A Control Strategy for Two-stage PV Grid-connected Inverter Based on Voltage Oriented Control

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Abstract. For the design of three-phase two-stage grid-connected PV inverter, the topology and control strategy of two-stage grid-connected inverter are analyzed. For the DC/DC converter control strategy, the shortcoming of conventional perturbation and observation method are analyzed, which is difficult to obtain high response speed and steady-state tracking accuracy due to its fixed disturbance step size. A duty cycle self-optimizing MPPT method is adopted and effectively alleviates the contradiction between tracking speed and accuracy. For the DC/AC converter control strategy, the grid voltage oriented vector control is adopted based on the analysis of the mathematical model of rotating coordinate. The current decoupling and grid voltage feedforward control in dq coordinate system are carried out. The control system parameters are designed and verified to be feasible.

1. Introduction
At present, the design of photovoltaic power generation system mainly adopts two-stage grid-connected inverter, including DC/DC converter and DC/AC converter [1]. The first stage consists of a DC/DC converter, which realizes maximum power point tracking and voltage boosting. The second stage consists of a DC/AC converter, which converts the DC power from the PV array into AC power with the same frequency and phase as the grid voltage. The power factor is approximately 1, and the active power is transmitted to the grid.

The DC/DC converter adopts MPPT control. In MPPT, the Perturbation and Observation (P&O) method has been widely used [2-4], which is difficult to ensure the tracking speed and accuracy at the same time. To reduce the conflict between tracking speed and accuracy of traditional perturbation observation method, a duty ratio self-optimization algorithm is adopted [5]. Compared with the perturbation observation method, the effectiveness of the improved algorithm is verified.

The DC/AC converter adopts double loop control. The outer voltage loop uses a PI controller to track the reference voltage of the DC link given by the system. The inner current loop performs decoupling control on the grid-connected dq axis current by two PI regulators in a rotating coordinate system synchronized with the grid voltage [6]. In order to improve the dynamic response speed of the current loop and eliminate the steady-state error, the PI parameters are optimized by using the classical control theory. The feasibility of the control strategy is verified by simulation.

2. DC/DC Converter Control Strategy
In the application of photovoltaic system, the interface between PV array and load usually adopts PWM DC/DC converter and DC/AC inverter. In the topology of this circuit, duty cycle D is a variable that can be controlled. The key to self-optimization control method of maximum power point tracking
is duty cycle self-optimization. The MPPT controller adjusts the input/output relationship of the converter by adjusting the duty ratio D of PWM signal, so as to achieve impedance matching. Therefore, the duty cycle D determines the output power P of PV array.

The P-D relationship is shown in Figure 1, from which it is easy to find that the relationship between P-D and P-U is similar. When \( \frac{dP}{dD} = 0 \), the output power reaches the maximum value, so the P&O method is still applicable. By comparing the current power with the power at the previous moment, the duty cycle can increase or decrease. This method takes duty ratio as the control parameter, thus reducing the difficulty of controller design.

![Figure 1. P-D Diagram](image)

In the duty cycle self-optimizing method, there is still the problem of adjusting step size when duty cycle D is adjusted. If the step size is too small, the tracking time will be longer, which will affect the dynamic response characteristics of the system. On the contrary, if the step size is too large, the fluctuation of output power will increase, and its average value is far less than the maximum value, so that the steady-state error of the system becomes larger. The solution here is to introduce a step-size automatic on-line adjuster. The formula for the step size lambda's automatic on-line regulator is shown in equation (1):

\[
\lambda(k+1) = \varepsilon |\Delta P| / \lambda(k)
\]

(1)

\( \lambda(k) \) is the adjustment compensation for duty ratio D (0 ≤ \( \lambda(k) \) ≤ 1). \( \Delta P \) is the size of the said power changes. \( \varepsilon \) is a constant.

![Figure 2. Flow chart of self-optimizing duty cycle method](image)

As is shown in Figure 2, t represents the threshold value set by the system, which determines the tracking accuracy of the controller. When |\( \Delta P \)| < t, the system has reached adjacent area of its maximum power point, no longer need to adjust the duty ratio D. N determines the direction of change in the duty ratio D, which is 1 or -1. When the power decreases, N is reversed, otherwise N remains unchanged. The constant determines the flexibility of the automatic on-line regulator. The greater the \( \varepsilon \)
is, the more sensitive the regulator is. Constants $t$ and $\varepsilon$ are determined according to actual control requirements and system characteristics.

3. DC/AC Converter Control Strategy

3.1. Voltage Oriented Control Strategy

Assuming that the $d$-axis of the $dq$ coordinate system coincides with the grid voltage vector $E$ and rotates synchronously, the system is called a synchronous rotating $dq$ coordinate system based on the grid voltage orientation [7]. The diagram of voltage oriented control is shown in Fig. 3.

![Voltage oriented control diagram](image)

Figure 3. Voltage oriented control diagram

From the definition above, it can be concluded that in $dq$ synchronous rotating system based on grid voltage orientation, there is $e_{d}=|E|$. According to instantaneous power theory, instantaneous active power $p$ and reactive power $q$ are respectively

$$
p = \frac{3}{2} (e_d i_d + e_q i_q)
$$

$$
q = \frac{3}{2} (e_d i_q - e_q i_d)
$$

Since $e_d=|E|$, then $e_q=0$ and equation (2) can be simplified to equation (3).

$$
\begin{align*}
    p &= \frac{3}{2} e_d i_d \\
    q &= \frac{3}{2} e_d i_q
\end{align*}
$$

Assume that the grid is a stable power supply, that is, $e_d$ is a constant. Therefore, the instantaneous active power $p$ and reactive power $q$ are proportional to $dq$-axis component $i_d$ and $i_q$. This shows that if the grid voltage is constant, the active power and reactive power of the grid-connected inverter can be controlled separately by $i_d$ and $i_q$.

Since the total output power of PV array is active power, then the instantaneous active power $p=u_{dc}i_{dc}$ can be obtained. If the loss of the inverter is not considered, it can be known from equation (3)

$$
    i_{dc} u_{dc} = p = \frac{3}{2} e_d i_d
$$

As is shown in equation (4), when the grid voltage is constant and the inverter's loss is neglected, the DC link voltage $u_{dc}$ of the grid-connected inverter is proportional to the $d$-axis component $i_d$ of the inverter output current. The active power $p$ of the grid-connected inverter is also proportional to $i_d$, so the DC link voltage $u_{dc}$ of inverter can be controlled by the active power $p$ [8].

3.2 Double Loop Control Strategy of PI Controller

The control system consists of a DC outer voltage loop and an active and reactive inner current loop [9]. The DC outer voltage loop is to stabilize the DC voltage by a PI controller. Since the DC voltage can be controlled by $i_d$, then the output of outer voltage loop PI controller is the reference current $i_{dc}^{*}$ of the active inner current loop, thereby adjusting the active output power of the grid-connected inverter. The current reference value $i_q$ of the reactive inner current loop is obtained according to the reactive
power reference value $q^*$. When $i_q^*=0$, the inverter operates under unit power factor, that is, only the active power is delivered to the grid.

If the feedforward decoupling control is adopted, the decoupled $i_d$ current inner loop control diagram is shown in Figure 4 ($i_q$ and $i_d$ current loop are the same). When the switching frequency is high enough, the amplification characteristics of inverter can be approximated by the proportional gain $K_{PWM}$.

As discussed earlier, the DC link voltage $u_{dc}$ of the grid-connected inverter is controlled by the active power $p$ of the inverter, which is proportional the active current $i_d$. The relationship between $u_{dc}$ and $i_{dc}$ is given in (5).

$$
\begin{align*}
C \frac{du_{dc}}{dt} &= i_c \\
i_c &= i_{dc} - i_d
\end{align*}
$$

(5)

where $i_c$ is the current of DC link filter capacitor.

Therefore, the key to design the outer voltage loop is to obtain the transfer relationship between the output $i_d$ and the input current $i_{dc}$, which is given in equation (6).

$$
i_{dc} = \frac{3}{2} \frac{e_d i_d}{u_{dc}}
$$

(6)

Take steady state $u_{dc} = U_{DC}$.

$$
i_{dc} = \frac{3}{2} \frac{e_d i_d}{U_{DC}}
$$

(7)

Thus, the control diagram of the outer voltage loop can be obtained, as shown in Figure 5.

4. Simulation Verification

4.1 MPPT Simulation

In order to illustrate the effectiveness of duty cycle self-optimization method, the duty cycle self-optimization is compared with fixed-step P&O method under the standard condition and illumination variation condition respectively. The PV array parameters are set as follows: short circuit current $I_{sc} = 8.58A$, maximum power point current $I_m = 7.94A$, open circuit voltage $V_{oc} = 22V$, maximum power point voltage $V_m = 17.7V$.

4.1.1 Standard Simulation. The system parameters are set as follows: illumination intensity $G = 1000W/m^2$, temperature $T = 25^\circ C$, step size of fixed-step P&O is set to 0.001, the power change threshold of duty cycle self-optimization is set to 0.05.
As is shown in Figure 6, the fixed-step P&O finds the MPP at approximately 0.032s, and the duty cycle self-optimization finds the MPP at approximately 0.012s. After entering the steady state, the PV output power oscillates more minutely in duty cycle self-optimization than in fixed-step P&O. Therefore, the duty cycle self-optimization method can effectively alleviate the conflict between tracking speed and accuracy, and improve the dynamic tracking speed while ensuring steady-state accuracy.

4.1.2 Illumination Variation Simulation. The system parameters are set as follows: the initial light intensity $G=1000\text{W/m}^2$ and drops to $600\text{W/m}^2$ at 0.07s, the temperature $T=25^\circ\text{C}$. The step size perturbation method step is set to 0.001. The threshold of duty cycle self-optimization is set to 0.05.

As is shown in Figure 7, the MPP of PV array decreases with drop of illumination intensity. The fixed-step P&O finds the maximum power point at approximately 0.09s, and the adjustment time is approximately 0.02s. The duty cycle self-optimization finds the MPP at approximately 0.082s, and the adjustment time is approximately 0.012s. Compared with the fixed-step P&O, the duty cycle self-optimization can adapt to illumination variation and adjust the output power more quickly, thus improve the tracking speed.

4.2 Grid-connected Model Simulation

The inverter PI control parameters are set as follows: outer loop voltage proportional coefficient $K_{p1}=0.1$, integral coefficient $K_{i1}=0.05$, inner current loop proportional coefficient $K_{p2}=30$, integral coefficient $K_{i2}=5000$.

As is shown in Figure 8, the grid-connected voltage is basically in phase with the grid-connected current, indicating that the grid-connected current contains low harmonic. The system can effectively realize unit power factor grid-connected control. As is shown in Figure 9, the maximum output power of the PV array is 5kW. The output power of the inverter can quickly track the PV output power and ensure the stability of output active power. As is shown in Figure 10, the active power control is realized by tracking the reference current $i_{d,\text{ref}}$ with the active current $i_d$. 

![Figure 6. PV output power under standard condition](image)

![Figure 7. PV output power under illumination variation](image)
As is shown in Figure 11, the reactive current and power reference value are both set to 0 to realize unity power factor grid-connected control, so the power factor is 1. The inverter output reactive power can track the reactive power reference value rapidly and ensure unit power factor control. As is shown in Figure 12, the reactive power control is realized by tracking the reactive current reference value $i_{q \text{ref}}$. 

Figure 8. Grid-connected voltage and current of phase A

Figure 9. Active power tracking

Figure 10. Active current tracking

Figure 11. Reactive power tracking
5. Conclusion

In this paper a model of two-stage grid-connected PV inverter based on MPPT and VOC is designed and simulated.

To realize DC/DC converter control, the conflict between tracking accuracy and speed of fixed-step P&O method is analyzed. A duty cycle self-optimization method is adopted to alleviate the conflict and improve the tracking speed and steady-state accuracy effectively.

To realize DC/AC converter control, a grid voltage orientation method is adopted and the mathematical model of three-phase grid-connected inverter in dq coordinate system is analyzed. Feedforward decoupling is adopted to control the active and reactive power of the grid-connected inverter by controlling id and iq. In addition, in order to enhance the decoupling effect, a double-loop control strategy is adopted. The current id and iq of the inner current loop are compared with reference value id* and iq*. The steady-state error of id and iq is eliminated by PI control.

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