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Benchmarking of Constant Power Generation Strategies for Single-Phase Grid-Connected Photovoltaic Systems

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***Abstract*—With a still increase of grid-connected Photovoltaic (PV) systems, challenges have been imposed on the grid due to the continuous injection of a large amount of fluctuating PV power, like overloading the grid infrastructure (e.g., transformers) during peak power production periods. Hence, advanced active power control methods are required. As a cost-effective solution to avoid overloading, a Constant Power Generation (CPG) control scheme by limiting the feed-in power has been introduced into the currently active grid regulations. In order to achieve a CPG operation, this paper presents three CPG strategies based on: 1) a power control method (P-CPG), 2) a current limit method (I-CPG) and 3) the Perturb and Observe algorithm (P&O-CPG). However, the operational mode changes (e.g., from the maximum power point tracking to a CPG operation) will affect the entire system performance. Thus, a benchmarking of the presented CPG strategies is also conducted on a 3-kW single-phase grid-connected PV system. Comparisons reveal that either the P-CPG or I-CPG strategies can achieve fast dynamics and satisfactory steady-state performance. In contrast, the P&O-CPG algorithm is the most suitable solution in terms of high robustness, but it presents poor dynamic performance.**

***Index Terms*—Active power control, constant power control, maximum power point tracking, PV systems, power converters.**

I. Introduction

Photovoltaic (PV) systems have a high growth rate during the last several years, and will play an even more significant role in the future mixed power grid [1]–[3]. A majority of PV system is connected to the distribution grid (i.e., mainly single-phase systems) [2] where a Maximum Power Point Tracking (MPPT) is currently mandatory in most active grid codes, and also to ensure the maximum energy yield from the solar power [4]. At a high penetration level of PV systems in the near future, the grid may face a challenge of overloading during peak power generation periods through a day if the power capacity of the grid remains the same [5]–[7]. For instance, it was reported by BBC that parts of the Northern Ireland's grid were overloaded by the increased number of grid-connected PV systems in a sunny and clear day with strong solar irradiance [8]. In order to enable more PV installations and address such issues, the control algorithms have to be feasible to flexibly regulate the active power generated by PV systems [4], [9]–[12]. For instance, limiting the feed-in power of PV systems to a certain level has been found as an effective approach to overcome overloading [10], and thus it is currently required in Germany through the grid codes [13], where it is stated that newly installed PV systems with a rated power below 30 kWp have to be able to limit its maximum feed-in power (i.e., 70% of the rated power) unless it can be remotely controlled. In fact, this active power control strategy corresponds to an absolute power constraint defined in the Danish grid code [14], and it is also referred to as a Constant Power Generation (CPG) control in the prior-art work [15].

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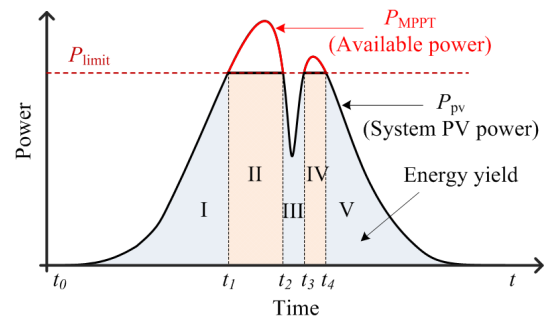

Fig. 1. Constant Power Generation (CPG) concept for PV systems: 1) MPPT mode during I, III, V, and 2) CPG mode during II, IV [15].

Actually, there are several methods to limit the feed-in power of the PV system in order to achieve a constant power production (e.g., integrating energy storage systems, installing dump load) [16]. However, the most intuitive and cost-effective way to achieve the CPG control is through the modification of the MPPT algorithm at the PV inverter level (also called power curtailment), and will be considered in this paper [17]. In this approach, the PV system continues operating in the MPPT mode with injection of the maximum power as long as the available PV power P_{MPPT} is below the set-point P_{limit}. However, when the available power reaches the level of P_{limit}, the PV system will inject a constant active power, i.e., $P_{\text{pv}} = P_{\text{limit}}$. The operational principle of the CPG scheme can be illustrated in Fig. 1 and summarized as:

$$P_{\text{pv}} = \begin{cases} P_{\text{MPPT}}, & \text{when} \quad P_{\text{MPPT}} \leq P_{\text{limit}} \\ P_{\text{limit}}, & \text{when} \quad P_{\text{MPPT}} > P_{\text{limit}} \end{cases} \tag{1}$$

where P_{pv} is the PV output power, P_{MPPT} is the maximum available power (according to the MPPT operation), and P_{limit}

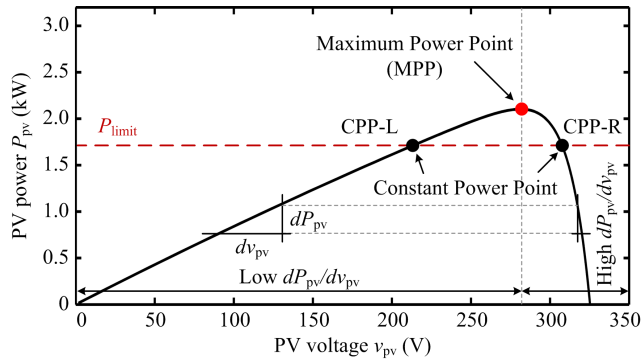

Fig. 2. Possible operating points of the PV system in Power-Voltage curve of the PV arrays during the CPG operation (i.e., Constant Power Point) at a certain level of power limit P_{limit} and irradiance.

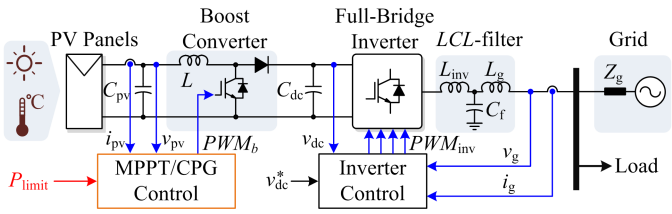

Fig. 3. Hardware schematics and overall control structure of a two-stage single-phase grid-connected PV system.

is the power limit, which is the set-point. The constant power production can be achieved by regulating the PV output power at the operating point below the Maximum Power Point (MPP), as it is shown in Fig. 2, and this operating point is called the Constant Power Point (CPP) in this paper [18].

In the prior-art work, several CPG strategies for PV systems have been introduced. In fact, more methods have also been proposed for other applications (e.g., frequency regulation, low-voltage ride through), but they can also be applied to achieve the CPG control as well. Accordingly, the CPG strategies presented in literature can be generally classified into three different approaches. In [15], [19]–[22], the CPG control is realized by directly regulating the PV power to be constant through the closed-loop power control. This can be implemented either at the dc-dc stage [15], [19], [22], where the boost converter is controlled directly, or at the dc-ac stage [20], [21], where a constant power reference P_{limit} is applied to the PQ controller of the PV inverter. Another way to limit the power generated from the PV systems is by controlling the PV output current i_{pv}, as it is discussed in [23] and [24]. This approach is based on the characteristic of the PV arrays where the PV output current i_{pv} is strongly dependent on the solar irradiance level, while the PV output voltage v_{pv} varies only in a small range during irradiance change. Thus, limiting the PV output current i_{pv} can effectively limit the PV output power P_{pv}. Alternatively, the CPG operation can also be realized by using the Perturb and Observe (P&O) algorithm, as it is proposed in [25]–[28]. In this method, the PV output voltage v_{pv} is continuously perturbed away from the MPP during the CPG operation mode, in order to reduce the PV output power according to the set-point (i.e., $P_{\text{pv}} = P_{\text{limit}}$).

TABLE I
PARAMETERS OF THE TWO-STAGE SINGLE-PHASE PV SYSTEM (FIG. 3).

PV rated power	3 kW
Boost converter inductor	L = 1.8 mH
PV-side capacitor	C_{pv} = 1000 μF
DC-link capacitor	C_{dc} = 1100 μF
LCL-filter	L_{inv} = 4.8 mH, L_{g} = 2 mH, C_f = 4.3 μF
Switching frequency	Boost converter: f_b = 16 kHz, Full-Bridge inverter: f_{inv} = 8 kHz
DC-link voltage	v_{dc}^* = 450 V
Grid nominal voltage (RMS)	V_g = 230 V
Grid nominal frequency	ω_0 = $2\pi\times50$ rad/s

Nevertheless, the performance of the three CPG approaches have not yet been compared. Thus, it is difficult to justify which method is suitable to be implemented in industry and applied in the future grid codes. Besides, most of the literatures only discuss the performance of the CPG strategy during steady-state (e.g., during a constant irradiance condition). In fact, depending on the mission profiles of the PV system (e.g., irradiance and temperature conditions), the operation mode transition between the MPPT and CPG can challenge the system performance, especially during a fluctuating irradiance condition (e.g., in a cloudy day). This will affect the system performance in terms of dynamics, accuracy, and stability of the CPG strategy, which have not yet been investigated so far.

In the light of the above issues, this paper first discusses about three different CPG strategies applied to two-stage single-phase PV systems. Then, the performance of the CPG strategies under both dynamic and steady-state conditions are benchmarked experimentally on a 3-kW two-stage single-phase grid-connected PV system, where real-field mission profiles are taken into consideration. Finally, conclusions are drawn from the comparison in § V.

II. Control Structure of Two-stage Single-Phase Grid-Connected PV Systems

A. System Configuration

In most single-phase PV systems (e.g., rated power of 1 - 30 kW), a two-stage configuration is widely used [29], [30]. The system configuration and its control structure are shown in Fig. 3, where the system parameters are given in Table I. The PV arrays are connected to a boost converter, allowing a wide-range operation during both MPPT and CPG operations [31]. In other words, with the use of the two-stage configuration, the PV system can operate at a lower PV voltage v_{pv} (e.g., at the left side of the MPP in the case of the CPG operation), since the PV output voltage v_{pv} can be stepped up by the boost converter to match the required dc-link voltage (e.g., 450 V) for the PV inverter [29]. This may not be possible in the single-stage configuration, where the PV output voltage v_{pv} is directly fed to the PV inverter (i.e., $v_{\text{pv}} = v_{\text{dc}}$ with v_{dc} being the dc-link voltage). Practically, the dc-link voltage v_{dc} is required to be higher than the peak grid voltage level (e.g., 325 V) to ensure the power delivery [32].

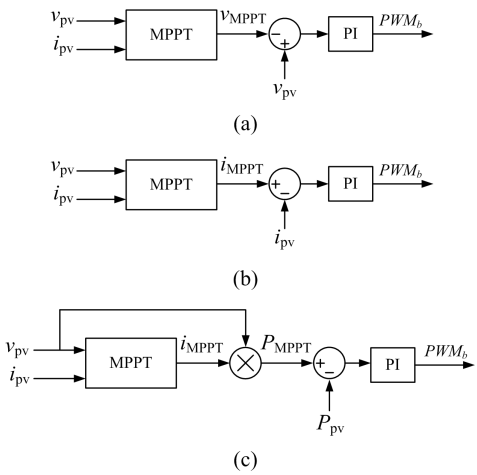

Fig. 4. Implementation of different MPPT controllers: (a) PV output voltage, (b) PV output current, and (c) PV output power, where PI represents a proportional-integral controller.

In the boost converter stage, either the MPPT or CPG control can be implemented in order to control the power extraction from the PV arrays. Then, the extracted power is delivered to the ac grid through the control of the full-bridge inverter. In this case, the control of the full-bridge inverter keeps the dc-link voltage to be constant through the control of the injected grid current [33].

B. Boost Converter Controller

As aforementioned, the boost converter plays a major role to control the power extraction from the PV arrays. Therefore, it is important to discuss about the possible control structures for the boost converter, where the CPG strategies will be implemented. Usually, the MPPT algorithm (i.e., the P&O MPPT) is implemented in the boost converter. For example, the P&O MPPT algorithm can give either the reference PV voltage v_{MPPT} or current i_{MPPT} to control the boost converter. Thus, the MPPT is usually achieved by regulating either the PV output voltage v_{pv} or current i_{pv} according to the reference from the MPPT algorithm, as it is shown in Figs. 4(a) and (b). Alternatively, it is possible to achieve the MPPT through the control of the PV output power P_{pv}. In this case, the reference PV current from the MPPT algorithm i_{MPPT} is multiplied by the measured PV voltage v_{pv} in order to obtained the reference PV power P_{MPPT}, as it is shown in Fig. 4(c). In this way, the PV power P_{pv} is controlled directly at any time, making it possible and flexible to be modified according to the power set-point (e.g., to realize the CPG operation). However, it should be mentioned that the variations in the PV voltage v_{pv} (e.g., due to the noise from measurements) can propagate to the reference P_{MPPT} through the direct multiplication, and thereby decrease the tracking accuracy of the MPPT operation. Nevertheless, the tracking errors are with permissible limits, which will be experimentally verified in § IV.

It is noteworthy to mention that tracking the MPP by controlling the PV current i_{pv} (i.e., Fig. 4(b)) is of less robustness [34]. This is due to the very steep slope (i.e., large $dP_{\text{pv}}/di_{\text{pv}}$) on the right side of the MPP in the power-current ($P-I$) curve of the PV arrays, as it is shown in Fig. 5. The operating point of the PV system may go into the short-circuit condition under a sudden decrease of the irradiance condition (if the MPPT algorithm cannot track fast enough, e.g., the PV system still operating at the same PV output current i_{pv}), when the PV output current is controlled [34]. This can be illustrated by the A→B trajectory in Fig. 5 when the irradiance level suddenly drops from 1000 W/m^2 to 700 W/m^2. This stability issue will be observed in a CPG control scheme which is based on the control structure in Fig. 4(b).

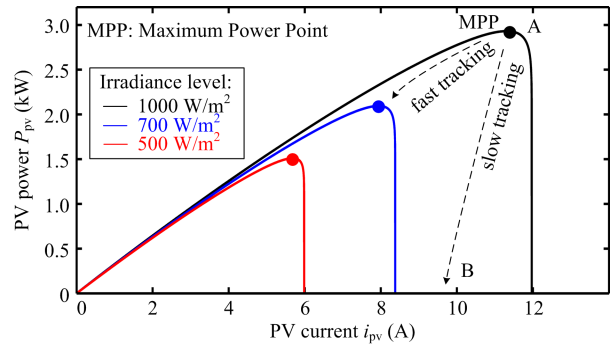

Fig. 5. Stability issues of the MPPT controller based on the PV output current due to the high slope ($dP_{\text{pv}}/di_{\text{pv}}$) at the right side of the MPP [34].

III. Constant Power Generation Strategies

Basically, the CPG strategy needs to regulate the operating point of the PV system at the CPPs in order to achieve a constant power production. According to the $P-V$ characteristic curve of the PV arrays shown in Fig. 2, there are two possible operating points – CPP-L and CPP-R for the CPG mode at a certain power level (i.e., P_{limit}) and a certain irradiance level. However, the CPPs continuously change (i.e., different PV voltage and PV current) under a changing irradiance condition, according to the $P-V$ curve of the PV arrays. Thus, the CPG strategy has to be able to follow the change in the $P-V$ curve, and track the CPP in the case of the CPG operation. Generally, the demands for the CPG control schemes are

- In the steady-state CPG operation, the CPG strategies should keep the PV systems operating at one of the CPPs with minimum deviations, in order to minimize the power losses in the steady-state.
- Under a changing irradiance condition (e.g., in a cloudy day), the CPG control scheme should be able to track either the MPP or the CPP, depending on the operating mode, and at the same time ensure a stable transition.

Accordingly, three previously mentioned CPG strategies are adapted to two-stage single-phase PV systems, and are discussed in the following based on: 1) a power control method (P-CPG), 2) a current limit method (I-CPG), and 3) the Perturb and Observe algorithm (P&O-CPG), where the above demands are taken as the benchmarking criteria.

A. CPG based on a Power Control Method (P-CPG)

Limiting the PV output power through the closed-loop power control is one of the most commonly used solutions

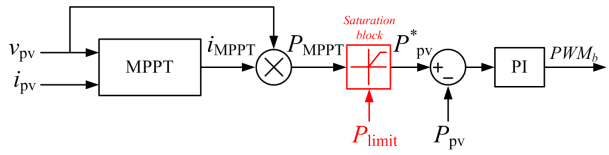

Fig. 6. Control structure of the Constant Power Generation (CPG) scheme based on a power control (P-CPG).

to achieve the CPG control in the previous work [15], [19]. In order to realize this control method in the two-stage single-phase PV system, the boost converter needs to directly control the PV output power during operation. As mentioned previously, it is possible to directly control the PV output power P_{pv} during the MPPT operating mode by employing the control scheme in Fig. 4(c), where the reference PV power in the MPPT mode P_{MPPT} is obtained by multiplying the reference current i_{MPPT} from the MPPT algorithm with the PV voltage v_{pv}. Regarding the CPG operation, a saturation block is added to the control scheme in Fig. 4(c) in order to limit the reference PV power P^*_{pv} to a certain power level P_{limit}, as it is shown in Fig. 6. Namely, when the reference PV power from the MPPT algorithm P_{MPPT} reaches the level of power limit P_{limit}, the saturation block will keep the power reference to be constant, i.e., $P^*_{pv} = P_{limit}$, and the PV system enters into the CPG mode. Otherwise, if the the reference PV power from the MPPT algorithm P_{MPPT} is less than the power limit P_{limit}, the saturation block will not be activated, and the PV system will operate in the MPPT mode with a maximum power injection (i.e., $P^*_{pv} = P_{MPPT}$), which is equivalent to the MPPT controller in Fig. 4(c). The operational principle can be further summarized as:

$$P^*_{pv} = \begin{cases} P_{MPPT}, & \text{when} \quad P_{MPPT} \leq P_{limit} \\ P_{limit}, & \text{when} \quad P_{MPPT} > P_{limit} \end{cases} \tag{2}$$

where P_{MPPT} is the maximum available power (according to the MPPT operation), and P_{limit} is the power limit, as defined previously.

B. CPG based on a Current Limit Method (I-CPG)

Another way to control the PV output power is through the control of the PV output current i_{pv} as it is discussed in [23], [24]. This is due to the fact that the PV voltage v_{pv} only varies in a small range during the irradiance change in the operating region on right side of the MPP (at the CPP-R), as it is shown in Fig. 7. Therefore, the PV output power P_{pv} can effectively be controlled through the PV output current i_{pv} in this region. From the control scheme in Fig. 4(b), it is possible to achieve a CPG operation by limiting the reference current from the MPPT algorithm i_{MPPT} according to $i_{limit} = P_{limit}/v_{pv}$ when calculating the reference PV output current i^*_{pv}. The control structure of the I-CPG method is shown in Fig. 8, and the power limit P_{limit} corresponds to the rectangular area under the CPP-R in Fig. 7.

According to the CPG concept in (1), the performance of the controller during the MPPT operation should not be

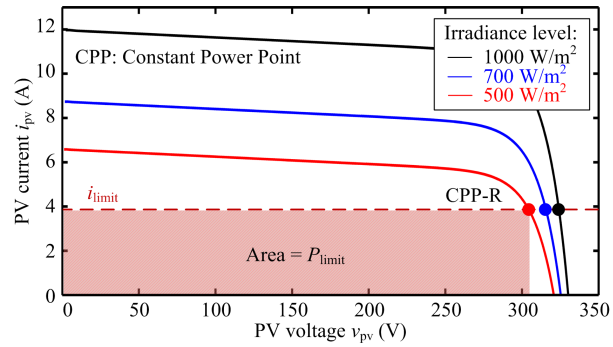

Fig. 7. Operational principle of the Constant Power Generation (CPG) scheme based on a current limit (I-CPG).

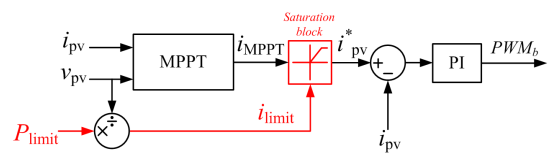

Fig. 8. Control structure of the Constant Power Generation (CPG) scheme based on a current limit (I-CPG).

diminished by the current limit. This can be ensured when considering

$$\frac{P_{MPPT}}{v_{pv}} \leq \frac{P_{limit}}{v_{pv}}$$

and thus,

$$i_{MPPT} \leq i_{limit}$$

where it can be seen that the current limit will not be activated as long as $P_{MPPT} \leq P_{limit}$, and the I-CPG method in the MPPT mode is simply equivalent to the MPPT controller in Fig. 4(b).

C. CPG based on the P&O Algorithm (P&O-CPG)

A CPG operation can also be realized by means of a Perturb and Observe (P&O) algorithm [25]–[28]. This method is based on the MPPT control structure in Fig. 4(a), where the PV voltage v_{pv} is controlled. In this approach, the modification is done at the control algorithm when determining the reference PV voltage v^*_{pv}. More precisely, during the MPPT operation, the reference PV voltage v^*_{pv} is set from the MPPT algorithm (i.e., P&O MPPT). However, in the case of the CPG operation, the PV voltage v_{pv} is continuously perturbed towards one CPP, i.e., $P_{pv} = P_{limit}$, as illustrated in Fig. 9. After a number of iterations, the operating point will be reached and oscillate around the corresponding CPP. Notably, the two-stage PV system with the P&O-CPG control can operate at either the CPP-L or the CPP-R, depending on the perturbation direction of the algorithm. However, the power oscillation in the steady-state is larger at the CPP-R compared to that at the CPP-L due to the high slope of the $P-V$ curve on the right side of the MPP (i.e., large dP_{pv}/dv_{pv}). This large power oscillation will decrease the tracking accuracy, and increase the energy losses as well as the power fluctuations in the steady-state, which should be avoided. On the other hand, the operating

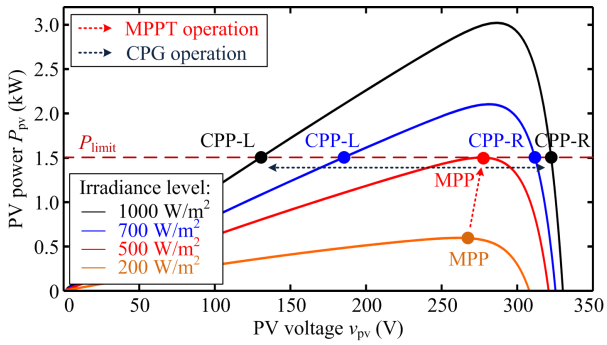

Fig. 9. Operational principle of the Constant Power Generation (CPG) scheme based on the P&O algorithm (P&O-CPG).

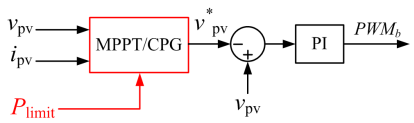

Fig. 10. Control structure of the Constant Power Generation (CPG) scheme based on the P&O algorithm (P&O-CPG).

region at the CPP-L requires a higher conversion ratio (i.e., v_{dc}/v_{pv}) which may affect the boost converter efficiency [35]. The control structure of the algorithm is shown in Fig. 10, where the reference PV voltage v^*_{pv} can be expressed as:

$$v^*_{pv} = \begin{cases} v_{MPPT}, & \text{when} \quad P_{pv} \leq P_{limit} \\ v_{pv} - v_{step}, & \text{when} \quad P_{pv} > P_{limit} \end{cases} \tag{3}$$

if the PV system operates at the CPP-L, or

$$v^*_{pv} = \begin{cases} v_{MPPT}, & \text{when} \quad P_{pv} \leq P_{limit} \\ v_{pv} + v_{step}, & \text{when} \quad P_{pv} > P_{limit} \end{cases} \tag{4}$$

if the PV system operates at the CPP-R, where v_{MPPT} is the reference voltage from the MPPT algorithm (i.e., the P&O MPPT algorithm) and v_{step} is the perturbation step size.

IV. Benchmarking of Constant Power Generation (CPG) Strategies

In order to benchmark the discussed CPG control strategies, experiments have been carried out referring to Fig. 3, where the experimental test-rig is shown in Fig. 11. The performance of the two-stage single-phase PV system during the MPPT operation are demonstrated in Fig. 12(a). Here, the sampling frequency of the MPPT (and also CPG) algorithms is chosen as 10 Hz (which is a typical sampling rate of the MPPT algorithm [36]). For the PV inverter controller, the dc-link voltage v_{dc} is regulated at 450 $\pm$ 5 V and the extracted power is delivered to a single-phase 50-Hz ac grid with a peak voltage of 325 V, as it can be seen from Fig. 12(b).

In the experiments, a 3-kW PV simulator has been adopted, where irradiance and ambient temperature profiles can be programmed to emulate the behavior of real PV arrays in different operating conditions. First, the performance of the CPG strategies are examined with a slow changing trapezoidal solar irradiance profile in Fig. 13, where three different values of power limit P_{limit} (i.e., 20 %, 50 %, and 80 % of the rated power) are used to verify the feasibility of the CPG strategies

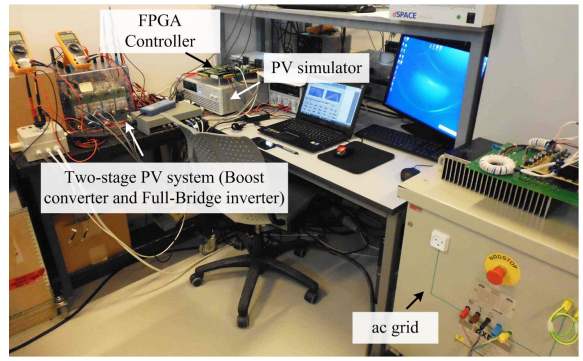

Fig. 11. Experimental setup of the two-stage grid-connected PV system.

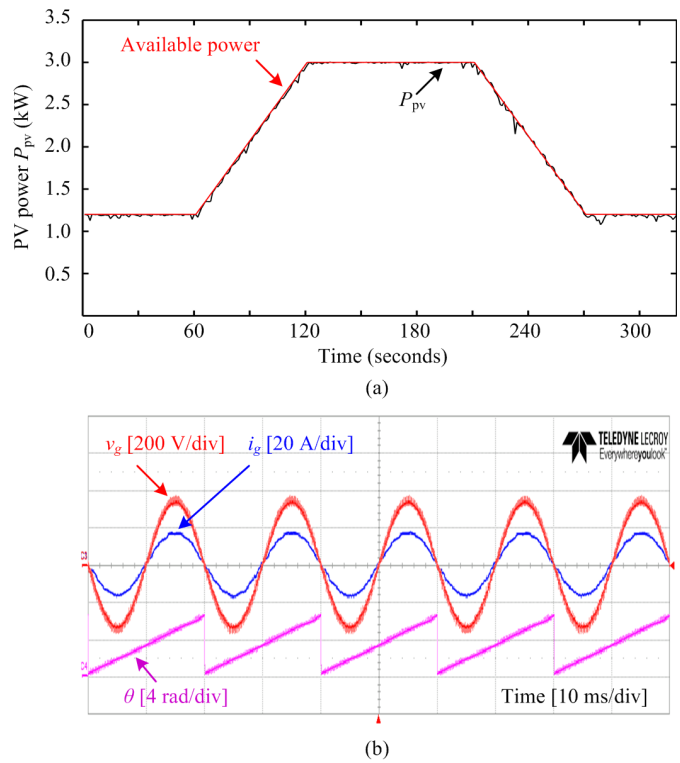

Fig. 12. Performance of the two-stage single-phase grid-connected PV system: (a) the PV power extraction during the MPPT operation, and (b) the grid voltage v_g, grid current i_g and the phase angle θ during the steady-state MPPT operation (3 kW).

under various set-points. Then, a fast changing trapezoidal solar irradiance profile in Fig. 14 is adopted, in order to challenge the dynamic of the CPG strategy and to observe the behavior of the algorithm during the operating mode transition (e.g., from MPPT to CPG mode). Furthermore, two real-field solar irradiance and ambient temperature profiles are also programmed in order to examine the performance of the CPG algorithms in the real operation, where P_{limit} = 1.5 kW (i.e., 50 % of the rated power). A clear day irradiance condition is used in Fig. 15, where the solar irradiance level changes relatively slowly and smoothly. In this condition, the CPG strategy mostly operates in steady-state condition. In contrast, the dynamic performance of the CPG strategy can clearly be seen during the fluctuating irradiance condition in Fig. 16,

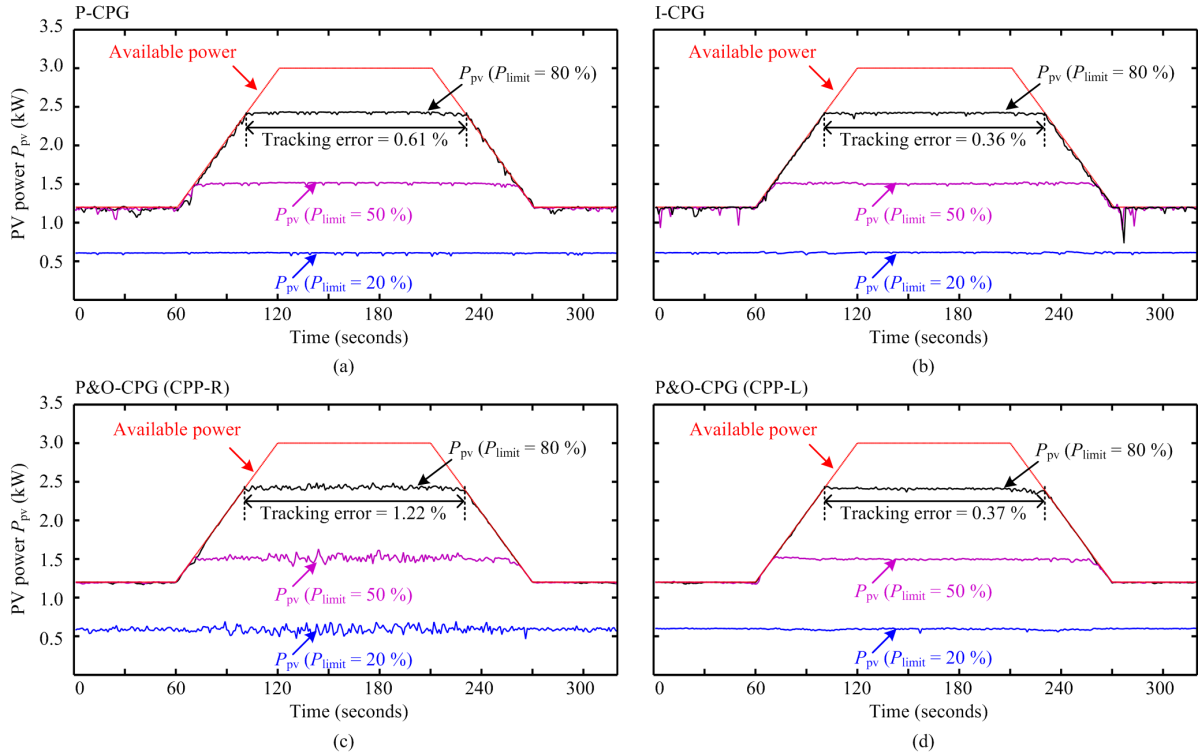

Fig. 13. Experimental results of the Constant Power Generation (CPG) scheme based on: (a) the power control, (b) the current limit, (c) the P&O at the CPP-R, and (d) the P&O at the CPP-L under a slow changing irradiance condition. The tracking error is calculated from the difference between the actual PV output power P_{pv} and its set-point P_{limit} = 80 % during the CPG mode (i.e., $|P_{pv} - P_{limit}|$), and then divided by the total energy yield.

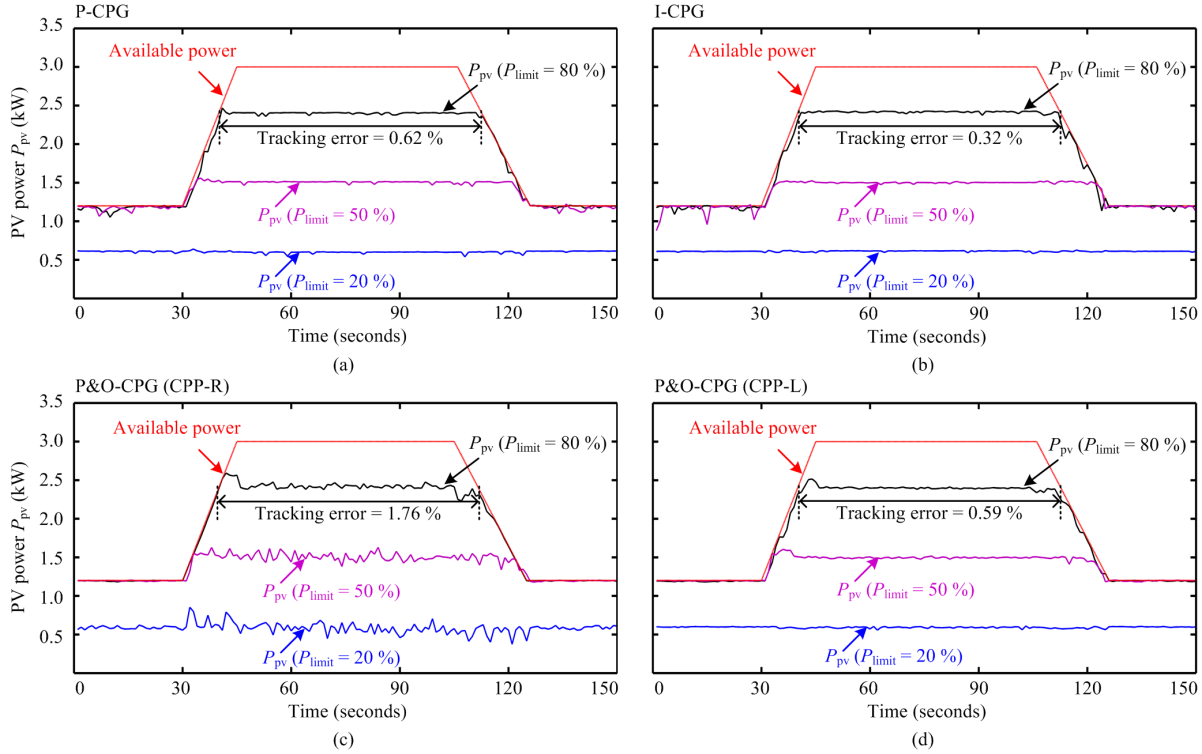

Fig. 14. Experimental results of the Constant Power Generation (CPG) scheme based on: (a) the power control, (b) the current limit, (c) the P&O at the CPP-R, and (d) the P&O at the CPP-L under a fast changing irradiance condition. The tracking error is calculated from the difference between the actual PV output power P_{pv} and its set-point P_{limit} = 80 % during the CPG mode (i.e., $|P_{pv} - P_{limit}|$), and then divided by the total energy yield.

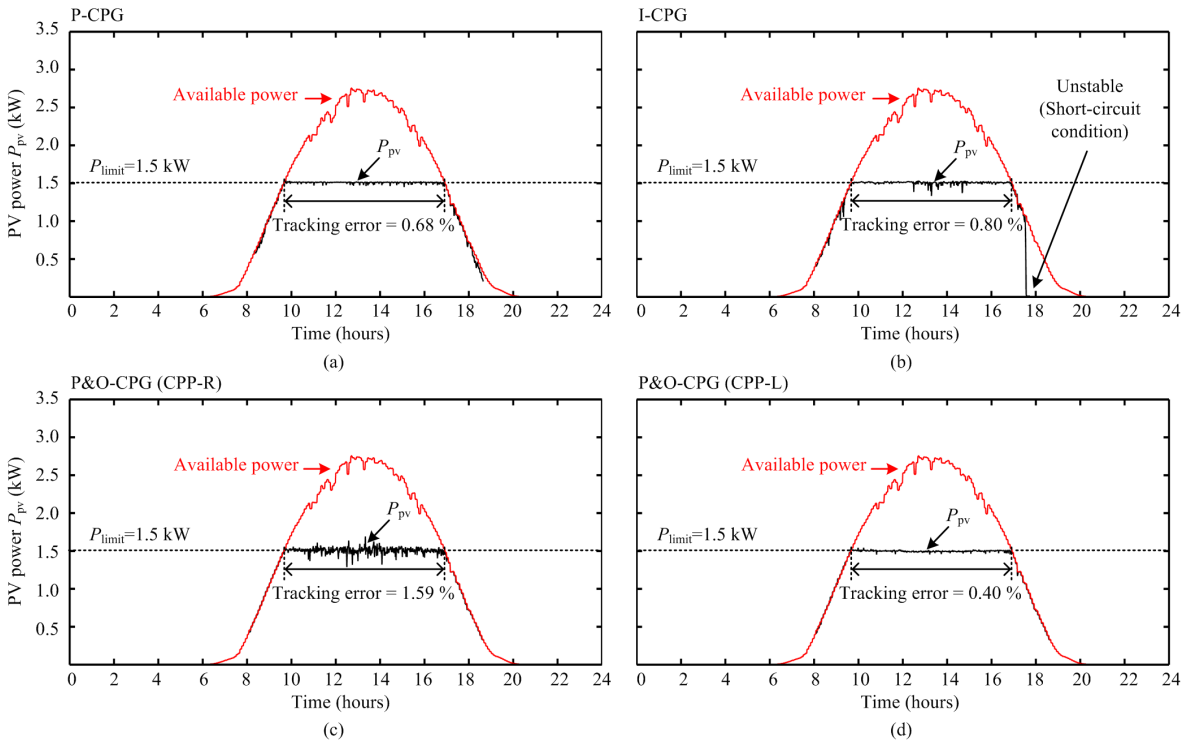

Fig. 15. Experimental results of the Constant Power Generation (CPG) scheme based on: (a) the power control, (b) the current limit, (c) the P&O at the CPP-R, and (d) the P&O at the CPP-L under a clear day condition. The tracking error is calculated from the difference between the actual PV output power P_{pv} and its set-point P_{limit} = 1.5 kW during the CPG mode (i.e., $|P_{pv} - P_{limit}|$), and then divided by the total energy yield.

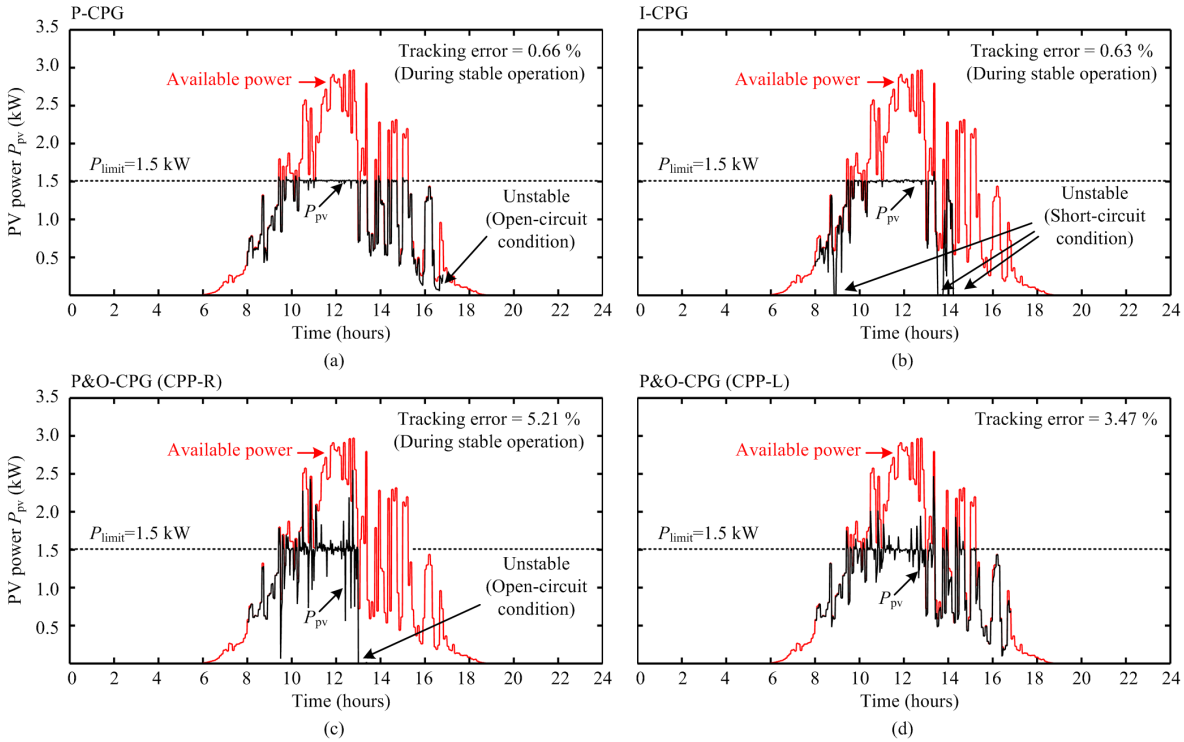

Fig. 16. Experimental results of the Constant Power Generation (CPG) scheme based on: (a) the power control, (b) the current limit, (c) the P&O at the CPP-R, and (d) the P&O at the CPP-L under a cloudy day condition. The tracking error is calculated from the difference between the actual PV output power P_{pv} and its set-point P_{limit} = 1.5 kW during the stable CPG mode (i.e., $|P_{pv} - P_{limit}|$), and then divided by the total energy yield.

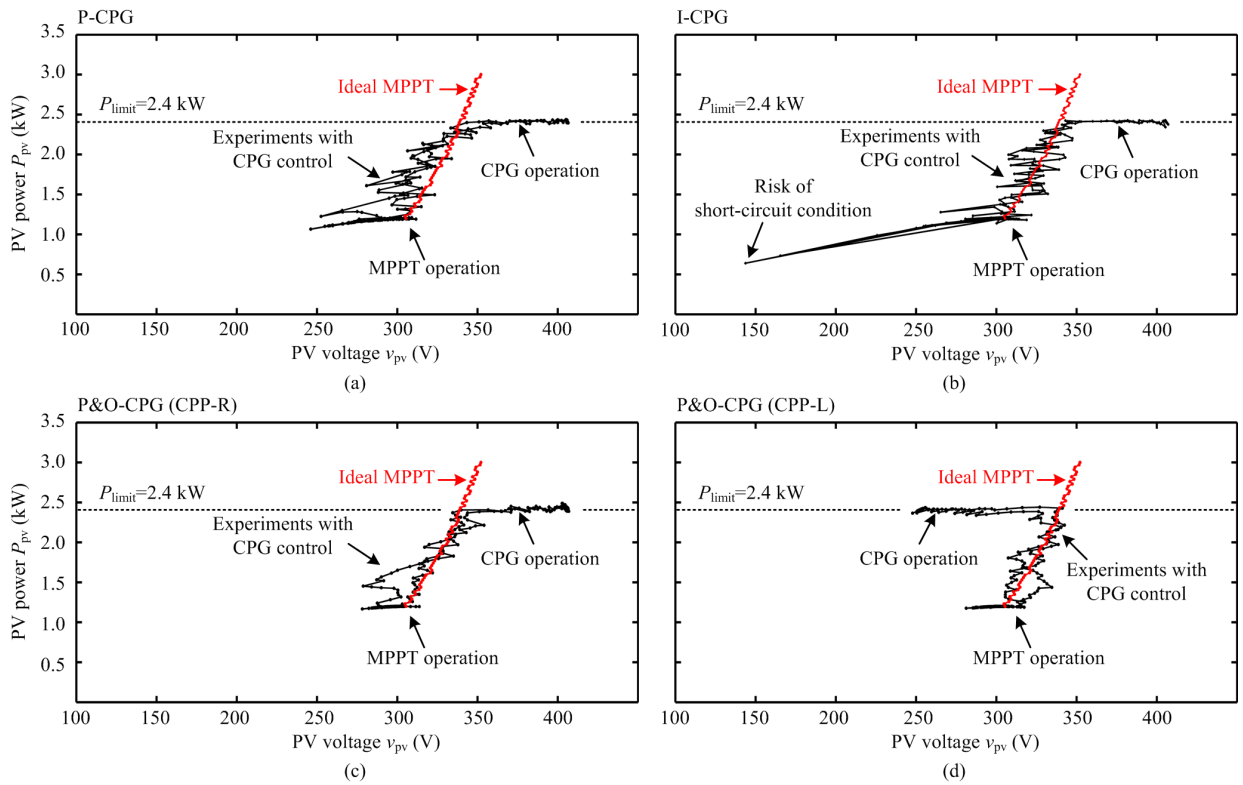

Fig. 17. Trajectory of the operating point of the Constant Power Generation (CPG) scheme based on: (a) the power control, (b) the current limit, (c) the P&O at the right side of the MPP, and (d) the P&O at the left side of the MPP under a slow changing irradiance condition (Fig. 13), when P_{limit} = 2.4 kW.

where the cloudy day irradiance profile is emulated. During the above tests, the average tracking error (in percentage of the total energy yield) during the CPG mode is also provided in the same figure. The tracking error is calculated from the difference between the actual PV output power and its set-point (i.e., $|P_{\text{pv}} - P_{\text{limit}}|$), and then divided by the total energy yield in order to make it comparable for different test conditions. This parameter can be used for comparing the tracking accuracy of different CPG strategies numerically. For instance, a large value of tracking error indicates a violation of the CPG constraint (i.e., $P_{\text{pv}} > P_{\text{limit}}$) and/or significant energy losses (i.e., $P_{\text{pv}} < P_{\text{limit}}$). Fig. 17 shows an example of the operating trajectories of the CPG strategies, where the irradiance condition in Fig. 13 is used. The detailed discussion about the results are given and benchmarked in the following.

A. Dynamic responses

The dynamic responses can be observed during the CPG to MPPT transition and vice versa. For the trapezoidal irradiance condition, this transition occurs when the available power reaches the level of power limit P_{limit}. In Fig. 13 all the CPG strategies have a smooth transition, since the irradiance changes relatively slowly. However, in the case of fast changing solar irradiance in Fig. 14, the dynamics of the CPG strategies are more challenged to follow the changes in the CPP. It can be observed from Figs. 14(c) and (d) that the P&O-CPG scheme presents large power overshoots during the MPPT to CPG transition. This is due to the fact that the P&O-CPG scheme is an iteration-based method, which requires a number of iterations in order to reach the corresponding CPP. A long-term dynamic response can be examined with the cloudy day irradiance condition in Fig. 16, where PV output power is continuously fluctuating. In this condition, similar power overshoots also appear in the P&O-CPG algorithm as it can be seen in Figs. 16(c) and (d). In contrast, the P- and I-CPG algorithms can regulate the PV output power to be constant almost without any overshoots during both short-term (i.e., Fig. 14) and long-term (i.e., Fig. 16) fast changing irradiance conditions. This fast dynamic performance is achieved because the P- and I-CPG strategies directly regulate the corresponding reference PV power P_{pv} (i.e., P-CPG) or PV current i_{pv} (i.e., I-CPG) through the close-loop control during the CPG mode. In other words, the algorithms do not require iterations in order to reach the CPP.

B. Steady-state responses

In the steady-state, the CPG algorithm should regulate the PV power P_{pv} to be constant with minimum deviations, as discussed in § III. This can be observed from Figs. 13 and 14 during the time period when the irradiance level is constant. A long-term steady state performance can also be seen in Fig. 15, since the irradiance level changes slowly and smoothly in the clear day condition. The experimental results in the above conditions show that most of the CPG algorithms have a satisfactory steady-state performance, where the PV output power P_{pv} is limited according to the set-point P_{limit} with very small deviations. However, when the P&O-CPG algorithm is employed to regulate the PV power at the right side of the

MPP (i.e., at the CPP-R), large power oscillations appear as shown in Figs. 13(c), 14(c), and 15(c). This is due to the large $dP_{\text{pv}}/dv_{\text{pv}}$ at the CPP-R (see Fig. 2). Actually, it can be noticed from Figs. 13(c) and 14(c) that the power oscillation becomes even larger at the low power limit level (e.g., when P_{limit} = 20%), as the slope $dP_{\text{pv}}/dv_{\text{pv}}$ increases when the operating point is further at the right side of the MPP.

C. Tracking error

The tracking error is another important performance aspect of the CPG strategy, which indicates numerically how well the algorithm follows the change in the CPP during the CPG operation. In fact, the tracking error is a consequence of both the dynamic and steady-state responses, depending on the irradiance profile. For example, the tracking error in steady-state is dominant in the trapezoidal irradiance profiles in Figs. 13 and 14, since the time period of a constant irradiance is much longer than the ramp-changing (considered only during the CPG mode). Therefore, the tracking errors of the P&O-CPG strategies when operating at the CPP-R in Fig. 13 are significantly higher than the other methods. It can also be noticed that the P&O-CPG strategies (both at the CPP-R and CPP-L) have larger errors in Fig. 14 compared to those in Fig. 13, while the tracking errors of the P- and I-CPG strategies remain almost at the same level. This increased tracking error is corresponding to the power overshoot in Fig. 14 as it has been discussed previously. A similar trend is also observed in Figs. 15 and 16, where it can be seen that the tracking error of the P&O-CPG method during the clody day condition is significantly larger than the case during the clear day condition, while the P- and I-CPG strategies have almost the same tracking error. Notably, only the tracking error during stable CPG operation is considered in this case.

D. Stability

Stability is one of the most important aspects for the CPG control schemes, since the PV system should be able to continuously deliver power to the grid regardless of the operating condition. Thus, the presented CPG strategies are also benchmarked in terms of stability. For the PV systems, instability may occur during a fast decreasing irradiance condition which can be further divided into two cases related to: 1) short-circuit condition, and 2) open-circuit condition. The occurrence of the short-circuit instability and its mechanism have been previously discussed in § II. This type of instability can occur with the I-CPG strategy where the PV current i_{pv} is regulated, as it can be observed in Figs. 15(b) and 16(b). In fact, it can also be seen from the operating trajectories in Fig. 17(b) that the operating point of the PV system almost goes into the short-circuit condition during a decreasing irradiance level. Another case of instability is when the operating point falls into (and stay at) the open-circuit condition. This open-circuit instability can occur in the case of the P- and P&O-CPG algorithms when the operating point is chosen at the CPP-R. The operating point may go into the open-circuit condition during a decreasing irradiance condition if the PV power is regulated too far at the right side of the MPP (i.e., at C), since

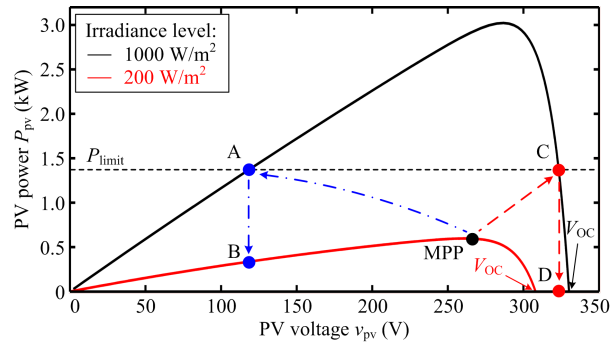

Fig. 18. Possible operating regions of the CPG strategy, where the instability issue during the fast decreasing irradiance condition is illustrated.

the open-circuit voltage in the $P-V$ curve decreases as the irradiance level drops (e.g., from 1000 W/m^2 to 200 W/m^2). The mechanism of the open-circuit instability is illustrated in Fig. 18 (i.e., C→D). Figs. 16(a) and (c) verify that the P-CPG or the P&O-CPG at the right side of the MPP can go into instability during transients. In contrast, it can be seen in Figs. 15 and 16 that the P&O-CPG algorithm can always ensure a stable operation regardless of the irradiance conditions, only when the PV system operating point is regulated at the CPP-L. In this operating region, the sudden drops in the irradiance will not lead to either the short-circuit or open-circuit instability, as it can be seen from Fig. 18 (i.e., A→B).

E. Complexity

When comparing all the above CPG strategies, it is found that the I-CPG algorithm has the simplest control structure, where only one additional current limiter needs to be added to the original MPPT controller in Fig. 4(b). Besides, the calculation of the i_{limit} is also simple by dividing P_{limit} by the measured PV voltage v_{pv}. The control structure of the P-CPG algorithm is more complicated, basically due to the MPPT controller in Fig. 4(c). In the case of the P&O-CPG algorithm, the modification needs to be done at the MPPT algorithm level as it can be seen from Fig. 10. This makes the design of a P&O-CPG controller more complicated than the other two CPG algorithms.

Table II further summarizes a comparison of the results of the CPG control schemes, in terms of dynamic and steady-state performances, tracking error, stability, and complexity. The benchmarking results have validated the effectiveness of the CPG strategies under various test conditions. It turns out that the P-CPG strategy can achieve very fast dynamics, especially during fast changing irradiance condition, compared to the other strategies. However, this method may induce instability during the sudden irradiance drops, if the PV system operates at a low level of power limit (i.e., CPP-R is far away from MPP). Thus, it is suitable to be implemented in the PV system with historical fast changing irradiance profiles (e.g., small scale PV system with cloudy conditions), and a high level of power limit (i.e., operate at the CPP-R close to the MPP), in order to minimize the risk of instability. On the other hand, the P&O-CPG algorithm (when operating at the CPP-

TABLE II
BENCHMARKING OF THE CONSTANT POWER GENERATION ALGORITHMS.

CPG Strategy	Dynamic Responses	Steady-state Responses	Tracking Error	Stability	Complexity
Power control (P-CPG)	+ +	+	+	-	-
Current limit (I-CPG)	+ +	+	+	- -	+ +
P&O-CPG at CPP-R	- -	- -	- -	-	-
P&O-CPG at CPP-L	- -	+ +	-	+ +	-

Note: the more +, the less tracking error, better stability, and less complexity.

L) is the most suitable approach to realize the CPG control practically due to its robustness and feasible to be used for the future grid codes. This method is also suitable when a wide range of CPG operation (e.g., at different level of power limit) is required. However, the tracking error of the P&O-CPG algorithm increases during fast changing irradiance conditions, which is a trade-off that should be considered.

V. CONCLUSION

In this paper, three Constant Power Generation (CPG) control solutions for single-phase grid-connected PV systems have been presented. A benchmarking of the three CPG control methods has also been conducted in terms of dynamic and steady-state performances, tracking error, stability, and complexity. Comparisons have revealed that the CPG strategy based on a current limit method (I-CPG) has the simplest control structure. Additionally, the power control based CPG scheme (P-CPG) has fast dynamics and good steady-state responses. However, instability may occur in both I-CPG and P-CPG methods during the operational mode transition, e.g., in the case of a fast change in the solar irradiance. It can be concluded that the CPG based on the P&O algorithm (P&O-CPG) is the best one in terms of high robustness among the three CPG strategies once the PV system is operating at the left side of the maximum power point.

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