Single-phase photovoltaic grid-connected inverter for predictive control method with power feed-forward

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Abstract. In the traditional photovoltaic grid-connected inverter control, there are problems such as slow system response speed, low stability and grid-connected current distortion. In this regard, a novel current prediction control method for grid-connected inverter with power feed-forward is proposed. The method consists of DC voltage outer loop control, current predictive control, power feed-forward and grid voltage feed-forward. The characteristic is that the current prediction control algorithm derived from the state equation of the grid-connected inverter effectively suppresses the influence of DC voltage fluctuation on the grid-connected current and enhances the robustness of the system; the introduction of power feed-forward accelerates the dynamic response of the system; The introduction of grid voltage feed-forward reduces voltage distortion or current distortion. And the traditional PI control module is not needed, the structure is simple, and the circuit is easy to implement. Matlab/Simulink simulation model and experimental results prove the effectiveness of the proposed control method, which is more practical than the traditional double loop control method.

1. Introduction

Nowadays, in the face of the depletion of traditional energy sources and the increasing demand for energy from society, it is of great significance to study power generation systems that use new energy sources such as solar energy, hydro energy, and wind energy. Photovoltaic power generation is the best choice for solving energy crisis with its clean, efficient and never-ending characteristics [1].

In the literature of the last years, a great attention has been devoted to mismatching operating conditions [2,3]. In mismatching conditions, the performance of PV systems could be strongly reduced if suitable measures are not adopted. To this aim, Reconfigurable architectures and Distributed MPPT (DMPPT) techniques have been proposed [4,5]. However, when DMPPT techniques are adopted in a grid connected system, the necessity of the joint adoption of DMPPT and Central MPPT (CMPPT) have been demonstrated leading to the so called Hybrid MPPT (HMPPT) [6,7]. On the other hand, photovoltaic grid-connected inverter is the core equipment of photovoltaic power generation, and its performance will directly affect the power quality and system operation efficiency of the power generation system to the grid. How to improve the response speed and reliability of photovoltaic power generation system and reduce the distortion of grid-connected current has become the research target and hotspot of photovoltaic grid-connected inverter control [8,9].

Most of the traditional grid-connected inverters adopt a double closed-loop control strategy [10-12]. From the perspective of simplified control and engineering applications, DC bus voltage outer loops mostly use proportional integral (PI) controller. The key to determining system performance is...
the current inner loop, which mainly includes PI control and proportional resonance (PR) control, hysteresis control, model predictive control, No beat control and etc. As proposed in the literature [11], the introduction of parallel or series resonance on the PI controller to obtain PR control can eliminate the phase and amplitude control errors caused by the PI controller of the AC command signal has good stability and strong anti-interference ability. Reference [12] proposes a digital modulation technique that achieves high performance and low power loss by applying variable slope fixed band current hysteresis control to the voltage source inverter structure. In [13], the MPC of the grid-connected inverter is proposed in the selected coordinate system. By constructing the prediction model and selecting the control method that minimizes the value function, the optimal control is realized.

The conventional PI controller has a simple structure easy to implement, but its current tracking has a steady-state error and a slow response speed. Compared with the PI controller, although the PR controller realizes the zero-steady-state error tracking of the current, it is less used in engineering due to the disadvantages of the parameter accuracy of the component and the poor harmonic suppression effect of the grid frequency offset [13-15]. Repeated control, model predictive control, etc. can improve the grid-connected control effect by compensating or correcting the command current, but the control parameters are many and the debugging is complicated, which needs further research.

In summary, this paper proposes a current prediction control method for grid-connected inverters with power feed-forward. The method consists of DC voltage outer loop control, current predictive control, power feed-forward and grid voltage feed-forward. The characteristic is that the current prediction control algorithm derived from the state equation of the grid-connected inverter effectively suppresses the influence of DC voltage fluctuation on the grid-connected current and enhances the robustness of the system; the introduction of power feed-forward accelerates the dynamic response of the system; The introduction of grid voltage feed-forward reduces voltage distortion or current distortion. No need for traditional PI control modules, the structure is simple, and the circuit is easy to implement. The system presented in this paper could also be used as the CMPPT stage in a HMPPT system. Finally, the effectiveness of the proposed control method is verified by building a simulation model and a single-phase photovoltaic grid-connected inverter experiment.

2. Model topology of single-phase photovoltaic grid-connected inverter

Figure 1 is a schematic diagram of the main circuit of a typical single-phase photovoltaic grid-connected inverter, including a photovoltaic cell, a full-bridge inverter circuit, and a L filter.

![Figure 1. Main circuit of single-phase photovoltaic grid-connected inverter.](image)

As shown in the figure: $C_{dc}$ is the DC side energy storage capacitor of the inverter circuit, used to buffer the energy exchange between the photovoltaic power and the grid power; $L$ is the filter inductor, which can filter the high frequency harmonics of the AC side of the inverter [16]; $R_L$ is the equivalent series resistance of $L$, and its value is relatively small and negligible.

For the single-stage grid-connected inverter circuit, this paper uses the commonly used conductance increment method to achieve maximum power point tracking (MPPT) [16-18]. Thereby, the reference value $V_{dcref}$ of the inverter DC bus voltage control is obtained. $V_s$ is the grid voltage; $i_s$ the voltage source inverter output current; $V_{dc}$ and $i_{dc}$ are the photovoltaic cell output voltage and current,
respectively.

3. Control strategy of grid-connected inverter

As shown in figure 2, the power feed-forward current prediction grid-connected control system structure adopts voltage and current double closed-loop control as a whole, including DC voltage outer loop PI control and power feed-forward based current prediction control. Finally, the inverter output modulation ratio $V_o$ is calculated by the current prediction function, and the duty cycle signal $d_i$ is generated by sinusoidal pulse width modulation (SPWM), thereby driving the switching tube.

![Diagram of the current predictive grid-connected control based on power feed-forward.](image)

### 3.1. DC voltage outer ring

The difference between the DC voltage reference value $V_{dcref}$ obtained by the MPPT [19] and the DC voltage average value $V_{dcavg}$ is used as the input of the PI controller, and after the output is limited, the current command amplitude $i_{ds}$ can be obtained:

$$i_{ds} = \left( k_p + \frac{k_i}{s} \right) (V_{dcref} - V_{dcavg})$$

Where $k_p$ and $k_i$ are the proportional and integral coefficients of the PI controller, respectively.

### 3.2. Power feed-forward and grid-connected current amplitude command

Power feed-forward control can speed up the transmission process of the DC side energy of the photovoltaic cell to the grid AC measurement energy. When the illumination or temperature changes, the power feed-forward can speed up the transient response of the system, enabling the grid-connected inverter to reach a new steady state [20]. The DC voltage and current output from the photovoltaic cell pass through the MPPT module, and the active power $P_{pv}$ of each sampling period is calculated. The RMS value of the $U_s$ is calculated by the Record Management System (RMS) module, and the amplitude of the feed-forward current command is $i_{ps}$ for:

$$i_{ps} = \sqrt{2} k_{pv} P_{pv} \frac{U_s}{V_{dc}} = \sqrt{2} k_{pv} V_{dc} i_{dc}$$

In the formula, $k_{pv}$ is the proportional coefficient of power feed-forward, and the value of $k_{pv}$ affects the response speed of the system. When the output energy of the photovoltaic cell is abrupt, the power feed-forward can accelerate the adjustment speed of the feed network current, so that it reaches the steady state quickly [21]. Since the inverter has active loss (<5%), $k_{pv} \leq 0.95$.

The current command amplitude $i_{ds}$ of the DC voltage loop control output is added to the feed-forward current command amplitude $i_{ps}$ to obtain the current inner loop command value amplitude $i_{cm}$. The grid voltage is processed by the phase-locked loop to obtain the synchronization factor $\sin(\omega t)$, and the grid-connected current instantaneous value command $i_{ci}$ in one sampling period is:
\[ i_{ci} = (i_{ds} + i_{ps}) \sin 2\pi f_0 T_s \]  

(3)

Where: \( f_0 \) is the grid frequency; \( T_s \) is the sampling period of the switch. The resulting instruction will be entered as a given value for current inner loop current prediction control.

### 3.3. Analysis of current prediction control principle

The core of the traditional grid-connected inverter control method is to compare the reference current signal \( i_{ref} \) with the measured grid-connected current is by phase-locking the collected grid voltage to obtain an error signal, which is compared with the triangular carrier after PI operation. The PWM drive signal is generated, and the control block diagram is shown in figure 3 [22]. The algorithm does not involve DC voltage, and it cannot eliminate the influence of DC voltage fluctuation on the grid-connected current, nor does it consider the impact on the grid voltage. In addition, the PI regulator itself requires more operations, and there is a process of gradually eliminating the error, the adjustment speed is relatively slow [23,24].

![Figure 3](image-url) Conventional grid-connected inverter control strategy.

In this regard, this paper proposes a new grid-connected inverter current prediction control method to solve the above problems. As shown in figure 4, for the single-phase equivalent circuit of a DC-AC voltage source converter, the voltage equation (4) can be derived as:

\[ V_p = L \frac{di_s}{dt} + R_L i_s + v_s \]  

(4)

![Figure 4](image-url) Single-phase equivalent circuit of DC/AC converter.

Where \( V_p \) is the basic value of the modulation voltage reflected by the DC voltage \( V_{dc} \), \( L \frac{di_s}{dt} \) and \( R_L i_s \) are the voltage drop of the output side of the inverter, and \( V_s \) is the effective value of the grid voltage [25,26]. If the duty cycle of one switching cycle is \( d \), the modulation voltage output by the inverter can be expressed as equation (5):

\[ V_p = V_{dc} \cdot d_i \]  

(5)

It can be seen from the above formula (1) that the current rate of change of the current inverter circuit is \( \frac{di}{dt} \). Assuming that the circuit current will change from the current value to the command value \( i_c \) during one switching cycle, the required current rate of change should be equal to the difference between the command value and the current value divided by the switching period \( T_s \), as follows:
\[
\frac{dx}{dt} = \frac{i_{cl} - i_s}{T_s} \tag{6}
\]

By substituting equations (2) and (3) into equation (1), a formula for predictive control function that produces a modulation ratio can be obtained:

\[
d_i = \frac{1}{V_{dc}} \left[ V_s + L \left( \frac{i_{cl} - i_s}{T_s} \right) + R_L i_{cl} \right] \tag{7}
\]

Assuming that the condition is satisfied, the duty cycle calculated by the above equation (7) will cause the inverter circuit line current to reach the "predicted value" at the beginning of the next switching cycle. Therefore, the control method can achieve a fixed switching frequency [27,28].

4. Simulation verification and analysis

The current prediction control strategy of photovoltaic grid-connected inverter with power feedforward is simulated and verified by Matlab/Simulink simulation software. The control method adopted is based on the control block diagram shown in Figure 2. The system parameters are as follows: the switching frequency is set to 10 kHz, the filter inductance is set to 1mH, the standard sinusoidal AC voltage with a peak value of 20 V and a frequency of 50 Hz is equivalent to the grid voltage, and the DC side filter capacitor is 10 mF. The parameters of the photovoltaic cell simulation model are shown in Table 1. The standard parameters are based on ambient conditions of light intensity of 1000 W/m² and temperature of 25°C.

Table 1. PV Panel simulation model parameters.

| parameter                             | value     |
|---------------------------------------|-----------|
| Open circuit voltage / V              | 34.8      |
| Short circuit current / A             | 7         |
| Maximum power point operating current / A | 6.7      |
| Maximum power point operating voltage / V | 27       |
| Current to temperature compensation coefficient | 0.00050|
| Voltage to temperature compensation coefficient | 0.00288|
| Voltage to light intensity compensation coefficient | 0.00020|

The grid-connected simulation waveform of the traditional double closed-loop control and the current predictive control with power feedforward is shown in Figure 5. From top to bottom are: DC voltage waveform controlled by MPPT, output power waveform of photovoltaic cell, grid active power and reactive power waveform, and grid-connected voltage and current waveform.

It can be seen from Figure 5 that the solar cell operates under standard conditions. When the system reaches steady state, the total fundamental power is close to the maximum power output of the PV array $P_{pv}=173.5$ W, which shows that the whole system achieves maximum power tracking. The traditional double closed-loop control MPPT DC voltage needs 1.2 s to keep up with the reference value, and the process has fluctuations, while the MPPT with power feedforward CPC only needs 0.04 s to keep up with the reference value, the voltage fluctuation is small, the waveform is smooth, basic achieve full tracking. Both control strategies can achieve unit power factor grid-connected. The traditional double-closed-loop control of the grid-connected current requires 0.1 s or 5 cycles to reach steady state, while the CPC with power feedforward only needs 0.02 s or 1 cycle.

In order to further verify the dynamic response of the current prediction control with power feedforward to the system operation, the initial illumination intensity is set to 1000 W/m² during simulation; at 0.8 s, the illumination intensity is abruptly changed to 800 W/m²; at 1.2 s, illumination the intensity was abruptly changed from 800 W/m² to 1200 W/m². The CPC with power feedforward
is compared with the transient process of the grid-connected inverter under the traditional double closed-loop control. The simulation waveform is shown in figure 6. From top to bottom are: DC voltage waveform controlled by MPPT, grid-connected active power and reactive power waveform and grid-connected voltage and current waveform.

![Simulation waveforms](image)

(a)

![Simulation waveforms](image)

(b)

**Figure 5.** Comparison of two control strategies when the light intensity is constant. (a) Traditional double closed loop control and (b) current predictive control with or without power feedforward.

It can be seen from figure 6 that when the external environment changes, the conventional double closed-loop control and the use of current prediction control have power fluctuations in the former, and the latter has almost no power fluctuation. When the irradiance drops from 1000 W/m² to 800 W/m², the CPC with power feedforward needs about 0.2 s to restore steady state, while the traditional
double closed loop control takes 1 s; when the irradiance increases from 800 W/m² to 1200 W/m², the CPC with power feedforward needs about 0.04 s, while the traditional double closed loop control takes about 1.15 s to recover MPPT, and the CPC with power feedforward has almost no fluctuation of DC voltage during transient change, and the system runs more stably. Obviously, the proposed control method speeds up the response of the system and reduces the transient response process.

Figure 6. Comparison of two control strategies when the light intensity changes. (a) Traditional double closed loop control and (b) current predictive control with or without power feedforward.

It can be seen from figure 7 that the total harmonic distortion rate of the grid-connected current under current predictive control with power feedforward is 0.57%, and the harmonic distortion rate of each current is less than 0.4%; while the traditional double closed-loop control current harmonics mainly concentrated with the switching frequency and double switching frequency, the current total harmonic distortion rate is 1.69%, which is higher than CPC by about 1.12%. In addition, when the external environmental conditions change, the harmonic distortion rate of the grid-connected current with power feedforward changes little, which has little effect on the steady-state operation of the system.
5. Experiment analysis

In order to verify the feasibility and effectiveness of the proposed grid-connected inverter current prediction control method, a unit single-phase grid-connected experimental platform was built, as shown in figure 8. The platform consists of a real-time simulator OP5600 produced by OPAL-RT and actual peripheral hardware circuits. The main technical parameters involved in the experiment include: using the photovoltaic simulation power supply 62100H-600S produced by Chroma to simulate the characteristics of photovoltaic cells, DC voltage is 26–36 V; 2 mH filter inductor; voltage inverter via 20/311 isolation transformer and 220 V The grid is connected; the switching frequency is 10 KHz.

Further, in order to verify the control performance and dynamic characteristics of the system under steady state operation, two PV characteristic curves are simulated by using the photovoltaic analog power supply, curve 1 and curve 2, as shown in figure 8, by switching between the two curves. To simulate the completion of the change in photovoltaic cell output power.

When the system is in steady state operation, the inverter output voltage $V_o$, the grid current $i$, and the grid voltage $V_s$ waveform are as shown in figure 9. The grid-connected current and the grid voltage are in the same phase at the same frequency. The FFT analysis of the experimental data shows that the total harmonic distortion rate THD is 3.75%, less than 5%, which meets the requirements for grid connection. It can be seen that the current prediction with power feedforward control has a good effect on the grid connection.
Figure 9. Steady state experiment. (a) Inverter output voltage and grid operation and grid current harmonic analysis.

As shown in figure 10, when the light intensity changes, using the photovoltaic analog power output, switching from curve 2 to curve 1 after 1.5 seconds, then switching back to curve 2, the light intensity of the photovoltaic cell is first reduced and then increased. DC voltage $V_{dc}$, voltage reference value $V_{dcref}$, grid-connected current and grid voltage $V_s$ waveform are shown in figure 3. The experimental results show that under the condition of the change of photovoltaic cell output power, MPPT can respond in time, DC voltage can quickly track the reference voltage; grid-connected current recovers with the grid voltage in one cycle, and the distortion rate is 4.07%. The proposed control method provides good dynamic response.

Figure 10. Dynamic experiment of P-V curve change. (a) Dynamically changing overall waveform, (b) grid current harmonic analysis and (c) dynamic change decomposition waveform.

6. Conclusions
In this paper, a single-phase photovoltaic grid-connected inverter is proposed, and a current prediction grid-connected control method with power feedforward is proposed. The conclusions are as follows:

- For the problems of traditional grid-connected inverter control, the single-phase inverter
structure is studied and the conductivity prediction function formula is pushed. The output power of the photovoltaic cell is added to the current inner loop as the feedforward, which can effectively suppress the DC Voltage fluctuations and effects on grid-connected currents.

- The Matlab/Simulink simulation model and experimental platform are built. The results show that the grid-connected current and the grid voltage are in the same phase at the same frequency in steady state operation, and the total harmonic distortion is less than 5%, which meets the requirements for grid connection. In dynamic operation, the introduction of power feedforward can speed up the adjustment of DC voltage and reduce the fluctuation; and it has high-quality grid-connected current waveform and high power factor, realizes reactive power compensation, and has good dynamic characteristics.

- The method does not need to use the PI controller in the conventional grid-connected inverter control, so that the structure is simple, the calculation amount is small, the dynamic response of the system is faster, the number is easy to implement, and the utility model has certain use value.

- When DMPPT techniques are adopted in a grid connected system, the system presented in this paper could also be used as the CMPPT stage in a HMPPT system.

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