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# Development of Flexible Active Power Control Strategies for Grid-Connected Photovoltaic Inverters by Modifying MPPT Algorithms

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***Abstract*—As the penetration level of grid-connected PV systems increases, more advanced control functionality is demanded. In order to ensure smooth and friendly grid integration as well as enable more PV installations, the power generated by PV systems needs to be flexible and capable of: 1) limiting the maximum feed-in power, 2) ensuring a smooth change rate, and 3) providing a power reserve. Besides, such flexible power control functionalities have to be achieved in a cost-effective way in order to ensure the competitiveness of solar energy. Therefore, this paper explores flexible active power control strategies for grid-connected PV inverters by modifying maximum power point tracking algorithms, where the PV power is regulated by changing the operating point of the PV system. In this way, no extra equipment is needed, being a cost-effective solution. Experiments on a 3-kW grid-connected PV system have been performed, where the developed flexible active power control functionalities are achieved per demands.**

***Index Terms*—Active power control, power limiting control, power ramp rate control, power reserve control, maximum power point tracking, power curtailment, PV systems.**

## I. Introduction

In recent years, the installation of grid-connected Photovoltaic (PV) systems has been increasing with the aim to introduce more renewable energy into the mixed power grid [1]. As the penetration level of PV systems further increases, its integration into the power grid becomes important. In the case of wide-scale PV system installations, the grid may face challenges like overloading during peak-power generation periods, voltage fluctuations due to the intermittency of solar energy, and limited frequency regulation capability [2]–[4]. To address those issues and thus ensure a friendly integration of PV systems into the grid, the power injection from the PV systems needs to be flexibly controlled to actively participate in grid regulation (like conventional power plants). Accordingly, the grid codes in some countries have been revised recently and updated, where various active power control schemes are defined for grid-connected PV systems. For example, in grid regulations and recent research [5]–[11], the active power control is categorized into three main functionalities: 1) Power Limiting Control (PLC, also called absolute power control, and constant power generation control), 2) Power Ramp-Rate Control (PRRC), and 3) Power Reserve Control (PRC, also called delta power control). Examples of these active power control strategies are defined in the Danish grid code, as illustrated in Fig. 1 [7]. Similar control functionalities can be found in other grid codes (e.g., Germany, Puerto Rico, ENTSO-E), and they are expected to be more widely adopted when a relatively high penetration level of grid-connected PV system is reached in the near future [7]–[11].

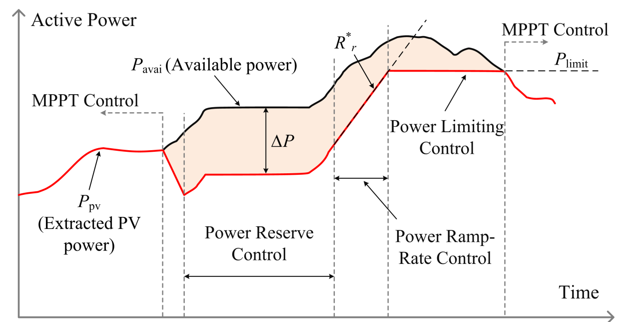


Fig. 1. Active power control strategies for grid-connected PV systems defined in the Danish grid code ($P_{\text{pv}}$: PV power, $P_{\text{avai}}$: available power, $P_{\text{limit}}$: the power limit level, $R_r^*$: the ramp-rate limit, $\Delta P$: the power reserve level) [7].

There are several ways to realize the active power control in PV systems. The most commonly-used solution is to integrate the energy storage system into the PV system, where active power injection to the grid can be flexibly controlled by charging and discharging the energy storage device (e.g., battery), as it is shown in Fig. 2(a) [12]–[14]. However, high cost and limited lifetime are associated with this approach, making it not very suitable for a cost-effective PV system [15]. This is in contradictory with the expectations that the cost of PV energy should be reduced significantly in next decades (e.g., by 50 % in 2020) [16]. Another way to achieve a flexible active power injection to the grid is by adaptively controlling the local load to absorb (e.g., smart loads) or dissipate (e.g., dump loads like resistors) the surplus PV power according to the active power control strategy [14]. The concept of this approach is illustrated in Fig. 2(b), where the

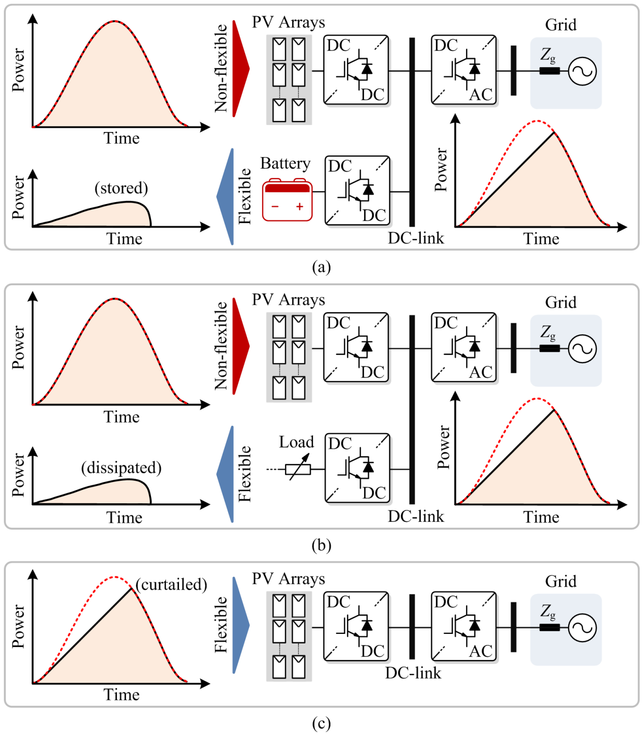


Fig. 2. Possible solutions to realize flexible active power control for grid-connected PV systems: (a) integrating energy storage systems (i.e., battery), (b) applying controllable loads to dissipate surplus PV power, and (c) modifying MPPT algorithms (i.e., power curtailment).

flexibility is provided by the load that has to be able to be controlled by a load management system. However, this is not (currently) available in most residential applications, as it may increase the cost and complexity of the overall system. Thus, a cost-effective solution that fulfills these flexible active power control requirements is needed. Accordingly, a power curtailment approach shown in Fig. 2(c) is considered to be a more cost-effective way to realize active power control strategies for PV systems [14]. In this case, Maximum Power Point Tracking (MPPT) algorithms have to be modified in such a way that the power extracted from the PV arrays is regulated below the Maximum Power Point (MPP), and follows the demand. By doing so, the active power control functionalities shown in Fig. 1 is achieved without any extra component. In other words, this solution can be implemented with the existing PV system and requiring minimum software modifications. Therefore, it is a cost-effective approach to realize flexible active power control in PV systems.

In this paper, the development of flexible active power control strategies is presented. An overview about the demands for flexible active power control in grid-connected PV systems is provided in § II. Then, the control solutions to realize active power control strategies by modifying MPPT algorithms are discussed in § III. Experiments are carried out on a 3-kW grid-connected PV system to demonstrate the control performance of these strategies, and the results are provided in § IV. Finally, concluding remarks are given in § V.

## II. Overview of Active Power Control Demands

This section presents the challenges associated with the still increasing penetration level of grid-connected PV systems. Potential problems like overloading during peak-power periods, voltage fluctuations, and limited frequency control capability will be discussed. Also, solutions through flexible active power control will be explored in order to address these issues.

### *A. Overloading during PV Peak Power Generation Periods*

Under a large PV installation scenario, overloading of the grid is one of the associated and the most concerned issues [4]. When many PV systems are connected to the grid, they can introduce a significant peak surplus power during midday (i.e., when the PV power production is the highest). This will increase the power loss and lead to overvoltage (if the grid capacity remains the same), and thus should be avoided as it will overstress the equipment in the systems.

This issue has been increasingly concerned recently. For instance, it has been reported that parts of the distribution grid in Northern Ireland have experienced a severe overloading due to a high number of PV systems connected to the grid [17]. In order to solve this problem, the power limiting control scheme has been introduced in grid regulations, where the active power injected from the PV systems has to be limited to a certain value if demanded, as it is shown in Fig. 1 (i.e., the power limiting control). By doing so, the peak power from PV systems can be avoided. This requirement is currently adopted in Germany through the grid codes [6], where the newly installed PV systems have to be able to limit its maximum feed-in power (i.e., 70 % of the rated power). Similar requirements have also been defined in the grid codes of other countries (e.g., Denmark and Japan).

### *B. Voltage Fluctuation due to the Intermittency*

Another potential problem caused by PV systems is due to the intermittent nature of solar energy. It is well known that the PV power can be fluctuating considerably in the case of cloudy days, where the power production can suddenly drop (e.g., due to passing clouds). This problem is usually pronounced in small-scale PV systems (e.g., rooftop PV applications), since a passing cloud can easily cover a major area of the PV panels. In the case of a wide-scale grid-connected PV system, those sudden changes in the PV power can potentially induce severe grid voltage fluctuations [3], which thus should be addressed.

In order to reduce the power fluctuation from the PV system, a power ramp-rate control is introduced to limit the PV output power change rate to a certain value. Namely, during the fluctuating solar irradiance condition, the PV systems are not allowed to increase its output power with the change rate higher than a certain limit. Instead, the PV power should be controlled in a ramp manner with the change rate corresponding to the maximum limit, as it is illustrated in Fig. 1 (i.e., power ramp-rate control). Otherwise, if the PV output power change rate is below a maximum limit, the PV systems are allowed to continuously operate in the MPPT mode with the maximum power injection (i.e., normal operation).

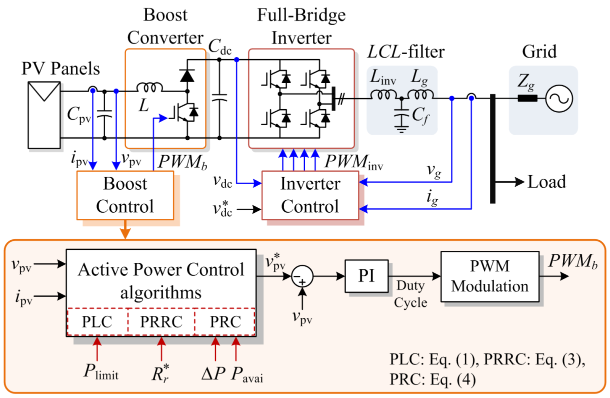


Fig. 3. System configuration and control scheme of a single-phase PV system with active power control strategies (PLC: Power Limiting Control, PRRC: Power Ramp-Rate Control, PRC: Power Reserve Control).

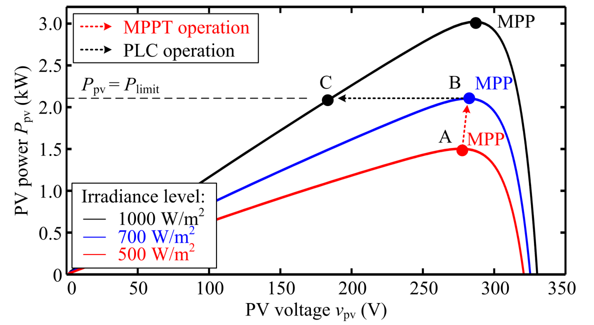


Fig. 4. Operational principle of the Power Limiting Control (PLC) algorithm: MPPT mode (A→B) and PLC mode (B→C), where $P_{\text{limit}}$ is the power limit.

### C. Limited Frequency Regulation Capability

In the conventional power systems, the grid frequency is normally regulated by large conventional power plants (e.g., coal-fired, gas turbines), which are considered as dispatchable sources of electricity. However, as the installation of grid-connected PV system increases, the system operator will have less capability to stabilize the grid in the case of frequency deviations, as a large portion of PV systems cannot be easily controlled by the system operator. Initially, some grid regulations require the PV systems to be disconnected from the power grid in the case of frequency deviations. However, as the penetration level of grid-connected PV systems increases, disconnecting the large amount of PV systems during the frequency deviation will challenge the grid stability due to a sudden loss of large power generation [18]. This is known as the 50.2-Hz problem, which is highly concerned in countries with a high PV penetration (e.g., Germany) [9].

With the above concerns, the frequency regulation has been implemented in grid codes, where the PV systems are not allowed to immediately disconnect from the grid in response to frequency deviations. Instead, the PV system needs to provide a power reserve by reducing its output power to a certain level (specified by the grid codes), as it is shown in Fig. 1 (i.e., the power reserve control). In this way, the PV systems are requested to contribute to frequency regulations and support the grid during frequency deviation.

## III. Flexible Active Power Control Strategies

In this section, the realization of the flexible active power control strategies by modifying MPPT algorithms is discussed. The implementation is based on two-stage grid-connected PV systems, where the system configuration and its control structure are shown in Fig. 3 [19], [20]. In this control scheme, the PV power extraction is controlled by the boost converter through the regulation of PV voltage $v_{\text{pv}}$ while the full-bridge inverter transfers the extracted PV power to the ac grid by regulating the dc-link voltage $v_{\text{dc}}$ to be constant. The active power control strategy is then implemented in the boost stage, which is achieved by determining an appropriate reference PV voltage $v_{\text{pv}}^*$ for a certain active power control strategy (e.g., power limiting control, power ramp-rate control, power reserve control), as it will be discussed in the following.

### A. Power Limiting Control (PLC) Algorithm

In order to limit the PV output power to a certain level $P_{\text{limit}}$, the operating voltage of the PV arrays $v_{\text{pv}}$ needs to be regulated along the horizontal line as shown in Fig. 4 [21]. During the power limiting operation (i.e., $P_{\text{pv}} > P_{\text{limit}}$), the reference PV voltage $v_{\text{pv}}^*$ is continuously perturbed towards the left side of the MPP, i.e., $P_{\text{pv}} = P_{\text{limit}}$. Otherwise, if the PV output power is below the power limit level (i.e., $P_{\text{pv}} \le P_{\text{limit}}$), the reference PV voltage $v_{\text{pv}}^*$ is set from the MPPT algorithm (e.g., P&O MPPT), and the PV system injects the maximum available power to the grid. The reference PV voltage can be summarized as the following

$$v_{\text{pv}}^* = \begin{cases} v_{\text{MPPT}}, & \text{when} \quad P_{\text{pv}} \le P_{\text{limit}} \\ v_{\text{pv}} - v_{\text{step}}, & \text{when} \quad P_{\text{pv}} > P_{\text{limit}} \end{cases} \tag{1}$$

where $v_{\text{MPPT}}$ is the reference voltage from the MPPT algorithm (i.e., P&O MPPT) and $v_{\text{step}}$ is the perturbation step size.

### B. Power Ramp-Rate Control (PRRC) Algorithm

The principle of power ramp-rate control is similar to the power limiting control. In this case, the criterion to curtail the PV power is coming from the change rate of the PV power, instead of an absolute PV power like in (1). Specifically, the PV power ramp-rate $R_r(t)$ is first calculated as

$$R_r(t) = \frac{dP_{\text{pv}}}{dt} \tag{2}$$

Then, if the change rate of the PV power $R_r(t)$ is above a certain limit $R_r^*$, the PV voltage $v_{\text{pv}}^*$ is perturbed towards the left side of the MPP, in order to reduce the change rate of the PV power to a certain value (i.e., $R_r(t) = R_r^*$). The operational principle of the power ramp-rate control algorithm is illustrated in Fig. 5 [22], where the reference PV voltage during operation is summarized as in the following

$$v_{\text{pv}}^* = \begin{cases} v_{\text{MPPT}}, & \text{when} \quad R_r(t) \le R_r^* \\ v_{\text{pv}} - v_{\text{step}}, & \text{when} \quad R_r(t) > R_r^* \end{cases} \tag{3}$$

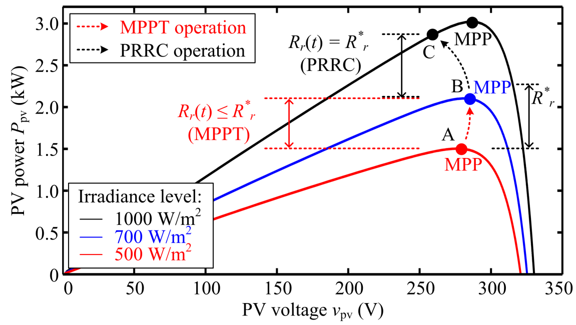


Fig. 5. Operational principle of the Power Ramp-Rate Control (PRRC) algorithm: MPPT mode (A→B) and PRRC mode (B→C), where $R_r(t)$ is the PV power ramp-rate and $R_r^*$ is the ramp-rate limit.

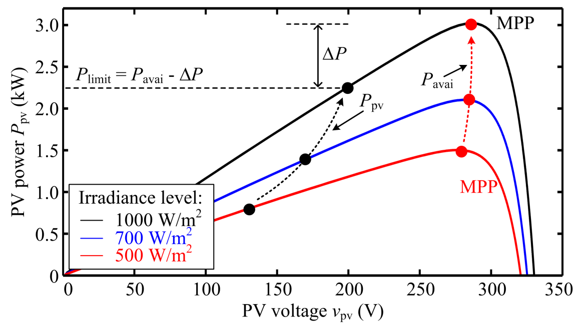


Fig. 6. Operational principle of the Power Reserve Control (PRC) algorithm, where $P_{\mathrm{avai}}$ is the available PV power and $\Delta P$ is the power reserve level.

### C. Power Reserve Control (PRC) Algorithm

For the power reserve control, the PV power needs to be regulated below the MPP with a certain power reserve level $\Delta P$. In fact, this control functionality can be considered as a special case of the power limiting control, where the power limit level $P_{\mathrm{limit}}$ is dynamically changed during operation, in order to achieve a certain power reserve level $\Delta P$. Thus, a similar algorithm in (1) can be employed, but the power limit level $P_{\mathrm{limit}}$ should be calculated by subtracting the available PV power $P_{\mathrm{avai}}$ with the required amount of power reserve as: $P_{\mathrm{limit}} = P_{\mathrm{avai}} - \Delta P$. The operating principle of the power reserve control strategy is shown in Fig. 6, where the extracted PV power $P_{\mathrm{pv}}$ is always kept below the available PV power $P_{\mathrm{avai}}$ with the amount of power reserve $\Delta P$ [23]. The reference PV voltage with the PRC algorithm can be summarized as

$$v^*_{\mathrm{pv}} = \begin{cases} v_{\mathrm{MPPT}}, & \text{when} \quad P_{\mathrm{pv}} \leq P_{\mathrm{avai}} - \Delta P \\ v_{\mathrm{pv}} - v_{\mathrm{step}}, & \text{when} \quad P_{\mathrm{pv}} > P_{\mathrm{avai}} - \Delta P \end{cases} \tag{4}$$

Here, the challenge is the estimation of the available PV power $P_{\mathrm{avai}}$ during the operation, which is required for determining the reference power limit (i.e., $P_{\mathrm{avai}} - \Delta P$). Different approaches to estimate the available PV power have been reported in literature: using solar forecasting data, installing solar irradiance measurements [24], using curve-fitting approximation [25], employing a hybrid operation between MPPT and PRC [15], etc. Notably, there is always a trade-off between the cost and the accuracy for each method.

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 | $C_{\mathrm{pv}}$ = 1000 $\mu$F |
| DC-link capacitor | $C_{\mathrm{dc}}$ = 1100 $\mu$F |
| $LCL$-filter | $L_{\mathrm{inv}}$ = 4.8 mH, $L_{\mathrm{g}}$ = 2 mH, $C_f$ = 4.3 $\mu$F |
| Switching frequency | Boost converter: $f_b$ = 16 kHz, Full-bridge inverter: $f_{\mathrm{inv}}$ = 8 kHz |
| DC-link voltage | $v^*_{\mathrm{dc}}$ = 450 V |
| Grid nominal voltage (RMS) | $V_g$ = 230 V |
| Grid nominal frequency | $\omega_0 = 2\pi \times 50$ rad/s |
| MPPT algorithm sampling rate | 10 Hz |
| MPPT pertubation step size | $v_{\mathrm{step}}$ = 4 V |

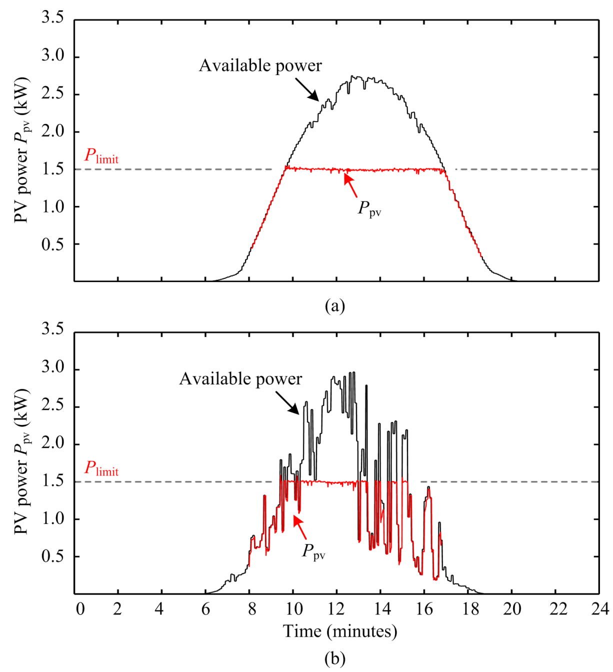


Fig. 7. PV output power with the Power Limiting Control (PLC) strategy under: (a) a clear day and (b) a cloudy day irradiance conditions, where the power limit level $P_{\mathrm{limit}}$ is 1.5 kW.

## IV. RESULTS AND DISCUSSIONS

Experiments with the above active power control strategies are performed on the system shown in Fig. 3, whose parameters are given in Table I. A PV simulator is adopted in the tests in order to emulate the PV panel characteristic under different operating conditions (e.g., during clear day and cloudy day conditions). Moreover, accelerated tests have been performed, where the accelerating factor is 60 times (e.g., a 24-hour solar irradiance profile is emulated within 24 minutes during the tests). The sampling rate of the active power control strategies (i.e., PLC, PRRC, PRC) is chosen to be 10 Hz (which is a typical sampling rate of the MPPT algorithm). Fig. 7 shows the performance of the PV system with the power limiting control scheme, where the reference power limit level is chosen as $P_{\mathrm{limit}}$ = 1.5 kW. It can be seen from Fig. 7 that the maximum

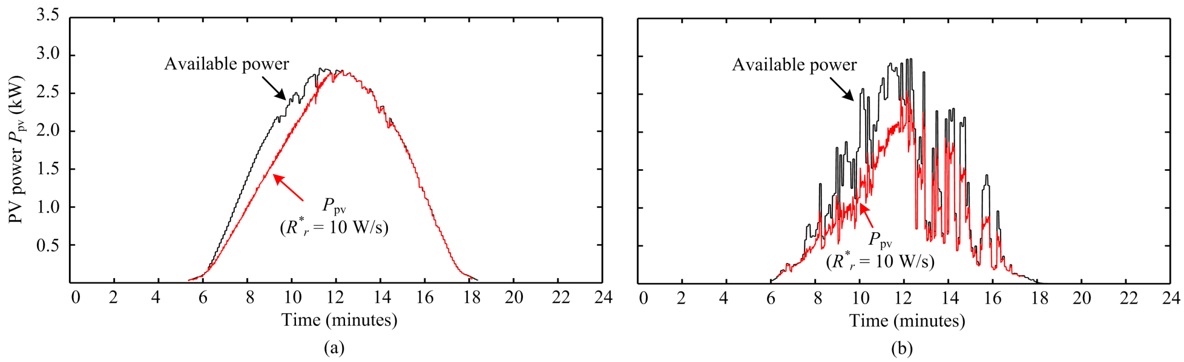


Fig. 8. PV output power with the Power Ramp-Rate Control (PRRC) strategy under: (a) a clear day and (b) a cloudy day irradiance conditions, where the ramp-rate limit $R_r^*$ is 10 W/s.

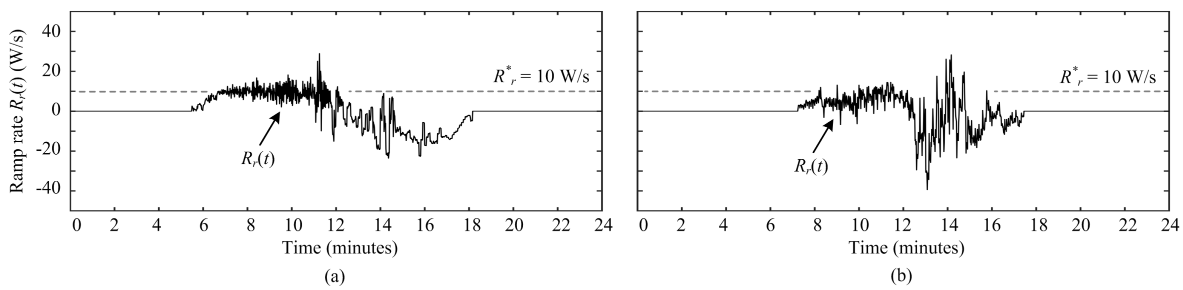


Fig. 9. Measured power ramp-rate of the Power Ramp-Rate Control (PRRC) strategy under: (a) a clear day and (b) a cloudy day irradiance conditions, where the ramp-rate limit $R_r^*$ is 10 W/s.

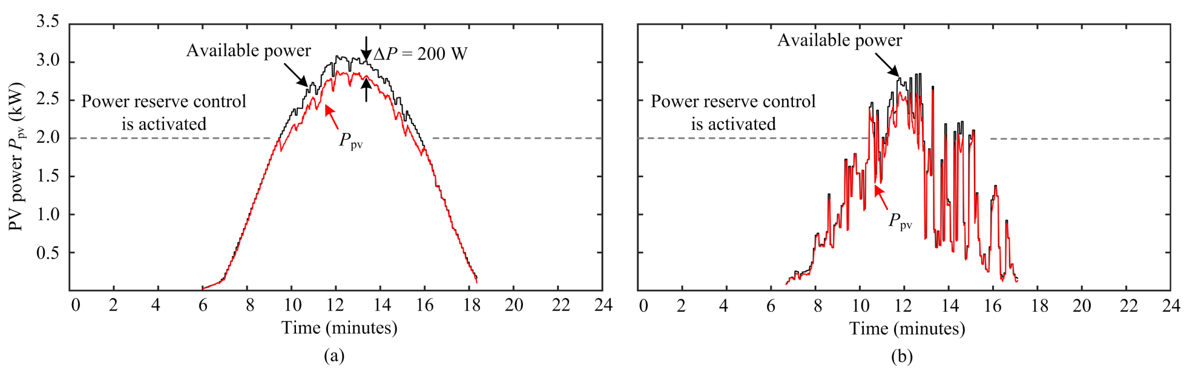


Fig. 10. PV output power of the Power Reserve Control (PRC) strategy under: (a) a clear day and (b) a cloudy day irradiance conditions, where the reference power reserve level $\Delta P$ is 200 W and the PRC strategy is activated when $P_{\mathrm{pv}} > 2$ kW.

PV power injection is limited according to the set-point during the entire operation. Another active power control scheme is demonstrated in Fig. 8, where the power ramp-rate control scheme is implemented, and the PV power follows a ramp change manner. The measured power ramp-rate is shown in Fig. 9, which verifies that the change rate of the PV power can be limited according to the maximum allowable value (i.e., $R_r^*$ = 10 W/s). The performance of the power reserve control strategy is shown in Fig. 10, where the reference power reserve level is chosen as $\Delta P$ = 200 W. It can be seen from Fig. 10 that the PV power is reduced with the amount corresponding to the power reserve level once the power reserve control is activated. The measured power reserve during operation is also shown in Fig. 11, where it can be seen that the power reserve can be accurately controlled during the clear day irradiance condition. However, a large variation in the power reserve is observed during the cloudy day irradiance condition, as it is shown in Fig. 11(b). Notably, it is challenging to control the power ramp-rate and power reserve during the fluctuating solar irradiance (see Figs. 9(b) and 11(b)). In these cases, the sampling rate of the control algorithm needs to be increased in order to improve the control dynamics. Nevertheless, the above results verify the flexibility of active power control in PV systems by simply modifying the MPPT control algorithms.

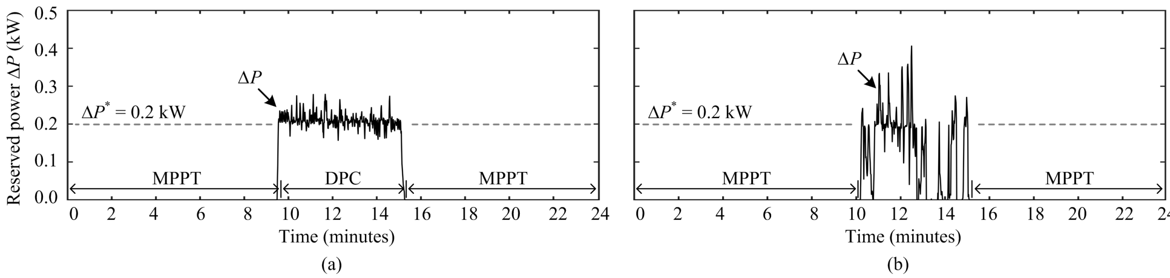


Fig. 11. Measured power reserve of the Power Reserve Control (PRC) strategy under: (a) a clear day and (b) a cloudy day irradiance conditions, where the power reserve level $\Delta P$ is 200 W.

## V. Conclusion

In this paper, various flexible active power control strategies have been developed for grid-connected PV systems by simply modifying the MPPT algorithms. The developed solutions include a power limiting control, a power ramp-rate control, and a power reserve control strategies. More specifically, the power control strategy is achieved by operating the PV system below the maximum power point. That is, the developed solutions can achieve flexible active power control without any extra devices, being of high cost-effectiveness compared to the prior-art solutions. Experimental results carried out on a 3-kW single-phase grid-connected PV system have demonstrated and validated the performance of those solutions, where the discussed active power control strategies are achieved.

## Acknowledgment


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