A Novel Frequency Regulation Strategy for a PV System Based on the Curtailment Power-Current Curve Tracking Algorithm

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\begin{abstract}

The challenges of modern power systems with a high level of renewable generation penetration will impose increased ancillary service on Photovoltaic (PV) systems, including frequency regulation. In this paper, a frequency regulation strategy for PV systems without energy storage is proposed. The proposed strategy is divided into two layers: the frequency regulation layer and the power reserve control layer. In the power reserve control layer, a novel power reserve control is proposed as the core element and novel feature. The existing power reserve control for PV systems must estimate the maximum available power, which is difficult because of the variation in environmental conditions and complex modeling of PV systems. Instead, a power tracking control method based on a curtailment power-current curve is proposed. It can automatically track a given reserve ratio under any environmental condition without an irradiance sensor. In the frequency regulation layer, the combination of droop control and virtual inertia control is used to adjust the given power reserve ratio. Simulation results show that the proposed strategy offers good accuracy and tracking speed and can significantly improve the frequency response of the power system.

\end{abstract}

\begin{keywords}
PV system, power reserve control, frequency response, voltage tracking.
\end{keywords}

\section{I. INTRODUCTION}

System frequency indicates the balance between power generation and consumption in an electric power grid. It should be maintained within an allowable range at all times to ensure stable operation. Unlike conventional generators, PV systems have no rotor kinetic energy and cannot provide inertial support. In addition, PV systems usually work in maximum power point tracking (MPPT) mode and do not participate in power system frequency regulation. Replacing a large number of conventional generators with PV systems will reduce a system’s inertia and frequency support capability and worsen the power system frequency stability [1]–[3]. One of the reasons for the Great Blackout in the UK on August 9, 2019 was that renewable energy generation accounts for a considerable portion of the British grid, which results in insufficient frequency support power being provided when a frequency event occurs [3].

To minimize this problem, PV generation is now required to participate in frequency regulation in some jurisdictions [4], [5]. PV systems, which have no natural inertia, must reserve a portion of their active power to contribute to frequency regulation. This power reserve capability is typically realized by two methods, either providing energy storage devices [6]–[8] or power reserve control (PRC) [9]–[23]. Furthermore, compared with the installation of energy storage devices, PRC is much simpler and has a lower implementation cost. This paper focuses on the latter method.

The basic concept of PRC is that PV systems (PVs) operate at a suboptimal power point rather than at their maximum power point [10]. Thus, a given amount of active power can be reserved, either in terms of absolute power (kW/MW) or as a fraction of maximum power (reserve ratio). The reserve active power can be released to the system during system contingencies.
To date, several PRC methods have been proposed for PV generation. The critical problem of these methods is how to obtain the maximum available power (MAP). However, MAP is difficult to estimate because it is affected by both irradiance and temperature, especially irradiance. The existing MAP determination methods can be categorized into two categories: direct measurement-based methods and curve-fitting-based methods.

For the former category, in [12], master PVs were engaged in MPPT mode to monitor the MAP, while slave PVs directly utilized the measured MAP. However, this method is only suitable for large PV plants with identical component conditions and requires a communication system. In [13], the PVs alternately worked in MPPT mode and power reserve mode in one period. In the MPPT mode, the constant voltage MPPT method was utilized to quickly measure the MAP. However, this method needs to store the excess energy in a DC capacitor to avoid affecting the grid-side output power, which results in the DC capacitor voltage fluctuating close to its upper limit.

For the latter category, the curve-fitting-based methods can be further classified into three subcategories by means of the curve-fitting function. In terms of the first subcategory, the fitted curve of MAP versus irradiance/temperature is fitted by means of offline test data. Accurate measurements of irradiance and temperature from sensors are required to calculate the MAP in actual weather conditions [14]–[16]. However, additional sensors will increase both the cost and complexity of the whole system.

In the second subcategory, a mathematical modeling of the PV array is applied to estimate the MAP, and the parameters of the modeling are estimated by the voltage and current measurement from the DC/DC converter. In particular, linear-quadratic or quadratic models were employed in [17]–[19], while a single-diode mathematical model was applied in [20] and [21]. Linear-quadratic or quadratic models are simple and easy to calculate but are not accurate and are susceptible to noise. The single-diode mathematical model is more accurate and robust, albeit with complex calculations.

In the third subcategory, MAP has a linear relationship with open-circuit voltage (or short-circuit current), which is utilized to estimate MAP. The linear curve of MAP and open-circuit voltage (or short-circuit current) has previously been fitted according to datasheet values. Once the open-circuit voltage (or short-circuit current) under the actual weather conditions is obtained, the MAP can be calculated according to the linear relationship. In [22] and [23], a small PV module was added to measure the open-circuit voltage (or short-circuit current), which requires additional hardware and increases the cost and complexity. In [24], the short-circuit current was estimated by the sampled current and voltage, but it required PV array parameters and solved the complex Lambert-W function to calculate MAP. Furthermore, compromised by the inevitable deviations of actual PV array parameters from data sheet values, the accuracy of MAP estimates will be affected.

For renewable energy frequency regulation strategies, the commonly used methods include virtual inertial control, droop control, or a combination of the two. Virtual inertia control outputs frequency regulation power according to the derivative of grid frequency, which can simulate inertia characteristics similar to conventional generators. The droop control outputs the frequency regulation power according to the frequency deviation, which can simulate a governor of conventional generators. In terms of wind turbine generators, [25] analyzed and evaluated the inertial response and droop response provided by the wind farm and proved that it can significantly improve the frequency response of the power grid. Reference [26] moved the maximum power curve of the doubly fed wind turbine according to the derivative of grid frequency, $\frac{df}{dt}$, and changes the power injected into the grid to provide short-term frequency support for the grid.

In terms of PV systems, [9] and [17] combined PV power reserve control and droop control to enable PVs to participate in frequency regulation, which can significantly reduce steady-state frequency deviations. Reference [27] proposed a virtual inertia control strategy based on a two-stage PV power generation system, which indirectly changes the output of the photovoltaic array by changing the DC bus voltage according to the frequency deviation to reduce the frequency change rate. Reference [28] used a droop control strategy, and a virtual inertia control strategy was proposed for a two-stage PV system to actively participate in the frequency response, which can effectively offset frequency changes.

In light of the limitations of existing power reserve control methods, a novel frequency regulation control strategy based on PV power reserve control is proposed in this paper; this strategy can automatically track the given reserve power under different weather conditions without expensive irradiance sensors. It does not need to estimate the maximum point power, does not add additional hardware, does not need complex model estimation algorithms and offers good control accuracy and speed.

The remainder of this paper is organized as follows: Section II illustrates the linear characteristic of the maximum power-current curve of the PV array, and the algorithm to obtain the curtailment power-current characteristic curve is also presented. In Section III, the proposed PRC method based on the curtailment power-current curve is presented. In Section IV, the overall frequency regulation strategy based on the proposed PRC is described. In Section V, a simulation test under various scenarios is conducted. Finally, Section VI concludes the paper.

II. CURTAILMENT POWER-CURRENT CURVE OF PV ARRAY

The proposed PRC method in this paper must know a curtailment power curve of a PV array previously. It can be obtained by transforming the maximum power curve.

The maximum power-voltage curve and maximum power-current curve are shown in FIGURE 1 and FIGURE 2, respectively. In this paper, the maximum power-current curve is
selected rather than the maximum power-voltage curve. The reasons are as follows.

As seen from FIGURE 1, the maximum power-voltage curve has the following disadvantages:

(1) The first half of the maximum power-voltage curve almost coincides with the abscissa axis, while the latter half has a large slope, which is almost perpendicular to the abscissa axis. In other words, the maximum power-voltage curve is a nonlinear function, and it is very steep. Therefore, it is difficult to find a suitable function expression to fit the maximum power-voltage curve accurately. Reference [15] used piecewise linear functions to fit the maximum power-voltage curve. However, the fitting function was complex with many coefficients, and the segmentation method was different for different types of PV arrays.

(2) When the irradiance is large, the maximum power-voltage curve of the PV array is very steep. This means that smaller voltage changes cause larger power changes, which makes the process of control susceptible to noise.

(3) Since the maximum power-voltage curve is a nonlinear function, the power curtailment curve is difficult to be obtained from the maximum power-voltage curve by simply multiplying the curtailment factor. More details are given below.

A. THE MAXIMUM POWER-CURRENT CURVE

The single-diode model is a widely used PV array model with high accuracy and is given as

\[
I_{pv} = I_{ph} - I_0 \left( e^{\frac{(V_{pv} + R_s I_{pv})}{T}} - 1 \right) - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \tag{1}
\]

\[
V_T = A k T / q \tag{2}
\]

\[
I_{ph} = \frac{S}{S_{STC}} I_{sc,STC} [1 + \alpha(T - T_{STC})] \tag{3}
\]

\[
I_0 = \left( I_{ph} - \frac{V_{oc}}{R_p} \right) \left( e^{\frac{V_{oc}}{k T}} - 1 \right)^{-1} \tag{4}
\]

\[
V_{oc} = V_{oc,STC} [1 + \beta(T - T_{STC})] + V_{T0} \left( \frac{S}{S_{STC}} \right) \tag{5}
\]

where \( I_{pv} \) is the PV output current; \( I_{ph} \) is the photogenic current; \( I_0 \) is the diode reverse saturation current; \( q \) is electron charge, \( q = 1.6 \times 10^{-19} \) C; \( V_{pv} \) is voltage; \( R_s \) is series resistance; \( R_{sh} \) is parallel resistance; \( A \) is the ideal diode factor; \( S \) is the irradiance; \( V_{oc} \) and \( I_{sc} \) are the PV array open-circuit voltage and the short-circuit current, respectively; \( S_{STC} = 1000 \) W/m\(^2\) and \( T_{STC} = 25^\circ \)C are the standard test conditions; \( I_{sc,STC} \) and \( V_{oc,STC} \) are the short-circuited current and the open-circuit voltage under standard test conditions, respectively; and \( \alpha \) and \( \beta \) are the thermal correlation coefficients.

The SPR-305E-WHT-D (\( N_s = 1, N_p = 1 \)) PV cell manufactured by the SunPower Company is taken as an example for analysis, and the parameters are shown in Table 1 of the Appendix. Assuming that the temperature is fixed at 25 \( ^\circ \)C, the irradiance \( S \) is changed from 100 W/m\(^2\) to 1200 W/m\(^2\) with an interval of 20 W/m\(^2\). A scatter plot of the maximum power point-current under different irradiance conditions is shown in FIGURE 3.

A linear function is used to fit the maximum power-current curve as follows [29]:

\[
P_m(I) = k_m I \quad \tag{6}
\]
The power reserve ratio is the ratio of the reserved power to the maximum power, which is defined as

$$d = \frac{P_{\text{mpp}} - P_{\text{de}}}{P_{\text{mpp}}}$$  \hspace{1cm} (7)

where $P_{\text{mpp}}$ is the maximum power under certain weather conditions and $P_{\text{de}}$ is a curtailment power that is lower than the maximum power.

For the given reserve ratio, there are two curtailment power-current curves. One is on the left of the maximum power-current curve, $P_{\text{de2}} = P_{\text{de2}}(I)$, and the other is on the right, $P_{\text{de1}} = P_{\text{de1}}(I)$, as shown in FIGURE 5.

The right-side curtailment power-current curve, $P_{\text{de1}} = P_{\text{de1}}(I)$, is selected in this paper for the following reasons: 1) The right side of the P-I characteristic curve is approximately a straight line perpendicular to the abscissa. Based on this characteristic, the power curtailment curve can be obtained by transforming the maximum power curve. 2) The left curtailment power curve, $P_{\text{de2}} = P_{\text{de2}}(I)$, is too close to the P-I characteristic curve, which is not conducive to the voltage tracking method proposed later.

Assuming that the right part of the P-I characteristic curve is a straight line perpendicular to the abscissa, the curtailment power-current curve $P_{\text{de}} = P_{\text{de}}(I)$ is defined as

$$P_{\text{de}}(I) = (1 - d)P_{\text{mpp}}(I) = (1 - d)k_{m}I$$  \hspace{1cm} (8)

However, the curtailment power-current curve $P_{\text{de}} = P_{\text{de}}(I)$ defined in (8) is not accurate and requires further revision. With respect to FIGURE 6, the solid blue line is the curtailment power-current curve $P_{\text{de}} = P_{\text{de}}(I)$. The power at point A, $(I_{\text{de}}, P_{\text{de}})$, is the expected curtailment power, $P_{\text{ref}}$, which is given as

$$P_{\text{ref}} = (1 - d)P_{\text{mpp}} = (1 - d)k_{m}I_{\text{mpp}}$$  \hspace{1cm} (9)

However, point A is not on the P-I characteristic curve. Thus, the PV system cannot operate at this point. In fact, the intersection of the $P_{\text{de}}(I)$ curve and the P-I characteristic curve of the PV array is point B. It is obvious that the power of point B is larger than the power of point A, $P_{\text{ref}}$.

The power error between the two points is expressed as follows:

$$P_{\text{error}} = P_{\text{de}} - P_{\text{ref}} = k_{m}(1 - d)(I_{\text{de}} - I_{\text{mpp}})$$  \hspace{1cm} (10)

where $I_{\text{de}}$ is the current at point B.

Shift point B $(I_{\text{de}}, P_{\text{de}})$ down to $P_{\text{error}}$ to obtain a new point C, $(I_{\text{de}}, P_{\text{deR}})$. The power of point C is equal to the target power, $(1 - d)P_{\text{mpp}}$. Considering that the right part of the P-I characteristic curve is steep, point C is almost on the P-I characteristic curve of the PV array with a negligible error, as seen in FIGURE 6.

Thus, according to point C, a new curtailment power-current curve, $P_{\text{deR}}(I)$, can be redefined as

$$P_{\text{deR}} = k_{\text{de}}I = k_{v}k_{m}(1 - d)I$$  \hspace{1cm} (11)

where $k_{\text{de}}$ is the slope of the revised curtailment power-current curve and $k_{v}$ is defined as the current correct coefficient.

The power of point C can be calculated as

$$P_{\text{de1}} = P_{\text{deR}}(I_{\text{de}}) = P_{\text{ref}} = k_{v}k_{m}(1 - d)I_{\text{de}}$$  \hspace{1cm} (12)
Divide (12) by (9) and after some manipulation, the expression of \( k_{rv} \) can be obtained as

\[
I = \frac{I_{mpp}}{d_k} \quad (13)
\]

Thus, if \( k_{rv} \) is known, the revised curtailment power-current curve can be obtained by means of (11). Fortunately, \( k_{rv} \) is almost a constant value under different irradiance conditions. Taking the PV array data in Table 1 as an example, the \( k_{rv} \) data with a power reserve ratio of 0.1 under different irradiance conditions are shown in FIGURE 7. \( k_{rv} \) is almost constantly equal to 0.948 at the power reserve ratio of 0.1.

However, \( k_{rv} \) is affected by the power reserve ratio. The scatter plot of \( k_{rv} \) with different reserve ratios \( d \) is shown in FIGURE 8.

At \( d = 0 \), \( k_{rv} = 1 \), and then, \( k_{rv} \) decreases as \( d \) increases. A simple fitting function is used to represent the relationship between \( k_{rv} - d \)

\[
k_{rv} = 1 - b_0d + b_1 \quad (14)
\]

where \( b_0, b_1 \) and \( b_2 \) are fitting coefficients. In this paper, \( b_0 = 0.9405, b_1 = 0.0291 \) and \( b_2 = 0.0291 \). The fitted curve and sample data when \( T = 25 \)°C are shown in FIGURE 9.

The maximum error of the fitted curve is 0.0021, and the root mean square error (RMSE) is 0.002981. Thus, the fitting curve by (14) has good accuracy.

### C. INFUENCE OF TEMPERATURE

The output power of a PV array is affected by both temperature and irradiance. Considering the influence of temperature, the temperature compensation factor \( \mu T + \eta T \) is introduced, and (6) is modified as follows:

\[
P_{in}(I) = k_m(\mu T + \eta T)I \quad (15)
\]

\( \mu T \) and \( \eta T \) can be obtained by offline data fitting. In this study, \( \mu T = -0.003393 \) and \( \eta T = 1.085 \).

Furthermore, the current correct coefficient \( k_T \) is also influenced by temperature. At a given solar irradiance \( S = 1000 \) W/m\(^2\), the three-dimensional image of the \( k_{rv} \) data distribution at different temperatures \( T \) and different reserve ratios \( d \) is shown in FIGURE 10.

As seen from FIGURE 10, as the temperature increases, \( k_{rv} \) decreases. It is noticed that \( k_{rv} \) is approximately linear versus \( T \) at a fixed reserve ratio. Thus, a temperature correction factor \( \kappa_T \) is introduced to correct the \( k_{rv} - d \) curve (i.e., (14)), as follows:

\[
\kappa_T = K_T + C_T \quad (16)
\]

\[
k_{rv} = (K_T + C_T) \left( 1 - \frac{b_0d + b_1}{d + b_2} \right) \quad (17)
\]

where \( K_T \) and \( C_T \) are correction factors. \( K_T = -0.0001997 \) and \( C_T = 1.0005 \) in this paper.

Once the temperature information \( T \) and the power reserve ratio \( d \) are known, \( k_{rv} \) can be estimated by (17). Due to slow temperature changes and inexpensive temperature sensors, temperature information can be directly measured by the sensor. The reserve ratio \( d \) is given by the frequency controller, as shown in section III.

Thus, combining (12), (15), (16), and (17), the curtailment power-current curve considering temperature is

\[
P_{dcR}(I) = k_{rv}(1 - d)P_{in}(I)
\]

\[
= (K_T + C_T) \left( 1 - \frac{b_0d + b_1}{d + b_2} \right) (1 - d)
\]

\[
= (K_T + C_T) \left( 1 - \frac{b_0d + b_1}{d + b_2} \right) (1 - \frac{b_0d + b_1}{d + b_2})
\]
The parameters of (18) in the paper are listed in Table 2 of the Appendix.

At a given temperature \(T = 25^\circ\text{C}\), the error plot of the power curtailment curve under different conditions of irradiance and power reserve ratio is shown in FIGURE 11. The maximum error is 0.00739. p. u., and the root mean square error (RMSE) is 0.00354. p. u. (rated power is 305 W). Therefore, using (18) to express the power curtailment curve offers good accuracy.

Actually, realistic PV arrays have some inevitable deviations from data sheet values. In (18), the effect of the PV output power on the temperature is not significant. \(k_{pv}\) varies in a relatively narrow range, from 0.94 to 1 in the paper. Thus, \(K_T, C_T, \mu_T, \eta_T\), and \(k_{pv}\) can be obtained by offline test data from the data sheet, which does not obviously affect the PRC control accuracy. \(k_m\) is the only key parameter representing the output power characteristic of the PV array. It should be emphasized that the maximum power-current maximum power curve \(P_{m}(I) = k_mI\) is only a simple and proportional linear function. \(k_m\) can be estimated online for different realistic PV arrays. In detail, the realistic PV system can operate in MPPT mode at the initial operation stage to acquire the maximum power and current data. Then, the online maximum power and current data can be utilized to obtain \(k_m\) by simple curve fitting calculations, which is a great advantage for industrial applications.

III. PROPOSED POWER RESERVE CONTROL TRACKING ALGORITHM

A. POWER RESERVE CONTROL PRINCIPLE

The principle of the proposed power reserve control tracking algorithm is explained in FIGURE 12.

In FIGURE 12, the solid red line represents the curtailment power-current curve, and the remaining curves represent the P-I characteristic curves of the PV array under different irradiance conditions. There are several intersections between the curtailment power curve and the PV array characteristic curves, such as A, B, C, and D. These intersection points are the required curtailment power points. A tracking control algorithm needs to be designed if the PV system needs to operate on these intersections.

![FIGURE 11. Error plot of the power curtailment curve under different irradiance and power reserve ratios when \(T = 25^\circ\text{C}\).](image)

![FIGURE 12. Schematic diagram of power reserve control.](image)

![FIGURE 13. Schematic diagram of current tracking when irradiance suddenly changes.](image)

Taking \(I = I_{de}\) as the boundary, the P-I curve can be divided into two parts, namely, Area1 and Area2. In Area1, the difference between the P-I characteristic curve and the power curve curtailment value \(P_{de}(I)\), \(\Delta P_1\), is constantly positive. Similarly, \(\Delta P_2\) is constantly negative in Area2. According to this characteristic, the tracking control algorithm is designed as

\[
\Delta P(i) = P(i) - P_{de}(I(i)) \tag{19}
\]

\[
I_{ref}(i) = I_{ref}(i-1) + \text{sign}(\Delta P(i)) \Delta I \tag{20}
\]

In (19), \(i\) represents the current sample time, \(i-1\) represents the previous sample time, and \(\Delta I\) is the current disturbance step size. \(P(i)\) is the current PV array output power, which is obtained through measurement. \(P_{de}(I(i))\) is the value of the power curtailment curve corresponding to the current \(I(i)\).

Assume that the initial operating point of the PV system is at Area1, such as \(A_1\) in FIGURE 12. \(\Delta P(i)\) remains constantly positive in Area1. Thus, taking (19) to control, \(I_{ref}(i)\) will gradually increase, and point \(A_1\) continuously moves right to close the target point \(A\). If the initial operating point is at Area2, such as point \(A_2\), then \(\Delta P(i)\) remains constantly negative in Area2. Similarly, taking (19) as a control, \(I_{ref}(i)\) will gradually decrease, and point \(A_2\) continuously moves left until it converges to target point \(A\).

However, equation (19) shows the current tracking control. The DC-DC converter in the two-stage PV system is a voltage-type converter. An additional current controller is
required to realize current tracking. In addition, noticing that
the right of the P-I characteristic curve is very steep, if the
current tracking control shown in (19) is used, a slight current
change will bring a large power change, which will destroy
the tracking stability. Furthermore, because the right side of
the P-I characteristic curve is too steep, if irradiance suddenly
changes, the operating point may fall out of the P-I character-
istic curve. As shown in FIGURE 13, irradiance suddenly
changes from $S_1$ to $S_2$, and the operating current $I_1$ is beyond
the operation range.

To overcome these shortcomings of the current tracking
algorithm, a voltage tracking algorithm based on the curtail-
ment power-current curve is proposed in this paper.

**B. VOLTAGE TRACKING CONTROL ALGORITHM**

It is interesting to note that the operating point located on the
right side of the P-I characteristic curve will fall at the left
side of the P-V characteristic curve, and vice versa. This can
be illustrated in FIGURE 14. $A_1$ is the operating point, and
$A$ is the target point. $A_1$ is located on the right side of the P-I
characteristic curve, as shown in FIGURE 14(a). The same
point $A$, point $A_1$ at the P-V characteristic curve, is shown in
FIGURE 14(b) and is located on the left side.

The slope of the left side of the P-V characteristic curve
of the PV array is much smaller than the slope of the right
side of the P-I characteristics curve. Thus, compared with the
current tracking, the voltage tracking will be more stable. The
operating point will not fall out of the operating range and
does not require an additional current control.

Furthermore, the movement direction of the operating
point at the P-V characteristic curve is opposite to that at the
P-I characteristic curve. It can be illustrated in FIGURE 14.

In FIGURE 14(a), on the P-I characteristic curve, $A_1$ moves
to the right to close to target point $A$. In contrast, in
FIGURE 14(b), on the P-V characteristic curve, $A_1$ moves
to the left to close to target point $A$. The movement direction
is opposite. This means that if the PV array current needs to
increase on the P-I characteristic curve, the PV array voltage
should decrease on the P-V characteristic curve.

Based on the above analysis, the voltage tracking control
algorithm based on the curtailment power-current curve is presented as

\[
\Delta P(i) = P(i) - P_{deR}(I(i))
\]

\[
\Delta V(i) = \begin{cases} 
V_{cons} \text{if } (\Delta P(i) < 0) \\
-V_{cons} \text{if } (\Delta P(i) > 0)
\end{cases}
\]

\[
V_{ref}(i) = V_{ref}(i-1) + \Delta V(i)
\]
where $i$ is the current control period and $i-1$ is the last control period. $V_{\text{ref}}$ is the voltage reference value of the PV array, and $V_{\text{cons}}$ is the voltage disturbance step size.

In (21), $\Delta P(i)$ is the deviation power between the P-I characteristic curve of the PV array and the curtailment power-current curve. The sign of $\Delta P(i)$ determines the direction of voltage tracking, which is opposite to current tracking, as defined in (22). The voltage reference in the $i$ control period is determined by employing (23).

Theoretically, the voltage tracking control algorithm in this paper is the same as the hill climbing method for MPPT. Hill climbing method is a BANG-BANG control and has good stability in itself. The stability of Hill climbing method has been widely demonstrated, either in literature or industrial application. In addition, the voltage tracking control algorithm is a nonlinear control method, and it is difficult to model and analyze by classic control theory. The maximum power-current curve (or the power curtailment curve) and the P-V characteristic curve have only one intersection, obviously. This intersection is the equilibrium point, as seen in FIGURE 14. When the proposed control algorithm is adopted, the PV system finally converge to a target point under any disturbance.

**C. VARIABLE STEP SIZE VOLTAGE TRACKING ALGORITHM**

When a fixed voltage perturbation step size is used, the output power of the PV array will inevitably oscillate near the target power. The rate of power near the reserve power point is larger than the maximum power point ($dP/dV = 0$ near the maximum power point). To reduce the power oscillation problem, a variable voltage step size tracking method is proposed.

The voltage step size is set as follows:

$$\Delta V(i) = -\Delta P(i)/I(i)^2$$  \hspace{1cm} (24)

The voltage step size is determined based on $\Delta P$. As the operating point is closer to the target reserve operating point, the absolute value of $\Delta P$ is closer to 0. The step size of the voltage is closer to zero. The PV system will eventually converge to the target operating point without power oscillation.

Based on the above description, the flow chart of the power reserve control algorithm proposed in this paper is shown in FIGURE 15.

**IV. PV FREQUENCY CONTROL STRATEGY**

Integrating with the PV power reserve control method presented in Section III, the overall control scheme of the frequency regulation control strategy for the PV system is shown in FIGURE 16.

In FIGURE 16, the overall control strategy is divided into two layers: a frequency control layer and a power reserve control layer. The power reserve control layer used to realize PRC control is described in Section III. The power reserve ratio reference, $d$, is given by the frequency regulation control layer.

In the frequency regulation control layer, $f_s$ is the system frequency, $f_0$ is the system standard frequency (50 Hz in this paper), $f$ is the frequency deviation, $f_{\text{dev}}$ is the frequency deviation per unit value, $k_d$ and $k_i$ are the droop coefficient and inertia coefficient, respectively, $\Delta d$ is the change value of the power reserve ratio, $d_0$ is the initial value of the power
reserve ratio, and $d$ is the reference value of the power reserve ratio.

The frequency regulation control layer can be expressed as follows:

$$
\Delta d = k_d \Delta f_{[pu]} - k_i \frac{d \Delta f_{[pu]}}{dt} \tag{25}
$$

$$
d = d_0 + \Delta d \tag{26}
$$

The virtual inertia coefficient $k_i$ usually takes twice the virtual inertia time constant $H_{vir}$. The inertia time constant of the conventional generators is 2-6 s. $H_{vir} = 2$ s is selected in this study. Similar to conventional generators, the inverse of the droop coefficient $k_d$ is the compensative ratio $R$, that is, $R = 1/k_d$. The value range of $R$ is usually 2%-5%. $R$ is selected as 2% in this study, that is, $k_d = 50$.

According to equations (25) and (26), if the power system frequency changes, the frequency control layer will change the power reserve ratio $d$. The output power of the PV system will change along with the change in the power reserve ratio to participate in the grid frequency regulation.

V. SIMULATION RESULTS

To validate the proposed control strategy, two sets of simulations are designed. One set is used to verify the proposed PRC method under different cases. The other set is used to evaluate the performance of the proposed frequency regulation strategy for the PV system.

The former set of simulations is based on the RT-LAB semi-physical simulation platform, as shown in FIGURE 17. The PRC is implemented in the DSP control board, and the remaining physical components of the PV system are simulated in the RT-LAB platform. RS-485 bus communication is adopted to connect the embedded control board and RT-LAB. The DSP control board receives the voltage, current, temperature and other measurement information from the RT-LAB. A white noise signal with a signal-to-noise ratio of 10 dB is superimposed to simulate the sampling noise. The DSP control board sends the driving signal of a grid-connected converter to RT-LAB.

The latter set of simulations is built in the electromagnetic simulation platform.

A. VERIFICATION OF PRC ALGORITHM

To verify the effectiveness of the proposed PRC for the PV system, the frequency response layer in FIGURE 16 is omitted first. The power reserve ratios are directly given by the external command.

CASE 1: Temperature and irradiance are fixed; reserve ratio $d$ variation

Setting the solar irradiance $S = 1000$ W/m$^2$ and the temperature $T = 25$ °C, the power reserve ratio changes from 0 to 1 by increasing by 0.2 every second, as indicated by the dash line in FIGURE 18(a). The simulation results are shown in FIGURE 18.

As seen in FIGURE 18, when the solar irradiance and temperature are constant, the PRC method proposed in this paper can quickly reach the given power reserve ratio. The steady-state error and tracking time at different power reserve ratios are shown in Table 1. As seen from Table 1, the maximum steady-state error is only 0.008, and the maximum tracking time is only 0.16 s, which shows good tracking accuracy and speed.

CASE 2: Temperature is fixed; the power reserve ratio and irradiance change

The temperature is set to $T = 25$ °C, the solar irradiance $S$ changes according to the solid line shown in FIGURE 19(a), and the power reserve ratio changes according to the dash line.

FIGURE 17. RT-LAB Semi-physical simulation platform.

FIGURE 18. Power point tracking effect verification when $S = 1000$ W/m$^2$, $T = 25$ °C, and the reserve ratio changes.
### TABLE 1. The steady-state error and tracking time when the power reserve ratio changes.

| Time   | 3–4 s | 4–5 s | 5–6 s | 6–7 s | 7–8 s |
|--------|-------|-------|-------|-------|-------|
| Error  | 0.0007 | 0.0013 | 0.0015 | 0.0011 | 0.008 |
| Time   | 0.15 s | 0.16 s | 0.16 s | 0.13 s |       |

### TABLE 2. Steady-state error and tracking time when $T = 25 \, ^\circ C$, irradiance and power reserve ratio change.

| Time   | 3–4.5 s | 4.5–5.5 s | 5.5–7 s | 7–8 s |
|--------|---------|-----------|---------|-------|
| Error  | 0.0006  | 0.0014    | 0.0011  | 0.0004 |
| Time   | 0.21 s  | 0.17 s    | 0.18 s  | 0.15 s |

### TABLE 3. Steady-state error and tracking time when temperature, irradiance and power reserve ratio change.

| Time   | 3–4.5 s | 4.5–5.5 s | 5.5–7 s | 7–8 s |
|--------|---------|-----------|---------|-------|
| Error  | 0.0008  | 0.0006    | 0.0007  | 0.0013 |
| Time   | 0.2 s   | 0.19 s    | 0.16 s  | 0.18 s |

shown in FIGURE 19(b). The simulation results are shown in FIGURE 19.

In FIGURE 19, there are four different combinations of power reserve ratios and irradiance changes. At 3 s, both the irradiance and the power reserve ratio increased; at 4.5 s, the irradiance increased and the power reserve ratio decreased; at 5.5 s, the irradiance decreased and the power reserve ratio increased; at 7 s, both the irradiance and the power reserve ratio decreased. Table 2 shows the steady-state error and tracking time at different power reserve ratios. The maximum tracking time is 0.21 s, and the maximum steady-state error is 0.0014.

From the above simulation results, it can be seen that the PRC in this paper can automatically track the target reserve power point without measuring irradiance information. It offers good tracking speed and accuracy when the irradiance changes.

CASE 3: Power reserve ratio, temperature and irradiance change

Setting the solar irradiance $S$ continuously changes according to the solid line shown in FIGURE 20(a), the temperature $T$ continuously changes according to the solid line shown in FIGURE 20(b), and the power reserve ratio changes according to the dash line shown in FIGURE 20(c). The simulation results are shown in FIGURE 20.

As shown in FIGURE 20, even though the irradiance and temperature continuously change, the PRC proposed in this paper can track the given power reserve ratio quickly. Table 3 shows the steady-state error and tracking time at different power reserve ratios. The maximum steady-state error is 0.0013, and the maximum tracking time is 0.2 s. The simulation results show that the PRC in this study has good tracking accuracy and speed when the irradiance and temperature continuously change.

### B. PERFORMANCE OF THE PROPOSED FREQUENCY REGULATION FOR PV SYSTEMS

To evaluate the performance of the proposed frequency regulation control strategy, a small independent power system shown in FIGURE 21 is simulated. The system includes two power sources, a thermal power unit and a PV power plant. The thermal power unit is rated at 3 MW, the PV power plant is rated at 1 MW, and the initial load is 3 MW.

The mathematical model of thermal power units is from [14], as shown in FIGURE 22.
In FIGURE 22, $T_G$ is the governor time constant, $F_{RH}$ is the fraction of turbine power from the high pressure section, $T_{RH}$ is the reheating time constant, $T_{CH}$ is the charging time of the high-pressure section, $k_d$ is the droop coefficient, $1/f$ is the frequency deviation, and $P_t$ is the output power of the synchronous generator. The values of the most significant parameters are summarized in Table 4 of the Appendix.

The PV generator adopts the frequency regulation strategy proposed in FIGURE 16, and its specific parameters are the same as in Table 2 of the Appendix. The PV power plant consists of 10 identical PV systems.

CASE 1: Load suddenly increases
At $t = 10$ s, the load suddenly increased by 0.2 MW, and the solar irradiance $S$ first increased and then decreased, as indicated by the solid line in FIGURE 23(a). The simulation results are shown in FIGURE 23.

When the load suddenly increases, the system frequency decreases. In FIGURE 23(b), the power reserve ratio decreases because the system frequency decreases. The output power of the PV array increases as the power reserve ratio decreases. The PV plant reduces the output power to support the system frequency. In FIGURE 23(e), when the PV plant does not participate in the power grid frequency regulation, the nadir of the system frequency is 49.70 Hz, and the steady frequency is 49.80 Hz. Comparatively, when the PV participates in frequency regulation, the nadir of the system frequency is 49.87 Hz, and the steady-state frequency is 49.88 Hz. The frequency response is significantly improved if the PV plants use the frequency regulation strategy.

CASE 2: Irradiance increases, and load reduces suddenly
At $t = 10$ s, the load suddenly decreased by 0.2 MW, and the solar irradiance $S$ changes as indicated by the solid line in FIGURE 24(a). The simulation results are shown in FIGURE 24.

As seen from FIGURE 24, when the load is suddenly reduced, the system frequency increases. In FIGURE 24(b), the power reserve ratio increases with increasing frequency. In FIGURE 24(d), the output power of the PV array decreases with decreasing power reserve ratio. The reserve power of PV is reduced to retard the rising system frequency. As seen in FIGURE 24(e), when the PV plant does not participate in the frequency regulation, the peak of the frequency is 50.37 Hz,
and the steady-state frequency is 50.16 Hz. Comparatively, when the PV participates in frequency regulation, the peak of the system frequency is 50.15 Hz, and the steady-state frequency is 50.09 Hz. The peak of the system frequency is significantly improved with the PV system participating in frequency regulation.

It is noted that in FIGURE 23 and FIGURE 24, the output power of the PV plant increases (or decreases) with increasing solar irradiance (or decreasing). The reason is that the proposed strategy changes the power reserve ratio to participate in the system frequency regulation. Thus, the output power of the PV plant changes as the solar irradiance changes.

CASE 3: Irradiance and load randomly change

Finally, considering the actual industry application scenario, 200 s of actual measured data of irradiance and load imported are imported into the simulation model, as indicated by solid lines shown in FIGURE 25(a) and FIGURE 25(b). The simulation results are shown in FIGURE 25.

As seen in FIGURE 25, under the solar irradiance and load random variation conditions, the frequency deviation with the PV plant participating in frequency regulation is significantly smaller than that with the PV plant not participating in frequency regulation. When the PV plant does not participate in the frequency regulation, the maximum frequency deviation is 0.45 Hz, and the RMSE is 0.1730 Hz. Compared with PV plant participation in frequency regulation, the maximum frequency deviation is only 0.19 Hz, and the RMSE is only 0.0891 Hz. From the above simulation results, the proposed frequency regulation strategy significantly improves the frequency response characteristics of the system.
VI. CONCLUSION

In this paper, a new frequency regulation strategy for PV systems is introduced. The core element and novel feature of the proposed strategy is the power reserve control based on the curtailment power-current curve voltage tracking algorithm. Compared with the other existing PRC strategies, it does not need to estimate the maximum power under actual environmental conditions. Thus, the proposed strategy does not require an irradiance sensor or complicated mathematical model estimation. The curtailment power-current curve is obtained by means of the maximum power-current curve, which is a simple linear function and can be obtained from on-line curve fitting. The given power reserve ratio from the upper frequency control layer is automatically tracked by the variable step size voltage tracking algorithm, regardless of the environmental conditions.

The proposed power reserve control is validated through semi-physical simulation testing under constant and varying environmental conditions. The results show that the proposed control strategy is reliable, fast and accurate, and the effectiveness of the whole frequency regulation is validated through simulations of a small independent power system.

### TABLE 4. Parameters of PV array.

| Parameter                                      | Value     |
|------------------------------------------------|-----------|
| Open circuit voltage under standard conditions $V_{oc,STC}$ | 64.2 V    |
| Short circuit current under standard conditions $I_{sc,STC}$ | 5.96 A    |
| Parallel resistance $R_{sh}$                    | 269.5934 Ω|
| Series resistance $R_s$                         | 0.37152 Ω |
| Open circuit voltage thermal correlation coefficient $\beta$ | -0.27269 |
| Short-circuit thermal correlation coefficient $a$  | 0.061745  |
| Diode ideal factor $A$                          | 0.94504   |

### TABLE 5. Fitted parameters.

| Parameter | Value |
|-----------|-------|
| $k_m$     | 54.63 |
| $b_1$     | 0.9405|
| $b_2$     | 0.0291|
| $b_3$     | 0.0291|
| $\mu_T$   | -0.003393|
| $\eta_T$  | 1.085 |
| $K_T$     | -0.0001997|
| $C_T$     | 1.0005|

### TABLE 6. Parameters of the PV system.

| Parameter                                      | Value     |
|------------------------------------------------|-----------|
| PV array MPP voltage $V_{mpp}$                 | 273.5 V   |
| PV array MPP current $I_{mpp}$                 | 368.28 A  |
| PV array series and parallel number $n_p \times n_s$ | 66*5      |
| PV system capacity $P_{pv}$                    | 100 kW    |
| DC-link capacitance $C_{dc}$                   | 6 mF      |
| Grid inductance $L_f$                          | 250 μH    |
| Droop coefficient $k_d$                        | 50        |
| Virtual inertia coefficient $k_i$              | 4         |
The PV system can significantly improve the system frequency response under load suddenly increasing, suddenly decreasing and randomly changing cases.

**APPENDIX**

See Table 4–7.

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