A New Feed-forward Compensation Inverter Control Strategy

YUE ZHAO, YUANHUI CUI, WEI LI, YANPING WANG and ZHISEN WANG

ABSTRACT

With the development of new energy research, photovoltaic inverter is widely used in solar photovoltaic power generation system. In this paper, a new static feed-forward compensation control strategy for current loop is proposed for the shortcomings of the single-phase PV inverter in the use of the typical \( \text{I} \)-type system in the double closed-loop control system. Through the improved Park transformation, the equivalent model of the single-phase inverter is obtained. The control equation of the current is obtained by the method of feed-forward decoupling control in the equivalent inverter model. For the interference signal in the current control equation, the static feed-forward compensation control method eliminates the interference signal present in the inner loop of the current. Through this control method, the current loop in ensuring the performance of good follow at the same time effectively improve the current loop anti-jamming performance. At the same time, current loop control and voltage outer loop control using \( \text{PI} \) control, the formation of double closed-loop control system. The simulation results show that the anti-jamming performance of the double closed-loop inverter control system with static feed-forward compensation is better, the output waveform distortion rate of the inverter is low, and the PV inverter is stable in the presence of disturbance.

INTRODUCTION

With the increase in traditional energy consumption and the various environmental problems caused by it, the research and utilization of renewable energy is also accelerating. Solar, as the world's wide source, less pollution, one of the new renewable energy has been widely used [1]. According to statistics, by the end of 2016, China's new installed capacity of photovoltaic power plant 34.53 million \( \text{kw} \cdot \text{h} \), the cumulative installed capacity of 77.42 million \( \text{kw} \cdot \text{h} \). However, due to the existence of photovoltaic power generation output instability caused by the shortcomings.

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Therefore, the inverter technology research can be better development and use of new energy. The traditional inverter control strategy is mainly: proportional - resonance control, its control method is simple, but cannot eliminate the nonlinear model of the error[2];

Voltage single closed loop instantaneous feed-back method, although its fast, but the disadvantage is that it cannot achieve steady-state without net gain control. In this paper, the static current feed-forward anti-jamming current inner ring and the voltage outer loop double closed-loop control strategy are adopted. By using the improved Park coordinate transformation, the DC voltage component of the inverter is changed to the DC component under the new coordinate system, the output of the PI controller is used to control the generation of the SPWM wave to realize the inverter control. This method has the advantages of simple control structure, good anti-jamming performance, less harmonic content of inverter output waveform.

PRINCIPLE AND DESIGN

In this paper, the static feed-forward decoupling control link is applied to the inner loop of the double closed loop control of the PV inverter. At the same time, the anti-jamming performance index of the inner loop is also stability. The structure shown in Figure7. In the Park coordinate transformation, an ideal inverter with exactly the same output as the actual single-phase inverter is used. The output voltage hysteric’s the actual inverter of the single-phase inverter 90° as the q-axis and the inverter output voltage phasor is taken as the d-axis. Its structure shown in Figure1. Through this coordinate transformation, can realize the inverter output flow to the Park coordinates under the direct flow of the change [3]. In this way, the double closed-loop PI control of the inverter can be realized. And then through the Park coordinate inverse control SPWM wave generation. Among them, the Park transformation matrix and the inverse transformation matrix are as follows [4]:

\[
\begin{bmatrix}
U_d \\
U_q
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
U_\alpha \\
U_\beta
\end{bmatrix}
\]

(1)

The inverse transformation matrix is as follows:

\[
\begin{bmatrix}
U_\alpha \\
U_\beta
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
U_d \\
U_q
\end{bmatrix}
\]

(2)

Where: \(u_\alpha\) is the actual circuit output voltage; \(u_\beta\) is the reference circuit output voltage; \(\theta\) is the angle between the \(d\)-axis and the actual voltage output \(u\) in the synchronous rotating coordinate system.
Figure 1. Design schematic.

Figure 2. Equivalent circuit diagram of voltage inverter.

Park transformation after the $d$-axis and $q$-axis models shown in Figure 3 and 4:

Equivalent Model of Inverter Circuit

The equivalent circuit structure of the voltage-type inverter can be obtained by the state space averaging method as shown in Fig. 2[5].

In the $d$-axis, $q$-axis model equivalent circuit diagram:

$D_d, D_q$ is to ignore the inverter bridge loss after the DC voltage source in the $d$-axis, $q$-axis of the equivalent voltage source, they are controlled by the DC voltage $E$.

$\omega L_I_q$, $\omega L_I_d$ are two controlled voltage sources for equivalent inductance coupling;

$\omega C U_{cq}$, $\omega C U_{cd}$ are two controlled current sources after equivalent capacitive coupling.

By the equivalent circuit can be obtained in the $d$-axis, $q$-axis inverter model is:

$$
\begin{align*}
    \begin{bmatrix}
        I_d \\
        I_q
    \end{bmatrix}
    &=
    E
    \begin{bmatrix}
        D_d \\
        D_q
    \end{bmatrix}
    - \frac{1}{L}
    \begin{bmatrix}
        U_{cd} \\
        U_{cq}
    \end{bmatrix}
    + \begin{bmatrix}
        0 & \omega \\
        -\omega & 0
    \end{bmatrix}
    \begin{bmatrix}
        I_d \\
        I_q
    \end{bmatrix} \\
    \end{align*}
$$

(3)
Where \( p \) is a differential operator

**Park transformation feed-forward decoupling control equation**

Select the phasors \( I_d \) and \( U_d \) on the \( d \)-axis as the controlled design controller. The following equations can be obtained by preloading the \( d \)-axis control equations:

\[
U_{cd}' = (K_{ip} + \frac{K_{mi}}{s})(I_d^* - I_d) + U_{cd} - \alpha L I_q
\]

\[
I_d' = (K_{ip} + \frac{K_{mi}}{s})(U_d^* - U_d) + I_{de} - \alpha C U_q
\]

Decoupled by the \( d \)-axis control equation available, the decoupling controller structure shown in Figure 5:

**Current loop controller design**

The structure of the current inner ring is shown in Figure 6.

In the figure, \( \tau_i = \frac{K_{ip}}{K_{id}} \)

Ignore the effect of voltage disturbances. When the current inner ring is designed according to the typical type I system, it can be seen from Fig. 6 that only the pole of the current control object transfer function can be used to cancel the zero point of the PI controller [7]. When the SPWM wave switching frequency is sufficiently high, the equivalent open-loop transfer function and the equivalent closed-loop transfer function of the inner loop are following equation:

\[
G_o(s) = \frac{K_{ip} K_{PWM}}{R \tau_i s(1.5T_s + 1)}
\]

\[
G(s) = \frac{1}{1 + \frac{R \tau_i}{K_{ip} K_{PWM}} s + \frac{1.5T_s R \tau_i}{K_{ip} K_{PWM}} s^2}
\]

![Figure 5. d Axis decoupling controller structure diagram.](image)
Where: PI controller proportional gain is $K_p$; PWM switch bridge gain is $K_{PWM}$; $\tau_i$ is the time constant; $T_s$ is a small time constant

When the damping ratio of the system is $\xi = 0.707$, the equivalent transfer function of the inner loop is:

$$G(s) = \frac{1}{3T_s s + 1} \tag{9}$$

By the transfer function we can see that when the current loop with a typical type I system, with good follow performance. However, when the grid voltage fluctuation on the current inner ring interference, the current inner ring of anti-jamming performance is instability.

It can be seen that the reason for the instability anti-jamming performance of the typical I type system is as follows: The typical time-constant $\tau_i = \frac{L}{R}$ of the zero-point of the current inner ring regulator and the open-loop transfer function of the typical type I system The ratio of the time constant $1.5T_s$, the ratio $h = \frac{\tau}{1.5T_s}$ is too large, that is, the intermediate frequency band is too wide to make the inner loop anti-jamming performance is poor.

In order to improve the anti-perturbation performance of the system, this paper adopts a static feed-forward compensation control strategy. In the typical type I system, a feed-forward compensation link is added to suppress the current disturbance, which improves the anti-jamming performance of the system while ensuring better system follow performance.

Based on the current inner loop of the static feed-forward compensation composite control structure shown in Figure 7:

Where: Static feed-forward compensation gain is $K_f$, and $K_f = \frac{1}{K_{PWM}} \cdot \frac{1}{K_{PWM}}$; $U_{cd}$ is the disturbance signal of the voltage outer ring at some time; $K_{PWM}$ is the inverter bridge gain; $I_a^*$ is the expected current value; $I_a$ is output current value.

It can be seen from the structure diagram that the closed-loop transfer function of the inner loop with static feed-forward compensation in accordance with the control of the voltage outer ring disturbance is shown in equation (8). When the system has only the voltage outer ring disturbance signal $U_{cd}$, the system transfer function structure shown in Figure 8:
Figure 7. Schematic diagram of the current inner ring with static feed-forward compensation composite control

Figure 8. The structure of the transfer function of the system under the action of the disturbance signal.

From the system structure diagram can be obtained under the action of the disturbance signal is:

$$G_e(s) = \frac{1.5T_s + 1 - K_f K_{PWM}}{1.5T_s + 1 - K_f K_{PWM} \tau_s s + 1}$$

By the principle of superposition, the output signal $I_d$ of the system is operated by the input signal and the algebraic sum of the action of the disturbance signal. Obviously:

$$I_d(s) = G_e(s)U_e(s) + G(s)U(s)$$

Where: $G_e(s)$ is the transfer function under the action of the disturbance signal; $G(s)$ is the transfer function under the action of the input signal.

When the switching frequency is high enough, the time constant $T_s$ can be ignored. In the analysis equation (10), it can be seen that at that time, $1 - K_f K_{PWM} = 0$ in other words $G_e(s) = 0$, the disturbance signal can be eliminated by the action of the proportional coefficient $K_f$. By introducing the feed-forward proportional coefficient $K_f$, it can achieve the better performance of the typical type I system, and also improve the anti-jamming performance of the system effectively.

**Design of voltage outer ring controller** [8]

As the main purpose of the voltage outer ring is to achieve the inverter output voltage anti-jamming performance and voltage stability. Therefore, the voltage outside the ring using $PI$ controller. The structure of the voltage outer ring controller is shown in Figure 9:
Figure 9. Voltage Outer Ring PI Control Circuit Block Diagram.

Figure 10. Compared with static feed-back compensation and without feed-back compensation.

Where: $U^*_d$ is expected voltage value; $U_d$ is output voltage value; $G_i(s)$ is the equivalent transfer function of the inner loop of the current; $I_{de}$ is the current disturbance.

**SIMULATION**

Current loop controller parameters: when the switching frequency is high enough to ignore the small time constant $T_s$ effect; PI regulator equivalent transfer function is:

$$G_{PI}(s) = K_{IP} \frac{\tau_i s + 1}{\tau_i s}$$

(12)

Where: $\tau_i = \frac{K_{IP}}{K_H}$; Current inner loop proportional gain is $K_{IP}$; Voltage outer ring integral gain; is $K_H$.

Calculations can be got: $K_{IP} = 1.5; K_H = 470; \tau_i = 1.41$. [9]

A step-by-step disturbance signal is given at $t = 0.06s$. A typical I-type system with a static feed-forward compensation composite control system is compared with the static feed-forward compensation control system as shown in Figure 10.

Where: 1 has a static feed-forward compensation control; 2 has not a static feed-forward compensation control; 3 is a disturbance signal.

From the analysis of Figure 10 shows that the rise time is about 0.02s, the current loop to follow the better performance. When the $t = 0.06s$ is added with the perturbation signal, the signal-to-noise ratio is 1.25. As can be seen from the graph analysis, the signal strength with static feed-forward compensation controller is reduced by about 10%, and the signal strength of the static feed-forward compensation controller is reduced by about 20%. It can be concluded that the anti-jamming performance of the current loop controller with a static feed-forward compensation...
controller is doubling the anti-jamming performance of the current loop controller without the feed-forward compensation controller. The inner loop with static feed-forward compensation controller has good anti-disturbance performance.

In the SIMULINK simulation parameters are as follows: DC side bus voltage 350V; SPWM frequency of 3.6 KHz; filter inductor 10 mH; filter capacitor 470 μF; load is pure resistance load, power 500W. SIMULINK by simulation, the load voltage and current waveform at both ends as shown:

![Figure 11](image1.png)

Figure 11. Load voltage and current waveform at output of the load.

![Figure 12](image2.png)

Figure 12. Voltage change waveform

![Figure 13](image3.png)

Figure 13. Inverter output voltage waveform.

Figure 11 shows that the load voltage at both ends of about 220V, the load current at both ends of about 2.2 A. Single-phase inverter load at both ends of the Park after the control by the PI controller control the sine is better, the control effect is ideal.

When \( t = 2 \) s, the load voltage suddenly increases when the simulation waveform shown in Figure 12:

Figure 12 and 13 analysis shows that \( t = 2 \) s when the load voltage suddenly increases, the amplitude is about 250V, the inverter output waveform appears only an amplitude of about 230V interference signal simulation proved that the voltage outside the ring controller Anti-jamming performance is good, can effectively inhibit the load voltage disturbance.

From (8), we can see that the interference signal of the inner loop is mainly generated by \( \omega_q U_q \), and the disturbance can be regarded as a specific DC disturbance signal under Park transformation. When \( t = 2 \) s, a given current inner loop of a step amplitude of 1.6 step disturbance signal, no static feed-forward compensation current loop output current waveform shown in Figure 14; static feed-forward compensation of the current loop output The current waveform is shown in Figure 15.
Figure 14. Without static feed-forward control current disturbance waveform.

Figure 15. With static feed-forward compensation control current disturbance waveform.

Table 1: Comparison of Static Feed-forward Compensation Controller with Without Static Feed-forward Compensation Controller Data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Loop Controller with Static Feed-forward Compensation</th>
<th>Current Loop Controller without Static Feed-forward Compensation</th>
<th>CNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjustment time (s)</td>
<td>0.05</td>
<td>0.43</td>
<td>1.375</td>
</tr>
<tr>
<td></td>
<td>0.09</td>
<td>0.65</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.7</td>
<td>1.1</td>
</tr>
</tbody>
</table>

It can be seen from Fig. 14 and 15 that when \( t = 2 \, \text{s} \), the current output waveform with static feed-forward compensation controller returns to its original state at \( t = 2.05 \, \text{s} \) for a step disturbance signal with a magnitude of 1.6 for a given inner loop. No static feed-forward compensation controller waveform at \( t = 2.2 \, \text{s} \) is still no recovery, it can prove that the static feed-forward compensation of the current loop controller anti-jamming performance is better.

Table 1 shows the current inner loop controller with static feed-forward compensation for different signal-to-noise ratios and the time-contrast of the current loop controller with no static feed-forward compensation at different signal-to-noise ratios.

From the analysis of Table 1, no static feed-forward compensation controller has poor anti-jamming performance and long adjustment time. The internal loop controller with static feed-forward compensation is better and the adjustment time is faster. The simulation results show that the current loop controller with a typical feed-forward compensation with typical type I system has good anti-jamming performance and can effectively improve the anti-jamming performance of the inner loop of the inverter current.
CONCLUSION

In this paper, based on the improved Park transform, the single-phase AC voltage is transformed into the DC voltage in the Park coordinate system. By using the double closed-loop control strategy, a static current feed-forward compensation control scheme is added to the typical I-type internal current control system. Method to suppress the interference signal of the inner loop. SIMULINK simulation can be obtained, with static feed-forward control of the current loop controller compared with a typical type I system controller anti-jamming performance is better. PV inverter output voltage current waveform contains fewer harmonics. Can meet the better performance and anti-jamming performance requirements. Simulation results are ideal. However, due to the transfer function equivalent process due to the higher frequency of SPWM wave switching and ignore the existence of a small time constant, so the method described in this article SPWM wave switching frequency is higher, the effect is more obvious.

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