Frequency support control of two-stage photovoltaic grid-connected system based on virtual governor

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Abstract
Given the urgent need for photovoltaic (PV) energy to participate in grid frequency regulation, a control strategy of the DC/DC converter of a two-stage PV system based on the virtual governor (PV-VG) is proposed in this paper. First, a one-step PV maximum power point estimation (MPPE) method is proposed, which can obtain the reference voltage corresponding to the maximum power point and the power deload point, and some complex iterative calculations and sampling processes are circumvented. Then, based on the constant DC bus voltage of the two-stage PV system, the coupling mathematical model of boost circuit duty cycle ($D$) and PV output power is established. According to the power setting and frequency deviation, the $D$ is taken as the direct control target to reflect the direct coupling characteristics of $D$ and grid frequency ($f$) so that the PV system can adjust the output power reference independently according to the grid frequency deviation. Finally, a simulation model is built in Matlab/Simulink and RT-LAB, and the results show that the accuracy of the proposed one-step MPPE method is over 99.8%, and the correctness and efficiency of the PV-VG control strategy are verified in some case study.

1 | INTRODUCTION

Photovoltaic (PV) power generation is the most important clean and renewable energy at present. Centralised development and grid connection is the best way to achieve efficient utilisation and consumption. With the large-scale integration of new energy such as wind and PV power into the grid, the active reserve capacity of the system will be weakened, and the frequency stability characteristics of the power system will be changed. With the same disturbance (such as external power loss caused by short-circuit fault), the grid frequency of high-permeability PV-plants will drop faster and deeper [1–3]. Therefore, as large-scale PV power generation is injected into the grid, the grid urgently needs to be able to provide certain active power support ability to improve its adaptability to grid frequency [4, 5].

The traditional frequency regulation (FR) control of PV system needs additional energy storage systems to provide frequency modulation power, which will increase the investment cost of the PV system, which is not the best way. Different from maximum power tracking (MPPT) mode operation, the PV grid-connected system operates in power deload control (PDC) mode, and it can keep part of the active power up-regulation capacity in real time to meet the demand of grid FR, without additional energy storage devices [6–10]. However, the premise of running in PDC mode is that the current maximum output power ($P_{\text{max}}$) is known, that is to say, the $P_{\text{max}}$ of PV system must be calculated in real time through the maximum power point estimation (MPPE) link as shown in Figure 1. A fast and accurate MPPE method is the necessary prerequisite for realising the active power reserve of the PV system and participating in FR [11–15].

Because of the above problem, in [8], first, the iterative method is used to calculate the parameters of PV modules; then, the linear regression method is used to fit the relationship between output power, irradiance ($G$) and temperature ($T$), and MPPE is realised according to the real-time $G$ and $T$ data lookup table. In [9], the Newton–Raphson iterative method

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is used to calculate the parameters of PV modules, and then the Levenberg–Marquardt (L-M) algorithm is used to solve the $P_{\text{max}}$. The above techniques need to use the iterative process to solve the PV module parameters, and clear $G$ and $T$ data are necessary, and its needs to obtain the specific irradiance and temperature of PV modules in real time by setting multiple sensor devices, which is difficult in the actual PV station.

Therefore, the sensorless MPPE method has been proposed successively. In [10], three operation points of the $P-V$ curve are sampled, and then the reference power value is obtained by the quadratic interpolation method. In [11, 12], ripple control is used to sample operation point data in real time; then, the L-M algorithm is used to calculate $G$ and $T$; finally, Lambert W function is used to calculate $P_{\text{max}}$. In [13], the master-slave control is adopted in the parallel PV arrays, in which the master array operates in MPPT mode, and $P_{\text{max}}$ is taken as the reference of the slave. In [14], the method of approximate open-circuit voltage is used to estimate the maximum power point voltage quickly, and the MPPE and PDC are realised through continuous mode switching. In [15], the short-circuit current and the maximum power point current are approximately calculated by sampling two operating points located on the linear region of the PV $I-V$ curve, and then the maximum power point voltage is calculated by Lambert W function.

However, the above methods must sample multiple operation points or need fast switching between control modes, and both parameter iterative solution and approximation methods need a multistep operation to realise MPPE, which increases the complexity of MPPE and reduces the reliability and response speed of the system.

In view of this, this paper proposes a control strategy of the DC/DC converter based on the virtual governor (VG), and the main features of this paper are as follows:

1. To achieve the PDC, a one-step PV MPPE method is proposed to obtain the maximum available power, which directly reflects the approximately linear relationship between PV output voltage and active power.
2. With the principle of boost circuit of DC/DC converter, the coupling mathematical model of duty cycle $D$ and output power is established. The duty cycle $D$ is used as the ‘valve’ control signal to release or reduce the PV output power to realise the direct coupling control of $P-D$, which not only has faster control speed but also has lower control complexity and output fluctuation.
3. VG control (VGC) calculates the frequency modulation power of the PV system in real time. It updates the reference power value of PV output power in real time, which realises the direct coupling control of duty cycle and frequency ($f-D$).

Comparison with the published method is shown in Table 1, and the content of this paper is arranged as follows. In Section 2, the structure of the two-stage PV grid-connected system and the control principle of the VG are introduced. The one-step MPPE method is introduced in Section 3. In Section 4, the VGC of the DC/DC converter is designed. In Section 5, a simulation model was built in Matlab/Simulink and RT-LAB, and some case study is used to verify the effectiveness of the proposed method. Finally, Section 6 summarises the main research work of this paper.

2 | INTRODUCTION OF TWO-STAGE PV SYSTEMS

2.1 | Two-stage PV grid-connected system

The two-stage PV grid-connected system is shown in Figure 1, in which the former DC/DC converter (boost circuit) realises the output active power control (such as MPPT control and PDC) of the PV arrays and raises the PV output voltage to the working range of the inverter, common power control

![Diagram of power deload control (PDC) of photovoltaic (PV) systems](image-url)
TABLE 1 Comparison between this paper and published maximum power point estimation (MPPE) method

| Method       | Control method     | Control complexity | Speed of MPPE | Operating point in steady state | Wave of output | Operating range |
|--------------|--------------------|--------------------|---------------|---------------------------------|----------------|-----------------|
| [15]         | Disturbance control| Medium             | Medium        | Repeated sampling               | Big            | Narrow          |
| [16]         | Disturbance control| Simple             | Fast          | Repeated sampling               | Small          | Medium          |
| [13]         | Ripple and PI control| Complex          | Medium        | Repeated sampling               | Medium         | Wide            |
| This paper   | Direct duty cycle control| Simple           | Fast          | Constant                        | Small          | Wide            |

FIGURE 2 Two-stage PV grid-connected system and virtual governor (VGC) control methods such as disturbance observation, conductance increment, constant voltage and constant power methods [16–18]. The middle DC capacitor (Cdc) link stabilises the DC bus line voltage and buffered PV output peak power. And DC/AC converter to realize power conversion DC/AC inverter to achieve power conversion, DC bus voltage and reactive power control [19], clarify the function and control purpose of the converter at all levels is the basis of PV system optimisation control. To sum up, the two-stage PV grid-connected system participates in the FR of the system and mainly relies on the DC/DC converter to adjust the PV output power in real time [14, 15].

2.2 Principle of PV VGC

The principle of PV-VGC is shown in Figure 2 and the symbol explanation in Table 2. The critical power $P_e$ is set by the administrator, when the PV output power is higher than $P_e$, and the PV system can be switched from MPPT to PDC mode to maintain the active reserve and participate in grid FR. The integrated FR control link ($P_f$ droop and $df/dt$ inertia response (IR)) adjusts the FR power in real time according to the grid frequency deviation. It then updates the PV output power reference value $P_{ref}$ as shown in Equation (1):

$$P_{ref} = P_{mppe} - \Delta P + \Delta P_1 + \Delta P_2 \quad (1)$$

where $P_{mppe}$ is the maximum available power values for MPPE output. MPPE is a necessary prerequisite for the realisation of precision FR power control of PV systems. Therefore, an efficient and fast MPPE method is essential and will be introduce in the next section. Based on MPPE, the output reference voltage is calculated according to the $P-V$ curve, and finally, the duty cycle $D$ is adjusted to achieve power control.

The whole process realises the signal transmission of $f \rightarrow P \rightarrow V \rightarrow D$, and the external characteristics reflect the control characteristics of $f-D$, and the transmission process is a simple linear calculation, so it has a faster power tracking speed.

3 THE PROPOSED MPPE METHOD

3.1 One-step MPPE method

There are two options for PV-PDC operation areas shown in Figure 2. The existing research shows that the PDC operation region is feasible on both sides, just to ensure the safe operation of the system [12, 14, 20, 21]. In this paper, the system is expected to operate in the linear area of $P-V$ curve, so region I is selected as the PDC operation region.

Under fixed irradiance and temperature conditions, the open-circuit voltage ($V_{oc}$) of the PV module and the maximum power point voltage ($V_{mpp}$) have an approximately linear relationship as follows [15]:

$$V_{mpp} = K \times V_{oc} \quad (2)$$

where the value of $K$ ranges from 0.78 to 0.88, which depends on the PV module. As can be seen from Table 3, the $K$ selected in this paper is 0.852 ($K = V_{mpp}/V_{oc} = 54.7/64.2$). It is worth noting that, $V_{oc}$ is less affected by irradiance, as shown in Figure 3, when the irradiance is in the range 0.6 to 1 kW/m², the $V_{oc}$ changes are minimal, and the $V_{mpp}$ value is relatively close. Because it operates in the PDC mode only when the PV output is higher than the critical power, it can be approximated that the $V_{oc}$ and the $V_{mpp}$ always remain constant during operation.
TABLE 2  Description of symbols in Figure 2

| Symbol | Description | Symbol | Description |
|--------|-------------|--------|-------------|
| I_{pv} | Output current of photovoltaic (PV) | V_{dc}  | Output voltage of inverter |
| V_{pv} | Output voltage of PV | I_{dc}  | Output current of inverter |
| V_{pv,ref} | Reference output voltage of PV | f | Frequency of grid |
| C_{pv}  | Capacitance of PV | θ  | AC voltage phase angle |
| C_{dc}  | Capacitance of DC bus | P_{pv}  | Output power of PV |
| V_{dc}  | DC bus voltage | MPPE  | Maximum power point estimation |
| V_{dc,ref} | Reference voltage of DC bus | ΔP_{1}  | Active power increment of droop control |
| D  | Duty cycle | ΔP_{2}  | Active power increment of inertia response |
| D_{ref} | Reference of duty cycle | P_{c}  | Critical power operating in maximum power tracking or power deload control mode |
| PLL  | Phase lock loop | VOC  | Voltage orientation control |

TABLE 3  Parameters of PV module (SPR-305E-WHT-D)

| Parameters | Value |
|------------|-------|
| Maximum power (P_{max}) | 305.2 W |
| Open circuit voltage (V_{oc}) | 64.2 V |
| Short circuit current (I_{sc}) | 5.96 A |
| Voltage at maximum power point (V_{mpp}) | 54.7 V |
| Current at maximum power point (I_{mpp}) | 5.58 A |
| Series\(\times\)parallel (N_s\(\times\)N_p) | 5\(\times\)66 |

FIGURE 3  P-V curve in different irradiance

In the two-stage PV grid-connected system, the former DC/DC converter uses a boost circuit. In this circuit, the input voltage is the PV array output voltage V_{pv}, and the boost circuit output voltage is the DC bus voltage V_{dc}. Then, the linear relationship between V_{pv} and V_{dc} can be represented by

Equation (3):

\[
\frac{V_{pv}}{V_{dc}} = 1 - D
\]  

where V_{dc} generally remains constant as a known quantity under the DC loop control of the inverter, so only the voltage corresponding to the given power reference value needs to be obtained to obtain the duty cycle D directly.

The left side of the V_{mpp} of the P-V curve can be equivalent to a linear region, and the linear curve passes through the origin (0,0), which can be expressed by a linear expression passing through the origin, and its slope can be expressed by Equation (4), which is the same as the PV output current.

\[
\tan \theta = \frac{P_{pv}}{V_{pv}}
\]  

Then, the maximum output power P_{max} can be expressed as

\[
P_{max} = V_{mpp} \cdot \tan \theta
\]  

Combining Equation (2), P_{max} can be expressed as Equation (6):

\[
P_{max} = V_{dc} \cdot K \cdot \tan \theta
\]  

From Equation (6), the maximum power can be estimated in real time. It is worth noting that this process does not need complicated calculation or additional irradiance sensor and only requires a simple one-step linear calculation to obtain P_{max}.

After introducing the active reserve, the PV output power can be expressed as

\[
P_{pv} = P_{max} - \Delta P
\]  

The duty cycle reference value can be calculated directly by combining Equations (3) (6) and (7) as shown in the following:
From Equation (8), the duty cycle of the boost circuit corresponding to any output power can be calculated in one step. When the maximum output power of the PV system is lower than the critical power, it only needs to set the reserve power to 0 to operate in MPPT mode, without switching between control modes, which reduces the complexity of PDC and FR and is more conducive to the stable operation of the system.

### 3.2 Selection principle of K value

It should be noted that $K$ is set to a constant value when operating in the PDC mode; since $\tan \theta$ changes with the reserved power level, the MPPE estimation value will have a large deviation, as shown in Figure 4, when the reserved power is set to 10% $P_{pv}$, and the ideal working point should be at point A, but the actual operation is at point B due to the MPPE estimation error. The output power can be express as

$$
D = 1 - \frac{P_{pv}/\tan \theta}{V_{dc}}
$$

(8)

where $P_{pv}$ is the MPPE droop coefficient of PFR.

It can be seen from Figure 4 that the estimated maximum power $P_{mppe}$ operating in the PDC mode will be higher than the actual value $P_{max}$, and the MPPE deviation will become more serious with the increase of the reserved power level, which will not lead to the output instability of the PV system but will result in the inaccuracy of the reserve power, leading to the misjudgment of the FR ability of the PV system.

Under standard conditions ($G = 1000 \text{ W/m}^2, T = 25^\circ \text{C}$), when the initial reserve power is set to 0, and then (0.5–2.5 s) is increased to 30 kW at the rate of 15 kW/s, the constant $K$ is used in MPPE process (the parameters of the PV system in [22] are adopted). The $\tan \theta$ is calculated in real time by the measured voltage and current, and its change trend is shown in Figure 5(b). Obviously, when running in PDC mode, due to the increase of $\tan \theta$, the estimated value of MPPE error is more severe, as shown in Figures 5(a) and (c), which is consistent with the conclusion of Equation (5).

To eliminate $P_{error}$, it is necessary to couple the selection of $K$ value with the level of power reserve to compensate for the error caused by the increase of $\tan \theta$. For this purpose, the correction factor is defined, and its change trend is shown in Figure 5(d), so Equation (1) can be converted into:

$$
V_{mppe} = K' \times V_{ac} = (K/\eta) \times V_{ac}
$$

(10)

where $\eta$ selection is related to standby power. It is represented by $\tan \theta$ from the increment under different reserved levels, as shown in Figure 5(d), and the expression of curve fitting for it is shown as

$$
\eta = a \times \tan \left(\Delta P \times 1 \cdot \epsilon^{-3} \right) + b \times \Delta P + \epsilon
$$

(11)

where the values of the coefficients are, respectively, $a = 0.03547$, $b = 3.681e$, $\epsilon = 0.9927$.

In summary, substituting Equations (11) into (10), the selection of $K$ will be coupled with the reserve power, which is equivalent to translating $K \times V_{ac}$ to the left, improving the MPPE precision, and ensuring the accuracy of PV output power regulation. The expression of $\eta$ is fitted under the standard conditions. Generally, the active reserve is only kept when the PV output is high (the irradiance is above 0.6 kW/m$^2$), so it can be approximately considered that the selection rules are unchanged under different irradiance conditions.

### 4 VGC FOR PV SYSTEMS

The FR control is composed of droop and IR controls, in which droop control simulates the power-frequency ($P_f$) characteristics of synchronous generator primary FR (PFR) and adds an increment $\Delta P_1$ to the active reference value according to the frequency deviation $\Delta f$. In contrast, IR control adds an increase $\Delta P_2$ to the active reference value according to the rate of change of frequency by simulating the swing equation of the synchronous generator. The mathematical model is shown in Equation (12):

$$
P_{f_{\text{act}}} = \frac{\Delta P_1}{P_{\text{F}}} + \left(\frac{df}{dt}\right) \frac{\Delta P_2}{D_{d-f}} + \left(\frac{df}{dt}\right) \frac{\Delta P_{\text{act}}}{D_{d-f}}
$$

(12)

where $P_{f_{\text{act}}}$ is the power required for FR; $f_n$ and $f_{grid}$ are the actual frequency and rated frequency of power grid, respectively; $D_{p-f}$ is the droop coefficient of PFR; $D_{d-f}$ is the IR coefficient.
After considering the FR power, the reference of PV output power ($P'_{pv}$) is converted from Equations (7) to (13). It should be noted that when the power required for FR is higher than the reserved power, the PV system outputs the maximum available power to operate in MPPT mode. With the grid frequency increases, when the PV output power is reduced by 30% of $P_N$, it can no longer be reduced.

$$
P'_{pv} = \begin{cases} 
    P_{mpp} & \Delta P' \geq 0 \\
    P_{mpp} - \Delta P + P_{j,	ext{need}} - 0.3P_n & -0.3P_n \leq \Delta P' < 0 \\
    P_{mpp} - 0.3P_n & \Delta P' \leq -0.3P_n
\end{cases} (13)$$

where $\Delta P' = P_{j,	ext{need}} - \Delta P$, is the remaining reserved active power of the PV system after considering FR.

The PV-VGC control model is composed of Equations (7), (11) and (12), and the flowchart is shown in Figure 6. First, it is necessary to sample the PV output voltage and current to calculate the output power in real time. When the PV output power is less than the preset critical power $P_c$, the system operates in MPPT mode as shown in block 1 in Figure 6. While the PV output power is higher than the $P_c$, the PV system will work in MPPT or PDC mode according to the upper administrator’s decision. If working in PDC mode, update in real time according to the reserve power capacity (use Equation 11), then Equations (9) and (4) are used to calculate the maximum power (MPPE block in Figure 6). It can be seen that MPPE is a simple numerical operation, so the process of MPPE is swift.

If the grid frequency deviation exceeds the preset deadband threshold, operating in VGC mode, the PV output power value is reset according to the reserved power and grid frequency deviation as shown in Equations (12) and (13). It is worth noting that there is no need for complex calculation and control in this process, and the duty cycle reference is calculated according to the expected value of the PV system output power as shown in blocks 2 and 3 in Figure 6.

### 4.1 Simulation analysis

In order to verify the correctness and efficiency of the proposed method, a 100 kW two-stage PV grid-connected simulation
system is built in Matlab/Simulink, and the main parameters of the grid-connected system are shown in [22].

4.2 Case1: Verify the effectiveness of PDC

First, critical power \( P_c \) is set to 60\%\( P_N \). If the PV output exceeds the \( P_c \), the system is operated in PDC mode autonomously, and the initial delta power is set to 15\%\( P_N \). During the whole process, the system frequency remains constant. The simulation output waveform is shown in Figure 7.

Figure 7(a) shows the comparison of output power running in MPPT (MPPT output power has the same meaning as \( P_{max} \)), PDC modes, and MPPE, respectively. During the whole operation process, MPPE always keeps a high accuracy, and the estimated accuracy remains above 99.8\% (the error remains within 200 W). The comparison between the reference value of reserved power (\( \Delta P \)) and the actual value is shown in Figure 7(b). During the operation of PDC mode, the reserved power is always tracked around the reference of 15\%\( P_N \), and the output fluctuation is caused by the change of irradiance but always within a certain range.

The output voltage and current comparison waveforms are shown in Figures 7(c) and 8(a), respectively. In the PDC mode, the output voltage and current are less than and higher than the maximum power voltage and current, which is consistent with the design of PDC mode operating on the left side of MPP. As the voltage in PDC mode is less than that in MPPT mode, it can be seen from Equation (3) that the duty cycle in PDC mode is higher than that in MPPT mode as shown in Figure 8(b). Figure 8(c) shows the output waveform of the DC bus voltage. During operation, the DC bus voltage fluctuation is kept...
in a small range (± 2 V), and the range of fluctuation mainly depends on the DC bus capacitance capacity.

To sum up, the one-step MPPE method proposed in this paper has high estimation accuracy and speed in the case of irradiance changes and does not need additional multiple repeated sampling and complex iterative solution process. At the same time, it also verifies the correctness of directly coupling the duty cycle and output power and the effectiveness of the control process shown in Figure 6.

4.3 Case 2: Verify the dynamic performance

To verify the dynamic performance of the method proposed in this paper, a valid test way is to set the simultaneous change of irradiance and Delta P. Set the initial value of irradiance to 0.8 kW/m², and increase at a slope of 0.1 kW/s from 0.25 to 2.25 s, and then keep constant at 1 kW/m². Meanwhile, the change of Delta P is set to 0 from the initial condition, and the change from 0.25 s is as follows:

\[
10\%P_n \rightarrow 15\%P_n \rightarrow 25\%P_n \rightarrow 20\%P_n \rightarrow 5\%P_n \rightarrow 0
\]

The change interval is 0.5 s.

Figure 9(a) shows the comparison of output power in MPPE, MPPT mode and PDC mode. With the irradiance and Delta P changing at the same time, MPPE always has a high accuracy, which lays a foundation for the accuracy of PDC operation. When the Delta P increases abruptly, it can respond quickly, and there is overshoot at the moment of sudden change, but it can soon stabilise near the reference value as shown in Figure 9(b). It is worth noting that compared with [16], the method proposed in this paper can operate in the non-linear region of the P-V curve (5% Pₙ) in PDC mode.
FIGURE 11 Movement trajectory of PV operation point in case of reference active power changes from $P_{\text{max}} \rightarrow 90\% P_{\text{max}} \rightarrow 80\% P_{\text{max}}$ (a) method in [15], (b) method in [16], (c) method in [13], (d) method in this paper.

Figures 9(c) and 10(a), respectively, show the comparison diagram of output voltage and current. It can be seen that in PDC mode, with the change of $\Delta P$, the change of current is smaller, while the change of voltage is larger. With the increase of $\Delta P$, the PV operation point constantly moves to the left of the $P-V$ curve, and the output voltage gradually decreases. It should be noted that due to the limitation of boost circuit, if the $\Delta P$ is too large, the PV output voltage cannot be raised to the average working voltage of the inverter. Therefore, for the sake of economy and safety, the $\Delta P$ should be kept in a specific range in the actual operation process. In future work, the best reserve power selection value will be optimised for the fixed application scenarios.

The duty cycle comparison between the two operation modes is shown in Figure 10(b). With the increase of $\Delta P$, the duty cycle comparison between the two operation modes

FIGURE 12 Result in case 4 (a) system frequency, and active power needed for frequency regulation, (b) output power comparison of MPPE, MPPT, and VGC, (c) comparison of reference and actual $\Delta P$, (d) the change trend of $K$.
cycle increases continuously. This is because the PDC mode operates on the left side of MPP. Figure 10(c) shows the DC bus voltage, with the sudden change in $\Delta P$, the DC bus voltage has overshoot, but it soon stabilises near the reference ($\pm 2$ V). To sum up, when the irradiance and $\Delta P$ change at the same time, the method in this paper can still accurately and quickly respond to the preset commands, with excellent dynamic performance.

4.4 Case 3: Comparison with the other PV-PDC method

The moving trajectory of the $P-V$ curve operation point is the most intuitive embodiment of power regulation in the process of PV-VGC. In order to show the efficiency of the proposed method in this paper, several published methods will be used for comparison.

If the change of reference power is set from $100\% P_{\text{max}} \rightarrow 90\% P_{\text{max}} \rightarrow 80\% P_{\text{max}}$, Figure 11(a) shows the method adopted in [15], which is to use the variable step size disturbance method to move to the preset working point (O $\rightarrow$ A). Besides, because MPPE is needed in real time, it has to switch to the MPP to measure the $P_{\text{max}}$, and then quickly switch to the previous deload working point. It is evident that the moving trajectory of the operating point in this process is repeated between O $\rightarrow$ A $\rightarrow$ O $\rightarrow$ A. In the process of switching from $90\% P_{\text{max}}$ to $80\% P_{\text{max}}$, it also needs to switch back and forth between O $\rightarrow$ B.

Reference [16] does not need to switch back and forth. Because the slope of the $I-V$ curve needs to be calculated in the linear area, two sampling points must be obtained through small-scale disturbance control. As shown in Figure 11(b), at points A and B, small disturbance control is required to be applied continuously for MPPE. However, the MPPE method can only be used in the linear region. If the reserved power is low and needs to work in the non-linear region, the method will not be applicable.

In [13], the output power is directly controlled by proportional integral (PI) control. To realise MPPE, ripple control must conduct reciprocating sampling in each cycle, then the maximum power is calculated by the L-M algorithm. Due to the
addition of ripple control, the fluctuation of PV output power is relatively large as shown in Figure 11(c).

The method proposed in this paper is shown in Figure 11(d). In the MPPE process, only the slope of the $P-V$ curve needs to be calculated in real time. With the standby power changes, only the values of $K$ need to be corrected in real time, according to Equations (9) and (10). Therefore, when reaching a steady state, there is no need for the complex disturbance sampling process or other iterative operations.

4.5 Case 4: Verify the VGC for the PV system

In order to verify the adaptability of the PV system to grid frequency, grid frequency mutation is the best test method. The grid frequency is set to drop suddenly by 0.3 Hz in $t = 1$ s and is returned to 60 Hz in $t = 1.5$ s; then, it is dropped suddenly by 0.6 Hz in $t = 2$ s, and returned to normal in $t = 2.5$ s; the frequency change trend is shown in Figure 12(a). The droop coefficient $D_p$ is set to 30,000, the moment of inertia $J$ to 0.2 kg·m² ($D_p = J w/dt$), and the initial Delta P to 15% $P_N$.

After detecting the grid frequency change, the VGC first calculates the power required for FR according to the grid frequency deviation. It then recalculates the PV output power reference value according to the preset Delta P. As shown in Figure 12(b), under the control of the VG, the output power of the PV system is independently regulated to participate in FR. The MPPE link estimates the maximum power in real time to provide a reference for power control. Due to the limitation of Delta P, the FR ability of PV system is limited. When the required FR power exceeds the Delta P, the PV system releases all the standby power and operates in MPPT mode. The change of Delta P is shown in Figure 12(c), with the frequency rising to the rated, the shielding IR, that is, setting $J = 0$ kg·m², can effectively reduce the power overshoot.
It can be seen from the third section that the selection of K value determines the accuracy of MPPE, and the change of K value in the PV-VGC process is shown in Figure 12(d); K and Delta P show a reverse trend, which is consistent with the modified results of Equations (10) and (11), and the accurate MPPE shown in Figure 9(b) also confirms this.

Figures 13(a) and (b), respectively, show the output voltage and current of the PV system. With the Delta P being released, the current shows a downward trend, and the voltage shows a growth trend, indicating that the PV operating point is always on the left side of the P-V curve and can effectively work in the non-linear area of the P-V curve. Figure 13(c) shows the DC bus voltage, which is kept within ±2 V during operation. The change of the duty cycle is shown in Figure 13(d), which once again shows the correctness of the coupling control of the duty cycle and output power in this paper.

4.6 Experimental results

In order to verify the effectiveness of the proposed method, the experimental tests are carried out with the experimental prototypes shown in Figure 14. The experimental platform is composed of RT-LAB (OP5600) real-time simulator and digital signal process (DSP) real-time controller. The model is mainly divided into the following modules: (1) The network table model is loaded into RT-LAB CPU, including infinite power supply, transmission lines, transformers and PV arrays; (2) power electronic converter model, including DC/DC boost circuits and PV inverters, because of more switching elements and higher control frequency require smaller simulation steps so they can be solved in the FPGA of RT-LAB; (3) control algorithm models, including boost circuits and inverter control algorithms, are implemented in DSP. The communication between RTLAB and DSP is through the input / output (I/O) port.

The performance of the proposed method is tested by setting delta power mutation (0→15 kW→25 kW→10 kW) under different irradiation intensities. To facilitate the observation of the output, analogue quantities are converted into voltage signals and converted into the measurement range of the oscilloscope.

The output waveforms of MPPE, P_{pp}, \Delta P_{ref} and \Delta P_{actual} are shown in Figure 15(a). The PV output power has higher tracking accuracy and speed when \Delta P_{ref} is abrupt. The results of the hardware-in-the-loop experiments are consistent with the simulation results, confirming the feasibility of the proposed MPPE method and power control of PV.

The DC bus voltage (V_d), duty cycle (D), output voltage (V_{pp}) and current (I_{pp}) waveform are shown in Figure 15(b). As the \Delta P_{ref} increases, the duty cycle increases and the PV output voltage decreases, which conforms to the expected design.

5 CONCLUSION

This paper proposes a control strategy for the DC/DC converter of a two-stage PV grid-connected system based on the VGC. In order to achieve PDC control, a one-step PV MPPE method is proposed to obtain the maximum available power and modify the PV output voltage and power to a linear approximation. Then, the coupling mathematical model of duty cycle D and output power is established. The duty cycle D is used as a ‘valve’ control signal to release or reduce the PV and reflects the direct coupling control of f-D.

Compared with MPPE and power control methods used in other references, the method adopted in this paper has faster control speed, lower control complexity and output fluctuation. The simulation results show that the accuracy of the proposed MPPE method is more than 99.8%, and the output power can be adjusted autonomously under the control of PV-VGC to participate in FR and maintain a high power regulation accuracy.

The P-V curve will have multiple peaks under partial shading conditions, at this time, the method of approximate open-circuit voltage may lead to the deviation of maximum power point voltage estimation. In future research, we will focus on the sensorless MPPE method under multiple working conditions.

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