Real-Time Constant Power Generation Method for PV Systems With Low Tracking Error

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ABSTRACT In this paper, a new constant power generation (CPG) method for photovoltaic (PV) systems is proposed to mitigate the power variations due to changes in external conditions. A power grid with the high penetration of renewables might face both voltage and frequency instability when the power variations from PV systems are large. The proposed CPG method estimates the constant power point (CPP) in real-time without requiring the time step used in the conventional methods. Thus, it can rapidly track the CPP, and it is able to generate the constant power effectively even for sudden changes in external conditions. The practical effectiveness of proposed CPG method is verified by experimental and hardware-in-the-loop tests. The results clearly show that the proposed CPG method provides a much faster response with a less tracking error than the conventional methods in different operating conditions. Thus, it can be an effective solution to further increase the penetration level of PV systems to power grid.

INDEX TERMS Constant power generation, maximum power point tracking, photovoltaic system, tracking error.

I. INTRODUCTION

The penetration level of photovoltaic (PV) system to power grid has been rapidly increasing worldwide [1], [2], [3]. In general, the PV system produces a large amount of power during a certain time period of day. Thus, the power grid might face the risk of overloading problem, which can cause both voltage and frequency instability [4], [5], [6]. Several grid codes have been developed in many developed countries to solve this problem. For instance, the PV systems with the rated power below 30 kW must be able to limit their maximum power in Germany unless they can be remotely controlled [7]. Also, the active power control strategy, which gives the absolute power constraint to PV systems, was defined in the Danish grid code [8]. Nevertheless, the maximum power point tracking (MPPT) control has been mostly applied to the PV system in practice. Therefore, the ability to effectively adapt its output power is required for generating the constant power. This is so-called constant power generation (CPG) control [9]. It can be performed through the installation of facilities such as energy storage systems or dump loads [10], [11], [12]. However, they require a high cost, and they increase the system complexity.

Therefore, many studies have focused on developing software-based methods by modifying the controller of PV system [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28]. The CPG methods can be classified into three (power, current, and voltage) control types. Each type has its own drawbacks. For example, the studies in [13], [14], [15], [16], [17], and [18] proposed the power controller for regulating the PV array power to be constant. However, they cause a high tracking error due to the measurement noise. This is because the noise is amplified when the real voltage and current signals are multiplied to calculate the PV array power. Furthermore, the current control method was proposed in [16], [19], and [20] to regulate
the PV array current. However, there is a risk of short-circuit condition when the irradiance is rapidly decreased. This is because the right side of power-current curve of PV array has the very steep slope.

In [21], the CPG method based on voltage control was suggested with the lookup table used to find a proper reference for the PV array voltage. It can rapidly adjust the PV array power according to the environmental change but requires a large amount of data storage space. In addition, the newton-quadratic-interpolation-based CPG method was suggested in [22] by estimating the shape of power-voltage (P − V) curve. However, it requires three different sample points whenever the environmental condition changes. Further, the CPG method in [23] obtained the power curve-tracking error, so that both the overshoot and generation loss steps. Therefore, it can rapidly track the CPP with the low transient condition. The curve has the advantage that it is not affected by the irradiance, but it is difficult to apply under the partial shading conditions.

The most widely used CPG method regulates the PV array voltage by using modified perturbation and observation (P&O) algorithm [16], [24]. In other words, the P&O CPG method empirically tracks the constant power point (CPP) instead of the maximum power point (MPP). Even though it is simple and easy to implement, it provides a slow tracking speed due to the fixed step size of voltage. Therefore, a large overshoot occurs when the irradiance is rapidly increased. To solve this, the general CPG [25] and variable step-size (VSS) CPG [26], [27] methods have been proposed by using the variable step size of voltage. Nevertheless, the former method does not become an optimal solution because only two step sizes of voltage (one is used in a steady-state, and the other is used in a transient condition) are available. In contrast, the latter method adjusts the step size of voltage to various values to achieve a fast tracking speed. However, all CPG methods by using the voltage-step approach have the limitation in mitigating the overshoot. Moreover, they have a large generation loss when the irradiance is rapidly decreased. This is because a time step is inevitably required between all voltage steps, which makes the control response slow. The comparison of various CPG methods is summarized in [28].

This paper proposes the new CPG method for PV systems by estimating the CPP in real-time without requiring the time step. Therefore, it can rapidly track the CPP with the low tracking error, so that both the overshoot and generation loss of PV system are significantly reduced. Thus, the PV system can generate the constant power regardless of the sudden changes of external conditions. Moreover, the proposed CPG method can operate as the MPPT control at low irradiance levels.

II. PROPOSED REAL-TIME CPG METHOD

A. SYSTEM CONFIGURATION

In general, the CPG method is implemented in two modes, which are the MPPT and constant power point tracking (CPPT) modes. In the MPPT mode, the maximum available power, \( P_{mpp} \) is lower than the pre-defined power limit, \( P_{limit} \). In contrast, the latter method adjusts the step size of voltage from the PWM generator. Therefore, the PV system adjusts its array power, \( P_{pv} \), to \( P_{mmp} \). In contrast, if \( P_{mmp} \) exceeds \( P_{limit} \) in the CPPT mode, the PV system keeps \( P_{pv} \) to \( P_{limit} \). In other words, the operational principle of CPG method is summarized as

\[
P_{pv} = \begin{cases} 
P_{mmp}, & \text{when } P_{mmp} \leq P_{limit} \text{ (in MPPT mode)} \\ 
P_{limit}, & \text{when } P_{mmp} > P_{limit} \text{ (in CPPT mode).} 
\end{cases}
\]

The \( P − V \) curve of PV array in both modes is shown in Fig. 1. Because the \( P − V \) curve is nonlinear, two CPPs exist on the left and right sides based on the MPP. They are referred to as CPP-L and CPP-R, respectively. If the CPG method tracks the CPP-R, it can achieve a fast tracking speed because the right side of \( P − V \) curve has the high slope. However, as the irradiance is rapidly decreased, the operating point of PV array might become an open-circuit condition, and therefore it makes the system unstable. In contrast, the operating point of PV array is always on the \( P − V \) curve even if the CPG method tracks the CPP-L even if the irradiance rapidly changes. As the result, the CPG method must operate on the left side of \( P − V \) curve to keep the system stable.

To allow the CPG method to track the CPP-L, a two-stage grid-connected PV system operating in a wide range of input voltage is required, as shown in Fig. 2. Firstly, the measured voltage, \( v_{pv} \) and current, \( i_{pv} \) from PV array are used as the input of CPG controller. Then, it outputs the proper duty cycle, \( D \), which is used in the pulse-width-modulation (PWM) generator. Thereafter, the boost converter is controlled by the switching signal, \( S_b \) from the PWM generator. The controller of grid-connected inverter regulates the DC-link voltage, \( v_{dc} \) to the reference, \( v_{dc}^* \) by using the measured voltage, \( v_{pv} \) and current, \( i_{pv} \) from the grid. Finally, the operating point of PV array is able to reach the CPP-L, which is on the...
The proposed CPG method aims to rapidly track the CPP-L for the changes of external conditions. It estimates the voltage of CPP-L in real-time without requiring \( T_{\text{step}} \). The control diagram and operational principle of proposed CPG method are shown in Figs. 5 and 6, respectively. In the CPPT mode, let’s assume that the operating point of PV array is initially on point I, where \( P_{\text{pv}} \) is higher than \( P_{\text{limit}} \), as shown in Fig. 6(a). Then, the blue straight line can be drawn from point I to point O. Thereby, the estimated voltage, \( v_{\text{est}} \), can be found by the intersection point, where the blue straight line and \( P_{\text{limit}} \) meet. \( v_{\text{est}} \) is set as \( v^*_\text{pv} \) because it is considered as the voltage of CPP-L, \( V_{\text{cpp}} \). As the result, the operating point of PV array moves toward the CPP-L along the \( P - V \) curve because the voltage controller in Fig. 5 regulates \( v_{\text{pv}} \) to \( v_{\text{est}} \). Note that \( v_{\text{est}} \) approaches to \( V_{\text{cpp}} \) in real-time, and it does not go beyond \( V_{\text{cpp}} \) during this operation. Therefore, \( v_{\text{pv}} \) eventually converges to \( V_{\text{cpp}} \), and the operating point of PV array is finally located at the CPP-L. The proposed CPG method is not implemented with a simple repetitive operation like the perturbation, which calculates \( v^*_\text{pv} \) in every \( T_{\text{step}} \) (0.01–1 s). It performs the real-time repetitive operation, which calculates \( v^*_\text{pv} \) in every switching period (10–100 \( \mu \)s) on the digital signal processor (DSP). The real-time estimation of \( v_{\text{est}} \) is simply implemented by

\[
v_{\text{est}} = \frac{P_{\text{limit}}}{P_{\text{pv}}} \cdot v_{\text{pv}} = \frac{P_{\text{limit}}}{I_{\text{pv}}} v_{\text{pv}}, \tag{3}
\]

Even in the other direction where \( P_{\text{pv}} \) is lower than \( P_{\text{limit}} \), the same principle in (3) is applied to track the CPP-L, as shown in Fig. 6(b). In other words, the blue straight line is drawn from point O to \( P_{\text{limit}} \) while passing through point I. Then, \( v_{\text{est}} \) can be obtained, and it becomes \( v^*_\text{pv} \), which is tracked by the voltage controller. In this operation, \( v_{\text{est}} \) also approaches to \( V_{\text{cpp}} \) in real-time when the operating point of PV array is closer to the CPP-L. As the result, the operating point of PV array converges to the CPP-L because \( v_{\text{est}} \) does not go beyond \( V_{\text{cpp}} \). Hence, the proposed CPG method can achieve the fast tracking speed in both directions, and it does not cause any oscillations around the CPP-L. The principle in (3) can be applied if the \( P - V \) curve passes through the origin, and it is convex upwards. Its validity is mathematically proved in the Appendix.

On the other hand, there is no CPP-L to be estimated in the MPPT mode, as shown in Fig. 7. Because \( v_{\text{est}} \) might be calculated beyond the open-circuit voltage, \( V_{oc} \) by (3), the PV array faces the risk of open-circuit condition, in which \( P_{\text{pv}} \) is not produced. Therefore, the proposed CPG method restricts
\( v_{pv}^* \) below the maximum voltage of PV array, \( V_{\text{max}} \) as

\[
v_{pv}^* = \min (v_{\text{est}}, V_{\text{max}}).
\]

Thus, \( v_{pv} \) tracks \( V_{\text{max}} \) in the MPPT mode, as shown in Figs. 7(a) and 7(b). In order for the PV array to generate \( P_{\text{mpp}} \), the point corresponding to \( V_{\text{max}} \) must be considered as the MPP. Therefore, \( V_{\text{max}} \) is determined as

\[
V_{\text{max}} = \begin{cases} 
V_{\text{max}}, & \text{when } v_{\text{est}} \leq V_{\text{max}} \\
v_{\text{mpp}}, & \text{when } v_{\text{est}} > V_{\text{max}}.
\end{cases}
\]

Initially, \( V_{\text{max}} \) is set to \( V_{\text{oc}} \) when the PV system starts operating, as shown in Fig. 7(c). Because \( v_{\text{mpp}} \) is the reference voltage from the conventional P&O MPPT algorithm, \( V_{\text{max}} \) can find the voltage on the MPP. Hence, the proposed CPG method can operate as the MPPT control at low irradiance level. In addition, when the irradiance is increased to the CPPT mode, \( v_{\text{est}} \) becomes lower than \( V_{\text{max}} \). Then, the value of \( V_{\text{max}} \) is fixed to the last value of \( v_{\text{mpp}} \), while preparing for the next MPPT mode.

### D. OPERATION IN PARTIAL SHADING CONDITIONS

The proposed CPG method can also be used under partial shading conditions, where the PV array has multiple peaks in the \( P - V \) curve. This is because the \( P - V \) curve with multiple peaks can be considered as the group of \( P - V \) curves with a single peak [30], as shown in Fig. 8. The operating point of PV array is recognized as being on the \( P - V \) curve with a single peak, which passes through the origin and is convex upwards. For example, the \( P - V \) curve in Fig. 8 has multiple CPP-Ls, and any of them can generate \( P_{\text{limit}} \). If \( P_{pv} \) is lower than \( P_{\text{limit}} \), the operating point of PV array will converge to the nearest CPP-L on the right. In contrast, it will converge to the nearest CPP-L on the left if \( P_{pv} \) is higher than \( P_{\text{limit}} \). In addition, the CPP-L with the voltage higher than \( V_{\text{max}} \) cannot be tracked because \( v_{pv}^* \) is restricted to below \( V_{\text{max}} \).

### E. PARAMETER DESIGN FOR TRANSIENT STATE

In order to expect the fast tracking speed for the proposed CPG method, the proper parametric design is required for the transient state. The PV system was shown in Fig. 2, and its transfer function, \( G(s) \), from \( \delta D(s) \) to \( \delta v_{pv}(s) \),
TABLE 1. Parameters of PV system.

| Parameter                  | Symbol | Value       |
|----------------------------|--------|-------------|
| Rated power of PV array    | $P_{\text{rated}}$ | 250 W       |
| Capacitor in PV side       | $C_{\text{pv}}$ | 270 $\mu$F |
| Capacitor in DC-link       | $C_{\text{dc}}$ | 1080 $\mu$F |
| Inductor of boost converter| $L_b$  | 2.2 mH      |
| Inductor of output filter  | $L_f$  | 1 mH        |
| Switching frequency of boost converter | $f_{\text{sw}}$ | 40 kHz |
| DC-link voltage            | $V_{\text{dc}}$ | 100 V       |

is expressed as follow [31].

$$G(s) = \frac{\delta V_{\text{pv}}(s)}{\delta D(s)} = -\frac{V_{\text{dc}}}{L_b C_{\text{pv}} s^2 - L_b K_{\text{pv}} s + 1}$$

(6)

$$K_{\text{pv}} = -\frac{I_0}{A e^{-\left(v_{\text{pv}} + R_s i_{\text{pv}}\right)/A} + I_0 R_s}$$

(7)

where $L_b$ is the inductor of boost converter, $C_{\text{pv}}$ is the capacitor in PV side, and $K_{\text{pv}}$ is the constant of PV array. Also, $I_0$ is the saturation current of PV array, $A$ is the modified diode ideality factor, and $R_s$ is the series resistance of PV array.

The pole-zero map of PV system is shown in Fig. 9, where $K_{\text{pv}}$ is obtained based on the PV module of MSX-60. The design of $C_{\text{pv}}$ affects both real and imaginary parts, which are in a tradeoff relationship. Thus, when $C_{\text{pv}}$ is low, the system shows a fast response with high frequency of oscillations. On the other hand, the design of $L_b$ only affects the imaginary part. The higher $L_b$ shows the lower frequency of oscillations. Therefore, it is important to design $C_{\text{pv}}$ to a low value, while considering the oscillations through $L_b$. The rise time, $T_{\text{rise}}$, which is the time required for the system to reach 100% of its final value, is obtained as follow:

$$T_{\text{rise}} = \frac{1}{\omega_n \sqrt{1 - \zeta^2}} \left[ \pi - \tan^{-1} \left( \frac{\sqrt{1 - \zeta^2}}{\zeta} \right) \right]$$

(8)

$$\omega_n = \frac{1}{\sqrt{L_b C_{\text{pv}}}}$$

(9)

$$\zeta = -\frac{K_{\text{pv}}}{2} \sqrt{\frac{L_b}{C_{\text{pv}}}}$$

(10)

where $\omega_n$ and $\zeta$ are the natural frequency and damping ratio of PV system, respectively. The rise time analyzed for $C_{\text{pv}}$ and $L_b$ is shown in Fig. 10. As with the result in the pole-zero map, small $C_{\text{pv}}$ is required to achieve a fast response in the transient state. In addition, $L_b$ affects $T_{\text{rise}}$ through the frequency of oscillations. In this paper, $C_{\text{pv}}$ and $L_b$ are set to 270 $\mu$F and 2.2 mH, respectively. Then, $T_{\text{rise}}$ is obtained as 1.2 ms, which can be neglected due to its small value during the operation of proposed CPG method.

III. SIMULATION RESULTS

Several case studies are carried out in simulation to evaluate the performance of proposed CPG method when the external condition is changed. The parameters of PV system in Fig. 2 are listed in Table 1. Also, $v_{\text{step}}$ and $T_{\text{step}}$ for the MPPT mode only are set to 0.2 V and 0.05 s, respectively. $P_{\text{limit}}$ is determined as 150 W.

A. CASE 1: INITIAL SETTING OF $V_{\text{max}}$

When the PV system starts operating under the constant irradiance at 600 W/m$^2$, the results are shown in Fig. 11. The initial operating point of PV array is on point A in Fig. 11(a), and $V_{\text{max}}$ is set to 82 V, which is $V_{\text{oc}}$ in this irradiance level. Because $v_{\text{est}}$ is calculated much higher than $V_{\text{max}}$, the proposed CPG method tracks $V_{\text{max}}$, which is determined by the P&O MPPT algorithm. Therefore, the operating point moves toward the MPP along the $P - V$ curve. Because $v_{\text{est}}$ is still...
obtained higher than $V_{\text{max}}$ on points B and C, the proposed CPG method finally reaches point D, which is the MPP at the irradiance of 600 W/m$^2$. After that, the operating point remains on the MPP by the P&O MPPT algorithm, as shown in Fig. 11(c). Thus, the PV array can generate $P_{\text{mpp}}$ in the MPPT mode.

**B. CASE 2: INCREASE OF IRRADIANCE**

In this case, the irradiance is suddenly increased from 600 W/m$^2$ to 700 W/m$^2$ to observe the trajectory of operating point on the $P - V$ curve. The results are shown in Fig. 12. Initially, the operating point of PV array is on point A, which is the MPP at the irradiance of 600 W/m$^2$, as shown in Fig. 12(a). When the irradiance is increased to 700 W/m$^2$ at 0.2 s, the operating point becomes point B while maintaining $v_{\text{pv}}$. Then, the CPP-L at the irradiance of 700 W/m$^2$ is estimated as point B’, and $v_{\text{est}}$ becomes lower than $V_{\text{max}}$. Thus, the proposed CPG method tracks $v_{\text{est}}$, and it fixes $V_{\text{max}}$ to the last value, as shown in Fig. 12(c). As the result, the operating point starts moving towards point B’ along the $P - V$ curve. During this process, the operating point can be on point C, where the proposed method estimates the CPP-L as point C’. Then, the operating point now moves towards point C’. Note that $v_{\text{est}}$ approaches to $V_{\text{cpp}}$ when the operating point is closer to the CPP-L. Therefore, the operating point converges to point D’, which is the real CPP-L at the irradiance of 700 W/m$^2$. Furthermore, the excess $P_{\text{pv}}$ is rapidly reduced to $P_{\text{limit}}$, as shown in Fig. 12(b). It is verified that the proposed CPG method is able to rapidly track the CPP-L when the irradiance is increased to the CPPT mode, while alleviating the effect of overshoot.

**C. CASE 3: DECREASE OF IRRADIANCE**

The irradiance is suddenly decreased from 700 W/m$^2$ to 600 W/m$^2$. The results are shown in Fig. 13. The operating point of PV array is initially on point A, which is the CPP-L at the irradiance of 700 W/m$^2$, as shown in Fig. 13(a). When the irradiance is decreased to 600 W/m$^2$ at 0.1 s, the operating point becomes point B while maintaining $v_{\text{pv}}$. Then, the
The proposed CPG method estimates the CPP-L as point B', and thereby it makes the operating point move towards point B' along the $P-V$ curve. When the operating point is on point C, $v_{est}$ becomes higher than $V_{max}$, which was fixed as in Case 2, as shown in Fig. 13(c). After that, the proposed CPG method tracks $V_{max}$, which is determined by the P&O MPPT algorithm. As the result, the operating point converges to point D, which is the MPP at the irradiance of 600 W/m$^2$. Furthermore, the decreased $P_{pv}$ is rapidly recovered to $P_{mpp}$, as shown in Fig. 13(b). In other words, the proposed CPG method can rapidly track the MPP when the irradiance is decreased to the MPPT mode, thereby reducing the generation loss.

IV. EXPERIMENTAL VERIFICATIONS

The practical effectiveness of proposed CPG method is verified by experimental tests. In particular, its performance is compared with that of conventional P&O CPG [16] and VSS CPG [27] methods. The same parameters of PV system as the simulation study are used (see Table 1). The boost converter of PV system is implemented by the intelligent power module of IFCM30T65GD, and it is controlled by DSP of TMS320F28377. The PV array and grid-connected inverter are emulated by using the Solvert PV simulator and p-Cube battery simulator, respectively. The hardware setup is shown in Fig. 14.

![Figure 14. Hardware setup for the experimental test.](image)

For all CPG methods, $v_{step}$ and $T_{step}$ are set to 0.5 V and 1 s, respectively. To compare the performances of CPG methods, the tracking error (TE) [16] is calculated by (11). It indicates how fast the CPG method tracks the CPP-L under the changes of external condition. That is, the low value of TE means that the CPG method can successfully reduce the output overshoot and generation loss. Several hardware experimental tests are carried out with various values of $P_{limit}$ when the irradiance is changed, and vice versa.

$$TE = \frac{\int |P_{pv} - P_{limit}|}{\int |P_{pv}|} \times 100. \quad (11)$$

A. CASE I: CHANGE OF IRRADIANCE IN LOW $P_{limit}$

In this case, the irradiance is increased from 600 W/m$^2$ to 1000 W/m$^2$, and then it is returned to 600 W/m$^2$, as shown in Fig. 15. Also, $P_{limit}$ is set to 125 W (i.e., 50% of $P_{rated}$) such that the boost converter always operates in the CPPT mode, even when the irradiance is changed. The experimental results are shown in Fig. 16. It is clearly observed that the large overshoot and generation loss occur by the conventional CPG methods when the irradiance is changed. In contrast, the proposed CPG method effectively maintains $P_{pv}$ to $P_{limit}$. Also, the response of $v_{pv}$ verifies that the proposed CPG method provides much faster tracking speed by estimating $V_{cpp}$ in real-time without using $T_{step}$. Correspondingly, the TEs of 11.48%, 9.88%, and 1.32% are obtained by the P&O CPG, VSS CPG, and proposed CPG methods, respectively.

B. CASE II: CHANGE OF IRRADIANCE IN HIGH $P_{limit}$

The same change of irradiance as in Case I is applied to this case. However, $P_{limit}$ is increased to 200 W, which is 80% of $P_{rated}$. The experimental results are shown in Fig. 17. Due to the high $P_{limit}$, the boost converter operates in the CPPT mode from 60 s to 140 s, whereas it operates in the MPPT mode during the other time periods. Like in Case I, the proposed
FIGURE 15. Variations of irradiance applied for cases I and II.

FIGURE 16. Experimental results for the change of irradiance in low $P_{\text{limit}}$ (Case I). (a) $P_{\text{pv}}$. (b) $v_{\text{pv}}$. (c) Trajectory of operating point on the $P-V$ curve.

CPG method still shows the best performances with the less overshoot and generation loss in $P_{\text{pv}}$ and faster response for $v_{\text{pv}}$, than the other conventional CPG methods. Because the VSS CPG method adjusts the step size of voltage only when $P_{\text{pv}}$ is higher than $P_{\text{limit}}$, the generation loss is not improved, when compared to the P&O CPG method. Correspondingly, the TEs of 9.25%, 5.47%, and 1.74% are obtained by the P&O CPG, VSS CPG, and proposed CPG methods, respectively. Also, it is observed that the proposed method successfully generates $P_{\text{mpp}}$ in the MPPT mode, as the conventional CPG methods do.

C. CASE III: CONSTANT IRRADIANCE WITH THE CHANGE OF $P_{\text{limit}}$

In this case, the irradiance of 1000 W/m$^2$ is kept constant. However, $P_{\text{limit}}$ is changed in the following order: 300 W $\rightarrow$ 200 W $\rightarrow$ 125 W $\rightarrow$ 200 W $\rightarrow$ 300 W. The experimental results are shown in Fig. 18. It is observed that all CPG methods successfully track the CPP-L even when $P_{\text{limit}}$ is changed. Nevertheless, the proposed CPG method still shows the fastest tracking performance for the CPP-L. The TEs by the P&O CPG, VSS CPG, and proposed CPG methods are 18.16%, 11.88%, and 1.64%, respectively. In summary, all experimental results clearly verify that the proposed CPG method can give the most effective solution to generate the desired constant power for PV system.
V. HARDWARE-IN-THE-LOOP TEST

The hardware-in-the-loop (HIL) test is carried out to demonstrate the superiority of the proposed CPG method. The HIL system makes it easy to test different methods under various conditions. Therefore, a number of state-of-the-art methods, such as the Power-based CPG [18], Current-based CPG [16], General CPG [25], P&O CPG [16], and VSS CPG [27] methods, are implemented on the DSP controller. The NovaCor real-time digital simulator (RTDS) is shown in Fig. 19, which is used in this test. The parameters of the PV system are the same as those in the simulation and experimental studies (see Table 1). The tests are conducted according to profiles for irradiance, $P_{\text{limit}}$, and partial shading conditions.

A. CASE I: CHANGE OF IRRADIANCE

The profile for the change of irradiance is shown in Fig. 20(a), and $P_{\text{limit}}$ is set to 125 W. The HIL test results are shown in Figs. 20(b) and 20(c). It is observed that the Power-based CPG method is vulnerable to measurement noise, thereby showing the momentary control error even at the constant irradiance. In addition, the short-circuit protection is triggered in the results of the Current-based CPG method under the rapid decrease of irradiance. Thus, these methods have the risk of destabilizing the system. The conventional voltage-based methods (i.e., General CPG, P&O CPG, and VSS CPG)
methods) operate the system stably, but they have slow tracking speed. Therefore, the large power variations are shown under the change of irradiance, similar to the experimental results. In contrast, the proposed CPG method can achieve both stability and high speed performances.

B. CASE II: CHANGE OF $P_{\text{limit}}$

The profile for the change of $P_{\text{limit}}$ is shown in Fig. 21(a), and the irradiance is set to 1000 W/m$^2$. The P&O CPG and VSS CPG methods show the similar results as in the experimental tests. As previously mentioned, the General CPG method uses only two voltage step sizes so that it shows poor tracking performance rather than the VSS CPG method. Note that the superiority of proposed CPG method is demonstrated when $P_{\text{limit}}$ is increased. It performs the real-time tracking operation even when $P_{\text{pv}}$ is lower than $P_{\text{limit}}$, while the other methods run in a repetitive step approach.

C. CASE III: PARTIAL SHADING CONDITION

In this case, half of PV modules that make up the PV array are shaded. The shaded modules are connected in series with the unshaded ones. The irradiance of shaded modules is set to 600 W/m$^2$, while that of others is kept in 1000 W/m$^2$, as shown in Fig. 22(a). Then, the PV array has multiple peaks in the $P-V$ curve, as shown in Fig. 22(d). If the CPG method is confused under the partial shading condition, it might track the local peak, which leads the generation loss. According to the results, only the proposed CPG and Current-based CPG methods correctly track the CPPs due to the fast tracking.
TABLE 2. Comparison of CPG methods by cases.

| Method         | TE(%) in Case i | TE(%) in Case ii | TE(%) in Case iii |
|----------------|-----------------|------------------|-------------------|
| Current-based CPG[18] | 12.85           | 4.99             | 1.80              |
| Power-based CPG[16]     | 8.98            | 8.57             | 19.30             |
| General CPG[25]         | 10.37           | 13.94            | 17.56             |
| P&O CPG[16]             | 11.03           | 18.80            | 16.79             |
| VSS CPG[27]             | 10.60           | 9.53             | 16.48             |
| Proposed CPG            | 1.38            | 3.23             | 1.51              |

The practical effectiveness of proposed CPG method was verified by several case studies based on the experimental and hardware-in-the-loop tests. The results showed that the proposed CPG method effectively mitigates the power variations with the fast response to changes of external conditions. It is expected that the proposed CPG method can further increase the penetration level of PV system to power grid.

VI. CONCLUSION

This paper proposed the new constant power generation (CPG) method for photovoltaic (PV) systems when the external conditions are changed. The proposed CPG method estimates the constant power point (CPP) of PV array in real-time without use of time step, and therefore it provides the much faster response with a less tracking error than the conventional CPG methods. As the result, it can significantly reduce both the overshoot and generation loss of PV system.

APPENDIX

A. VALIDITY OF OPERATING PRINCIPLE OF PROPOSED METHOD

The validity of (3) can be mathematically proved by the monotone convergence theorem. There are two lemmas for the property of converge in below [32].

**Lemma 1:** If a sequence \( \{x_n\} \) of real numbers is increasing and bounded above, then it converges to the limit.

**Lemma 2:** If a sequence \( \{x_n\} \) of real numbers is decreasing and bounded below, then it converges to the limit.

Assume that the function, \( f(x) \) passes through the origin, and it is convex upwards, as shown in Fig. 23. Suppose that there exists \( \alpha \) satisfying \( f(\alpha) = C \) for some \( C > 0 \). Then, (3) can be expressed with the sequence \( \{x_n\} \) as

\[
x_{n+1} = \frac{C}{f(x_n)} \cdot x_n.
\]  

(A.1)

Firstly, for the region 2 of Fig. 23, since \( f(x_n) > C \), the statement, \( x_n > x_{n+1} \) is true for all \( n \in \mathbb{N} \). Therefore, it is clear that the sequence, \( \{x_n\} \), is decreasing. Next, since \( f(x) \) passes through the origin, and it is convex upwards, the following inequality holds.

\[
f(t \cdot x) \geq t \cdot f(x) \quad \text{for} \quad t \geq 1.\]  

(A.2)

Since \( x_n > \alpha \), the following inequality also holds.

\[
C = f(\frac{\alpha}{x_n} \cdot x_n) \geq \frac{\alpha}{x_n} \cdot f(x_n).\]  

(A.3)

Then, the statement, \( x_{n+1} \geq \alpha \) is true for all \( n \in \mathbb{N} \). Therefore, it is clear that the sequence, \( \{x_n\} \), is bounded above in the region 1, it can be also proved that the sequence, \( \{x_n\} \), converges to \( \alpha \) as \( n \to \infty \) by the lemma 2. Because it is increasing, and it is bounded above in the region 1, it can be also proved that the sequence, \( \{x_n\} \), converges to \( \alpha \) as \( n \to \infty \) by the lemma 1.

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