main calculation steps are introduced: voltage-step and voltage-reference calculation. The voltage-step between consecutive operating points is dynamically modified based on the operation mode (i.e., *MPPT* or *CPG*). In this way, the performance of the control algorithm can be optimized accordingly. For instance, the power oscillation should be minimized during steady-state operation (for both *MPPT* and *CPG* modes), in order to reduce power losses. To achieve this target, a small voltage-step is applied during *steady-state* operation. On the other hand, a large voltage-step is employed during *transient* conditions to ensure the tracking dynamics. Afterwards, the selected voltage-step is applied in the voltage-reference calculation in order to determine the reference PV

Fig. 2. Circuit configuration and overall control structure of a two-stage GCPVPP.

voltage in the next perturbation according to the operating mode. When a power perturbation is larger than the nominal power of the PV panel during the *CPG* operation, the performance is similar to the conventional P&O *MPPT* algorithm. In the case of *CPG* operation, a control algorithm similar to [15] is implemented for the voltage-reference calculation. However, with the proposed method, the *CPG* performance can be improved through adaptive voltage-step calculation. The performance of the proposed strategy is evaluated through simulations and experiments under various operating conditions (e.g., irradiance level, power reference level). The results have validated the effectiveness and flexibility of the proposed control scheme in terms of fast dynamics, small -steady-state oscillations, and seamless operation transitions.

The remaining of the paper is organized as following. A system description of the two-stage GCPVPP and its control algorithms are provided in Section II. The proposed general active power control algorithm is discussed in Section III. Simulation results on a 50-kW two-stage GCPVPP are presented in Section IV, while the experimental validation on a down-scale 1-kW prototype is demonstrated in Section V. Finally, concluding remarks are given in Section VI.

II. SYSTEM CONFIGURATION

The system configuration of the two-stage GCPVPP is illustrated in Fig. 2. This topology consists of two power converters. The dc-dc converter extracts the power from the PV string, while the dc-ac inverter injects the extracted power from PV strings to the grid. The two-stage configuration has been widely adopted in the residential/commercial PV systems (1-30 kW) [16]. In this study, a boost converter is used for the extraction of the power from the PV string. Based on the operation mode, imposed by an external controller, either the *MPPT* or *CPG* operation can be assigned to the boost converter controller. The voltage reference is calculated through a *MPPT* or *CPG* algorithm and it is regulated by the boost converter to achieve the required power reference (P_{ref}).

A full-bridge, two-level inverter is used to connect the dc-link to the grid. The amount of the injected current to the grid is calculated by regulating the dc-link voltage (v_{dc}) to be constant. A proportional resonant current controller is

Fig. 3. Proposed control strategy for both *MPPT* and *CPG* operation modes.

applied to regulate the inverter current [17]. A bipolar pulse width modulation (PWM) technique is employed considering leakage currents [18]. A phase-locked loop is implemented to synchronize the inverter output current (i_g) with the grid voltage (v_g). The amount of the stored energy can also be controlled to some extent by adjusting the dc-link voltage [19].

III. PROPOSED GENERAL ACTIVE POWER CONTROL

A comprehensive schematic of the proposed algorithm for the operation of GCPVPPs during both *MPPT* and *CPG* modes is depicted in Fig. 3. Namely, the algorithm consists of two main calculation steps: voltage-step selection and voltage-reference calculation, which are generalized for both *MPPT* and *CPG* operations.

Firstly, three variables including Δv , Δp and Δp^* are calculated, in which v_{new} and p_{new} are the PV panel voltage and power in the current time-step, respectively. v_{old} and p_{old} are the PV panel voltage and power in the previous time-step, respectively. P_{ref} is imposed by an external controller during *CPG* operation or given by the *MPPT* algorithm during *MPPT* operation. Subsequently, the voltage-step and voltage reference calculation algorithms are implemented, which are explained in the following subsections. Notably, the proposed algorithm in this paper does not require any modification in the controller of the dc-dc converter or the grid-connected inverter.

A. Proposed Voltage-Step Calculation Algorithm

During *transients* (e.g., irradiance change), a fast dynamic response is required to ensure high tracking performance. On the other hand, minimum power oscillations are demanded during *steady-state* (i.e., constant irradiance condition) to minimize power losses. In this sense, variable voltage-step (V_{step}) values need to be applied, as illustrated in Fig. 4.

The proposed algorithm to select V_{step} is presented in Fig. 4. Depending on the operating requirements (e.g., requested by the system operator, grid regulation), the operating mode of the GCPVPP can be selected as either *MPPT* or *CPG*. For the *MPPT* operation, a nominal voltage-step is applied. Notably, the variable voltage-step can be applied during the

Fig. 4. Schematic of the proposed voltage-step calculation algorithm.

MPPT operation, but it increases the algorithm complexity. Notice that voltages of the maximum power points for various irradiance values are close to each other. Therefore, variable voltage-step may not be required during the *MPPT* operation in most cases.

In contrast, the operating voltage of the PV array during *CPG* operation may vary over wide range, depending on the operating conditions (e.g., *transient* or *steady-state*). In that case, different voltage-step values should be applied during *transient* and *steady-state* operation to improve the control performance. Thus, the operation condition needs to be detected first. This can be achieved by considering the change in the power reference, as depicted in Fig. 4. An operation boundary (Δp_{th}) is defined to distinguish the two operation conditions, as:

$$\begin{cases} |\Delta p^*| \leq \Delta p_{th} & \text{Steady-state} \\ |\Delta p^*| > \Delta p_{th} & \text{Transient} \end{cases} \quad (1)$$

This determination can be performed easily in the controller, as depicted in Fig. 4. However, the implementation of this simple comparison can result in a wrong selection of the operation condition, while the PV system operates at the maximum power point (*MPP*). This can happen under two circumstances:

- The controller is set to extract the maximum power from the PV system, instead of operation as *CPG*. In this case, the controller sets the power reference to a value larger than the nominal maximum power from the PV panel.
- Due to partial shading or other reasons, the maximum available power (p_{mpp}) from the PV system is smaller than the power reference during *CPG* operation.

In order to differentiate the above conditions, the proposed algorithm calculates $|\Delta p / \Delta v|$, which is the slope of the power-voltage (P-V) curve of the PV panel. Close to *MPP*, $|\Delta p / \Delta v|$ is close to zero. Therefore, this value is compared to a

Fig. 5. Schematic of the proposed voltage reference calculation algorithm at: (a) right-side of *MPP* and (b) left-side of *MPP*.

threshold (Thr) to identify the current operation point. If it is larger than Thr , the current operation point of the PV panel is not close to the *MPP* and a large voltage-step ($V_{step-cpg-tr}$) is selected to achieve fast dynamics.

B. Voltage Reference Calculation Algorithm

The schematic of the implemented algorithm for the calculation of the voltage reference during the *CPG* operation, with the movement to the left- or right-side of the *MPP* is presented in Figs. 5(a) and (b), respectively. This offers a more generalized control algorithm during both *CPG* and *MPPT* operation modes. The operation principles of the implemented algorithms for moving the operation point to the right- or left-side of *MPP* are presented in the following.

Proposed voltage reference calculation algorithm in the right-side of the MPP: At the beginning of the *CPG* operation, the current operation point of the PV string is determined by calculating $\Delta p / \Delta v$. If the current operating point is in the left-side of *MPP*, the voltage reference in the next execution step is increased as $V_{ref} = V_{ref-old} + V_{step}$. After ensuring that the operation point of the PV strings is in the right-side of *MPP*, the proposed algorithm determines the voltage reference, related to P_{ref} by calculating Δp^* . A positive Δp^* shows that the output power is larger than P_{ref} , and hence V_{ref} should be increased in the next time-step to reduce the output power. Similarly, for a negative Δp^* , the voltage reference of the next execution step should be decreased ($V_{ref} = V_{ref-old} - V_{step}$) in order to increase the output power.

TABLE I
PARAMETERS OF THE TWO-STAGE GRID-CONNECTED PV SYSTEM.

Parameter	Symbol	Simulation	Experiment
PV panel maximum power*	p_{mpp}	50 kW	1 kW
PV panel maximum power-point voltage*	v_{mpp}	420 V	137 V
PV panel maximum power-point current*	i_{mpp}	118 A	7.5 A
PV panel filling factor	FF	0.77	0.77
dc-bus voltage	v_{dc}	750 V	250 V
PV-side capacitor	C_{pv}	1000 μ F	200 μ F
dc-link capacitor	C_{dc}	3000 μ F	1100 μ F
dc-dc converter switching frequency *	f_{sw}	50 kHz	50 kHz
Calculation time-step	T_{step}	0.1 s	0.2 s
MPPT voltage-step	$V_{step-mppt}$	6 V	0.5 V
CPG transient voltage-step *	$V_{step-tr}$	Right: 8 V Left: 20 V	Right: 2 V Left: 4 V
CPG steady-state voltage-step *	$V_{step-st}$	Right: 1.5 V Left: 3 V	Right: 0.5 V Left: 1 V
Threshold power	Δp_{th}	4 kW	80 W
Threshold $\Delta p/\Delta v$	$Thr.$	50 W/V	4 W/V

* $Irr.$ = 1000 W/m² and $Temp.$ = 25°C.

Proposed voltage reference calculation algorithm in the left-side of the MPP: Similar to the mentioned algorithm, after determining the current operation point of the PV string by calculating $\Delta p/\Delta v$, if the operation point is in the right-side of the *MPP*, it is moved to the left-side of the *MPP* by decreasing the voltage reference in the next calculation step. Subsequently, the voltage reference is calculated by comparing the output power of the PV panel and P_{ref} and if Δp^* is positive/negative, the voltage reference is decreased/increased, as depicted in Fig. 5(b). The detailed implementation of these methods is presented in [15].

IV. SIMULATION RESULTS

A 50-kVA two-stage GCPVPP is modeled and developed using Matlab/Simulink© and the PLECS toolbox. The PV panels are modeled using SHARP NU-U235F1 panels. Two case scenarios with moving the operation point to the right or left-side of the *MPP* are investigated.

Case I: The performance of the proposed active power control strategy with the movement of the operation point to the left-side of the *MPP* is investigated in this case and the results are presented in Fig. 6. Before $t = 3$ s, the operation mode is *MPPT* and $Irr = 1000$ W/m². Accordingly, the proposed algorithm calculates the voltage reference as 420 V and the PV power is 50 kW. At $t = 3$ s, the operation mode changes to *CPG* with $P_{ref} = 35$ kW. Consequently, V_{step} changes to 20 V, which is the voltage-step during transients of the *CPG* operation. The voltage reference decreases to 280 V, which is point B in Fig. 6(d). Notice that the transient time

Fig. 6. Simulation results. *Case I:* CPG of the PV module with the movement of the voltage reference to the left-side of the *MPP*: (a) Voltage reference (v_{ref}), (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

is very short due to the use of the large voltage-step. After the PV power reaching to its reference value at $t = 3.95$ s, the operation mode changes to *steady-state* and the voltage-step changes to 3 V, which is $V_{step-st}$ for the operation in the left-side of the *MPP*.

A step decrease occurs in the irradiance at $t = 6$ s from $Irr = 1000$ W/m² to $Irr = 500$ W/m². In that case, the available PV power from the PV array is reduced to 33 kW, while P_{ref} is kept at 50 kW. Consequently, the proposed active power generation algorithm moves the operation point to C, which is the *MPP* of the PV panel under this irradiance. This shows the flexibility of the proposed algorithm, which is capable of the MPPT operation when P_{ref} is larger than the maximum available power.

The irradiance increases to $Irr = 750$ W/m² at $t = 9$ s. Therefore, the proposed algorithm reduces the voltage refer-

Fig. 7. Simulation results. *Case II*: CPG of the PV module with the movement of the voltage reference to the right-side of the MPP: (a) Voltage reference (v_{ref}), (b) PV voltage (v_{pv}), (c) extracted power from the PV module (p_{pv}) and (d) operation point of the PV module.

ence to move the operation point to the left-side of the *MPP*, as depicted in Fig. 6(d). Finally, the power reference decreases to 25 kW, while the proposed algorithm reduces V_{ref} to 230 V to regulate the power to its reference value.

Case II: In this case study, similar operation modes are implemented. However the movement of the operation point to the right-side of the *MPP* is considered and the results are depicted in Fig. 7. It can be seen that the proposed algorithm regulates the PV power to its reference under all operation conditions.

The voltage-step for the operation in the right-side of the *MPP* is selected to be smaller value compared to its value in the left-side of the *MPP*, because: i) The power oscillation during the *steady-state* operation in the right-side of *MPP* is larger, because the slope of the P-V curve is larger in this operation area and ii) The voltage difference between two

Fig. 8. Experimental verification. (a) Setup of the experiment and (b) schematic diagram of the dc-dc converter test system.

operation points, related to two different power references, is smaller in the right-side of the *MPP*. Therefore, the dynamic performance in both sides of *MPP* is similar in the proposed algorithm.

V. EXPERIMENTAL EVALUATION

The operation and performance of the proposed algorithm are demonstrated experimentally using a dc-dc boost converter setup (Fig. 8(a)) based on the CREE C2M0080120D SiC Power MOSFET. The complete parameters of the experimental setup are given in Table I and the circuit diagram of the experimental setup is shown in Fig. 8(b). The PV side is emulated using an ETS600/8 Terra SAS photovoltaic simulator. The dc-side voltage is regulated with a Sorensen SGI 400-38 dc power supply in parallel with a resistive load as in practical applications it is controlled by the inverter-side dc-voltage control.

The transient performance of the proposed algorithm in regulating the output power of the PV module to the required power reference is investigated and the results are depicted in Fig. 9. This test case demonstrates the typical operation of the proposed algorithm in the case of a network transient event (e.g. a voltage sag) with the aim to reduce the extracted power from the PV side to a constant value in order to accommodate the reactive power injection required from the inverter.

Under steady-state, the converter operates in the *MPPT* mode, and the maximum available power (1 kW under 1000 W/m^2) is extracted from the PV panels. The PV voltage is regulated to 138 V, the inverter dc-side voltage is equal to

Fig. 9. Experimental results (transient performance of the proposed algorithm): (a) PV panel voltage, current and power, and dc-link voltage, (b) voltage reference and dc/dc converter duty cycle, and (c) operation point of the PV panel.

$v_{dc} = 250$ V, with a duty cycle of approximately 0.45, and the PV panel operates at point A.

At $t = 0.1$ s, the operation mode changes from the *MPPT* to *CPG* mode for a duration of 0.2 s. Between $t = 0.1$ s and $t = 0.2$ s, Δp^* is larger than Δp_{th} , V_{step} is set to $V_{step-cpg-tr}$, as depicted in Fig. 9. The calculated reference voltage by the proposed algorithm during this *CPG* operation mode is 160 V in order to operate the PV panel at point B. Accordingly, p_{pv} decreases to the required power reference from 1 kW to 0.4 kW in less than 0.13 s. This result shows the fast performance of the proposed algorithm. The PV panel current and duty cycle of the dc/dc converter are also depicted in Fig. 9, where both of them are reduced during the *CPG* mode.

In order to achieve fast recovery to the *MPPT* operation, the voltage-step does not change instantaneously and is kept at $V_{step-cpg-tr}$, for a predetermined amount of time (T_d). The large voltage-step of the proposed voltage reference calculation

algorithm, during this time, helps the *MPPT* algorithm quickly recover to v_{mpp} . The length of T_d can be adjusted according to the *MPPT* algorithm. Subsequently, the voltage-step of the controller is set back to $V_{step-mppt}$ and the converter returns to the *MPPT* mode.

VI. CONCLUSION

A general algorithm to calculate the voltage reference of PV panels, which allows the combination of maximum power point tracking and constant power generation in PV systems, has been introduced in this paper. By modifying of the voltage-step, the algorithm is able to achieve similar performance compared with the conventional P&O algorithm in extracting the maximum power from the PV panel. Furthermore, small power oscillations and fast dynamics have been obtained through the proposed voltage-step selection algorithm. Simulation and experimental results have verified the performance of the proposed algorithm under various operation conditions.

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