An Improved MPPT Method with Dynamic Voltage Error Compensation under Two Varying External Conditions

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Abstract. This paper presents a new maximum power point tracking (MPPT) method which can improve the dynamic tracking ability under two varying external conditions, rapid irradiance variation and grid voltage fluctuation. Different from irradiance variation, the dynamic error of tracking voltage caused by grid voltage fluctuation is usually ignored by MPPT methods. The dynamic error of tracking voltage can make the unexpected power change of photovoltaic system and influence the dynamic MPPT efficiency. According to the different current increment changes under the irradiance variation and the grid voltage fluctuation, the reasons of dynamic voltage errors are analyzed and distinguished. And two corresponding modes of variable step size are designed in the tracking algorithm to regulate the voltage deviation from MPPs. The effectiveness and the improved dynamic tracking performance of the proposed MPPT method are verified by simulation results under the above two varying external conditions.

1. Introduction
Photovoltaic (PV) generation has been extensively applied in grid-connected generation systems, due to the renewable capability of solar energy, environmental benefits and cost reduction of PV modules [1]–[3]. Because of time-variable electrical characteristics, the voltage of PV array need to be regulated to track the maximum power point (MPP), by means of maximum power point tracking (MPPT) algorithms in the control system of PV inverters [2],[3].

The solar irradiance is the main environmental factor leading to the uncertain and rapid change of PV array current and MPP position. The dynamic tracking capabilities of classic MPPT methods, such as the incremental conductance (INC), are insufficient under the rapid irradiance variation [4], [5]. The rapid irradiance variation will also make the obvious dynamic error of PV voltage control in the PV inverter systems, and then make the unexpected variation of PV voltage and the indirect change the PV current. If the absolute value of voltage error is high enough, the indirect current change by voltage error can be more than the direct current change by irradiance variation, which will aggravate the power deviation of PV array.

The grid voltage fluctuation, which is usually ignored by MPPT methods, can also make the instantaneous voltage deviation from MPPs, due to the dynamic voltage error by the grid-side power oscillation [6], [7]. Different from the irradiance variation, the ideal MPP of PV array is not changed during the grid voltage fluctuation, so the tracking criterion for the irradiance variation will be useless to correct the change trend of tracking voltage. Meanwhile, the variable step size mode increases the sensitivity of MPPT control to the PV power change, so that the oscillations of PV voltage and current...
caused by the grid fault conditions also can be increased [6], [8], which make the greater negative impact on dynamic performance of MPPT schemes [9]. Compared with the two-stage PV systems, the single-stage PV systems track the MPP through regulating dc-link voltage without dc-dc converter [6], [10], which can simplify the system topology and improve the efficiency, but the dynamic error of dc-link voltage by grid voltage fluctuation will directly influence the tracking effect of MPPT.

In this paper, a new improved MPPT method for single-stage grid-connected PV systems has been proposed. The step size of the method is adjusted through the feedback dynamic error of MPPT reference voltage to compensate the power deviation of the PV array under two varying external conditions, rapid irradiance variation and grid voltage fluctuation. Through analyzing the reasons of dynamic voltage error change, two different variable step sizes modes are designed to respond to the irradiance variation and grid voltage fluctuation respectively, which are distinguished by the dynamic change from PV current or dc current of inverter. The proposed method can improve the dynamic tracking capability under the above two conditions. The simulation results in comparison with INC method are provided to demonstrate the effectiveness and advantage of the proposed method.

2. Improved MPPT method with dynamic voltage error compensation

2.1. Analysis of dynamic tracking voltage error

The topology of a single-stage grid-connected PV system is shown in Fig.1, which consists of a PV array, a voltage source inverter (VSI), a step-up transformer and the electrical grid. The PV array voltage \( V_{\text{pv}} \) is equal to the dc-link voltage \( V_{\text{dc}} \), and the reference voltage \( V_{\text{ref}} \) is regulated by the MPPT algorithm. The PV array current \( I_{\text{pv}} \) is transmitted to the three-phase grid as ac currents \( i_{\text{abc}} \). The output voltages \( v_{\text{abc}} \) of VSI are raised to the grid voltages \( e_{\text{abc}} \) through the transformer, and the voltage ratio is \( K_{\text{n}} \).

![Figure 1. Single-stage grid-connected PV system.](image)

When the INC method is used in the system of Fig.1, the criterion function \( F_{\text{pv}} \) is expressed as

\[
F_{\text{pv}} = \frac{\Delta I_{\text{pv}}(k)}{\Delta V_{\text{pv}}(k)} + \frac{I_{\text{pv}}(k)}{V_{\text{pv}}(k)}
\]

(1)

where \( \Delta I_{\text{pv}}(k) \) and \( \Delta V_{\text{pv}}(k) \) are the increments of \( I_{\text{pv}} \) and \( V_{\text{pv}} \) in the \( k \)-th MPPT period.

The MPP tracking criterions of INC are described as: \( V_{\text{pv}} \) is at the MPP when \( F_{\text{pv}} = 0 \), and the reference voltage \( V_{\text{ref}} \) is kept constant; \( V_{\text{pv}} \) is at the left side of MPP when \( F_{\text{pv}} > 0 \), and \( V_{\text{ref}} \) needs adding the step size \( V_{\text{step}} \); \( V_{\text{pv}} \) is at the right side of MPP when \( F_{\text{pv}} < 0 \), and \( V_{\text{ref}} \) needs reducing the step size \( V_{\text{step}} \).

There is an inherent limitation of INC method. The accuracy of \( F_{\text{pv}} \) is connected to the actual error between \( \Delta V_{\text{pv}}(k) \) and the step size \( V_{\text{step}} \), but the dynamic error of tracking voltage is not considered in the design of tracking algorithm. In the control strategy of single-stage PV inverter, \( V_{\text{pv}}(k) \) is the dc-link voltage \( V_{\text{dc}}(k) \). According to the control characters of \( V_{\text{dc}}(k) \), the actual value of \( \Delta V_{\text{pv}}(k) \) is

\[
\Delta V_{\text{pv}}(k) = \Delta V_{\text{dc}}(k) = V_{\text{step}} + V_{\varepsilon}(k)
\]

(2)

where \( V_{\varepsilon}(k) \) is the control error of dc-link voltage, which is

\[
V_{\varepsilon}(k) = V_{\varepsilon}(k-1) - V_{\varepsilon}(k-1)
\]

(3)

\( V_{\varepsilon}(k) \) is decided by the disturbance from external conditions to the dc-link voltage control. Under ideal conditions, the voltage control can achieve the steady state in each MPPT period, so that the value of \( V_{\varepsilon} \) will be close to zero, and \( F_{\text{pv}} \) can make the correct judgment to the location of MPP. Because the dynamic response of dc-link voltage control is slower than the current change rate, the
external factors from PV side and grid side can both make the rapid current change and thus lead to the obvious change of $V_c$. The voltage error $V_e$ can change all parameters of $(1) \Delta I_{pv}(k)$, $\Delta V_{pv}(k)$, $I_{pv}(k)$ and $V_{pv}(k)$ simultaneously. Accordingly $F_{pv}$ will be interfered to make the wrong direction judgment of MPP when the absolute value of $V_e$ is too high.

According to the circuit configuration of figure 1, $\Delta V_{dc}(k)$ is approximate to

$$\Delta V_{dc}(k) \approx \frac{T_m}{C_{dc}}(I_{pv}(k) - I_{dc}(k))$$

(4)

where $T_m$ is the sampling period of MPPT algorithms.

And the current increments $\Delta I_{pv}(k)$ and $\Delta I_{dc}(k)$ are defined as

$$\Delta I_{pv}(k) = I_{pv}(k) - I_{pv}(k-1), \Delta I_{dc}(k) = I_{dc}(k) - I_{dc}(k-1)$$

(5)

According to (2), $V_e(k)$ and $V_e(k-1)$ can be expressed as

$$V_e(k) = \Delta V_{dc}(k) - V_{step}, \quad V_e(k-1) = \Delta V_{dc}(k-1) - V_{step}$$

(6)

By combining (4), (5) and (6), the increment of $V_e(k)$ can be quantified as

$$V_e(k) - V_e(k-1) \approx \frac{T_m}{C_{dc}}(\Delta I_{pv}(k) - \Delta I_{dc}(k))$$

(7)

which means the change of $V_e$ depends on the relationship of $\Delta I_{pv}$ and $\Delta I_{dc}$. Assume $V_e(k-1)=0$, if $\Delta I_{pv}(k)$ is equal to $\Delta I_{dc}(k)$, $V_e(k)$ will still be almost zero. Otherwise, the dynamic change of $\Delta I_{pv}$ or $\Delta I_{dc}$ will make the different change of $V_e$.

The irradiance variation, as the main external reason of PV current change, can make the continuous change of $\Delta I_{pv}$. When the irradiance decreases or increases rapidly, $I_{pv}$ will decrease or increase in the same direction and not follow the I-V curve of the former irradiance, the position of $V_{dc}$ at the MPP will also move in the same direction of irradiance variation. According to (7), $V_e$ will decrease or increase in the same direction of $\Delta I_{pv}$, and thus $\Delta V_{dc}$ is continuously affected by $V_e$ until the end of irradiance variation. The uncertain changes of voltage and current will disturb the tracking direction of $V_{ref}$ to reduce the tracking speed.

Furthermore, the instantaneous change of $\Delta I_{dc}$ caused by grid voltage fluctuation can also make the obvious change of $V_e$. Due to the grid faults or grid load switching in distribution networks, the amplitude fluctuations of grid voltages frequently occur and make the instantaneous perturbation of ac power [6], which leads to the sudden increase in the absolute value of $\Delta I_{dc}$. Meanwhile $\Delta I_{pv}$ follows the I-V curve of PV array under uniform irradiance. Therefore, different from the moment of irradiance variation, the relationship between $\Delta I_{pv}(k)$ and $\Delta I_{dc}(k)$ at the moment of grid voltage fluctuation can be given as

$$|\Delta I_{pv}(k)| < |\Delta I_{dc}(k)|$$

(8)

2.2. The proposed MPPT algorithm

The flow chart of the proposed MPPT algorithm is shown in Fig.2. The mean values $V_{dc}(k)$, $I_{pv}(k)$ and $I_{dc}(k)$ are computed in each MPPT cycle, in order to calculate $\Delta V_{dc}(k)$, $\Delta I_{pv}(k)$, $\Delta I_{dc}(k)$, $V_{dc}(k)$ and $F_{pv}$.

The inequality (8) is utilized as the current criterion to distinguish the current increment change caused by the grid voltage fluctuation, and the variable step size $N_1V_e$ is utilized to regulate the oscillation of $V_{dc}$.

According to the associated variation of irradiance and $V_e$, the variable step size $N_2V_e$ is added to the fix step size $N_0$, in order to compensate the misjudgment of $F_{pv}$ caused by the irradiance variation. Under the steady external conditions, the static efficiency of INC is retained in the proposed method, and the tracking speed is mainly decided by $N_0$ due to $V_e \approx 0$. Under the varying irradiance conditions, the dynamic tracking speed is improved by the complex step sizes $N_0$ and $N_2V_e$. For avoiding the overshoot at the first period of algorithm switching, the compensation value should be less than the value of voltage error, so the coefficients $N_1$ and $N_2$ should be less than 1.
3. Simulation results

The simulation models of the grid-connected PV system are built with Matlab/Simulink to compare the performance of the proposed MPPT method with the INC method. The main parameters of the system have been listed in Table 1. The simulation results of the INC method and the proposed method under the same varying external conditions are respectively presented in this section.

### Table 1. Parameters of PV Inverter System.

| Parameters                        | Values       |
|-----------------------------------|--------------|
| DC-link capacitor ($C_{dc}$)      | 4400μF       |
| LC filter inductance ($L_f$)      | 0.33mH       |
| LC filter capacitor ($C_f$)       | 37.5μF       |
| Transformer ratio ($K_n$)         | 290/400      |
| Switching frequency               | 5kHz         |
| Grid frequency                    | 50Hz         |
| Grid voltage (line to line, rms)  | 400V         |

#### 3.1. The simulation results during the rapid change of irradiance

The initial value of irradiance is 1kW/m², and decrease linearly to 0.8kW/m² in a period of 1s, which happens before the initial MPP (1kW/m²) is reached. After 2s, the irradiance increase linearly back to 1kW/m² again in the period of 1s, which happens after the second MPP (0.8kW/m²) is reached. The temperature is set at 25°C during the simulation. The ideal maximum power points are 61.64kW at 1kW/m² and 48.05kW at 0.8kW/m², and the ideal voltages of MPP are 436.8V at 1kW/m² and 432.1V at 0.8kW/m² respectively.

Fig.3 is the simulation results of the dc-link voltage $V_{dc}$ and the reference voltage $V_{ref}$ of MPPT, and two time points of reaching the MPP are marked by $t_1$ and $t_2$. The reference voltage $V_{ref}$ of INC method (in Fig.3 (a)) appears oscillation during the irradiance decreasing, and $V_{ref}$ is higher than the MPP voltage during the irradiance increasing. Hence the MPP tracking process is delayed, where $t_1$ and $t_2$ are 3.6s and 5.7s respectively. In Fig.3 (b), due to the additional step size $N_2$, which corrects the misjudgment of INC criterions, the tracking accuracy of $V_{ref}$ is improved in connection with the irradiance variation by the proposed method. And $t_1$ and $t_2$ are reduced to 3.2s and 5.2s which means less tracking time of MPP is needed. Fig.4 shows the comparison of dynamic MPPT efficiency, which
is the percentage of real-time PV array power divided by the ideal maximum power. As a result, the proposed method has the better dynamic MPPT efficiency than INC method under the irradiance rapid change.

![Graph showing DC-link voltage and reference voltage of MPPT during the rapid change of irradiance.](image)

**Figure 3.** DC-link voltage and reference voltage of MPPT during the rapid change of irradiance.

![Graph showing comparison of MPPT efficiency during the rapid change of irradiance.](image)

**Figure 4.** Comparison of MPPT efficiency during the rapid change of irradiance.

3.2. The simulation results during the grid voltage fluctuation

The grid voltage amplitude is rapidly reduced to 95% within a period of 0.25s during the tracking process, and begins to return to normal at the same speed after 1.25s. The irradiance is 1kW/m², and the temperature is 25°C during the simulation.

Fig.5 shows the simulation results of the dc-link voltage $V_{dc}$ and the reference voltage $V_{ref}$ of MPPT, and two time points of reaching the MPP are marked by $t_1$ and $t_2$. In Fig.5(a), each grid voltage fluctuation makes the obviously change of dc-link voltage $V_{dc}$, the reference voltage $V_{ref}$ of INC method takes a roundabout way to the MPP voltage, and the time points $t_1$ and $t_2$ of reaching the MPP are 4.4s and 5.8s respectively. In Fig.5(b), the proposed method regulates the direction of $V_{ref}$ to correct the dynamic error through the variable step size $N_1V_e$, therefore the route of $V_{ref}$ is shorten and tracking speed is increased. The time points $t_1$ and $t_2$ are reduced to 4.05s and 5.45s respectively. The comparison of dynamic MPPT efficiency is shown in Fig.6, each voltage fluctuation makes two efficiency decreases in the INC method, and the proposed method lowers the first decrease and eliminates the second to improve the dynamic MPPT efficiency during the grid voltage fluctuation.
4. Conclusion
In order to enhance the dynamic tracking performance of MPPT control under two varying external conditions, an improved MPPT method has been proposed in this paper, which provides different step size modes by means of dynamic voltage error compensation. The dynamic voltage errors by PV array side factors and grid side factors are both considered in this paper, based on the MPPT control characteristic of single-stage grid-connected PV system. Compared with the INC method, the proposed method can provide the better dynamic tracking performance under both the rapid irradiance variation and the grid voltage fluctuation, which is verified by the contrast simulation results.

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