Research on DC side power decoupling control of photovoltaic inverters

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Abstract. Inverter is a vital component in photovoltaic power generation system, and it is related to the performance and efficiency of photovoltaic power generation. When the inverter is connected to the grid, the instantaneous power on the DC side and the AC side is unbalanced, and the instantaneous power pulsation of double frequency will be generated on the DC side, which directly affects the current stability and power utilization rate of the inverter on the DC side. This paper proposes a Power Decoupling Circuit (PDC) based on a single-phase photovoltaic inverter. This circuit uses a closed-loop feedforward power decoupling control strategy to compensate for the unbalanced pulsating power on both sides of the inverter. Eliminate low-frequency harmonics on the DC side, achieve the purpose of power decoupling, stabilize the DC side voltage of the photovoltaic inverter, and improve the performance and efficiency of photovoltaic power generation.

1. Introduction
Photovoltaic power generation systems include photovoltaic components, controllers, DC-DC converters, DC-AC converters and so on. Among which DC-AC converters are also called inverters [1]. Inverter is used as the interface between DC input and AC output to realize the conversion of energy from the DC side to the AC side. Its stable operation will bring huge benefits to the grid and photovoltaic power generation system. The electric energy generated by the photovoltaic power generation system can be directly supplied to the load, and can also be integrated into the power grid. In the process of merging into the power grid, if the instantaneous power of the inverter's DC side and AC side is to be balanced, the DC side will inevitably produce double-frequency power pulsation, which will affect the utilization rate of photovoltaic power generation on the DC side. And it will increase the total harmonic distortion of the grid-connected AC current [2, 3]. Therefore, it is very necessary to solve the problem of double-frequency power pulsation on the DC side of a single-phase inverter. According to the traditional method, a large electrolytic capacitor is connected in parallel on the DC side of the inverter, although it can solve the above problems, but there are problems such as large electrolytic capacitor and short life span [4]. In response to this problem, many scholars have also given different solutions. Literature [5] proposed a method of using a full-bridge buck unit as a decoupling circuit to form a new single-phase converter topology with the full-bridge circuit. The advantage of this circuit is that the voltage of the decoupling capacitor is sinusoidal. The wave voltage can make full use of the bipolarity of the film capacitor, and the energy on the capacitor can be used to compensate the double frequency power generated on the DC side. However, the cost of this circuit is relatively high and it is not easy to control. Literature [6] uses a DC Buck decoupling circuit on the
basis of Literature [5]. Structurally, this topology circuit structure reduces two switching tubes compared to the topology circuit in Literature [5], therefore, the switching loss of the circuit components is reduced, and the cost is reduced. The voltage of the decoupling capacitor in the Buck circuit is the product of the duty cycle and the DC side voltage. Through decoupling control, the voltage on the capacitor is controlled to a sine wave, and it is always lower than the DC input source voltage, and the voltage value can be as low as 0. Although the circuit topology is simplified at this time and the utilization rate of the capacitor is also improved, the control strategy of the circuit is also more complicated.

Combining the advantages and disadvantages of the above two circuit topologies, this work proposes a single-phase photovoltaic inverter power decoupling circuit (PDC), which uses small-capacity decoupling capacitors and PDC to replace large-capacity electrolytic capacitors. PDC adopts a closed-loop feedforward control strategy, which combines the theoretical value of the decoupling capacitor voltage with the actual value to control the on and off of the switching tube. Through the cooperation of the switching tube and the decoupling capacitor, the unbalanced pulsating power on both sides of the inverter is compensated, and the low-frequency harmonics on the DC side are eliminated, achieves the purpose of circuit decoupling, stabilizes the DC side current of the photovoltaic inverter, and reduces the total harmonic distortion of the AC current output by the grid.

2. Proposal of power decoupling control

After the single-phase photovoltaic energy is transformed by the inverter, it is filtered by the inductor $L_f$ and the capacitor $C_f$ and then connected to the grid. The grid voltage $v_o$ and current $i_o$ can be expressed as:

$$ v_o = V_o \sin(\omega t) $$
$$ i_o = I_o \sin(\omega t + \phi) $$

Then the instantaneous power fed by the inverter to the power grid can be expressed as:

$$ p_o = v_o i_o = \frac{V_o I_o}{2} \cos \phi - \frac{V_o I_o}{2} \cos(2\omega t + \phi) = \frac{v_o i_{od}}{2} - \frac{v_o i_{oq}}{2} \cos(2\omega t) + \frac{v_o i_{od}}{2} \sin(2\omega t) $$

Where, $V_o$ is the peak of grid voltage, $I_o$ is the peak of grid current, $\omega$ is the angular frequency of grid voltage, $\phi$ is the phase difference between grid voltage and grid current, $i_{od}$, $i_{oq}$ is the value of the grid current after $d$-$q$ transformation.

Therefore, the instantaneous power through the filter capacitor is:

$$ p_{c_f} = v_c i_{c_f} = v_C C_f \frac{dv_C}{dt} = \frac{V_o^2 \omega C}{2} \sin(2\omega t) $$

Where, $i_{c_f}$ is the filter capacitor current, and $C_f$ is the capacity value of the filter capacitor.

From the Equations (2) - (3), it can be seen that the double frequency instantaneous pulsation power of AC side of the inverter comes from the grid power and the filter capacitor, in order to balance the inverter AC side and DC side of pulse power, this paper puts forward the inverter DC side increase a power decoupling circuit, twice the frequency of inverter AC pulse power can be compensated. The structure of the inverter with power decoupling circuit is shown in Figure 1.

![Figure 1. Circuit structure with power decoupling inverter.](image-url)
As shown in the Figure 1, the power decoupling circuit is located on the DC side of the inverter, the inverter removes the large-capacity electrolytic capacitor on the DC side and adds a power decoupling circuit. The DC power supply $V_d$ is connected in series with a small-capacity decoupling capacitor $C_d$ group and then connected to the DC bus, and the DC bus voltage is $V_{link}$. The power decoupling circuit is composed of switch tubes $S_1$, $S_2$, diodes $V_{D1}$, $V_{D2}$, energy storage inductor $L$, and decoupling capacitor $C_d$. The input source $V_d$ is the output voltage of the photovoltaic panel. The PDC also has a boost function, which can make the DC bus side voltage $V_{link}$ always higher than the input voltage $V_d$ to meet the inverter’s requirements for the DC bus voltage. The inverter is composed of switch tubes $S_3$, $S_4$, $S_5$, and $S_6$, and the AC output of the inverter is connected to the grid after being filtered by the inductor $L_f$ and the capacitor $C_f$.

3. Analysis of working conditions of power decoupling circuit

The working state of the decoupling circuit is determined by the switching states of the switching tubes $S_1$ and $S_2$. There are four operating modes:

Method 1: when $S_1$ is turned on and $S_2$ is turned off, the DC voltage $V_d$ forms a loop by $S_1$ and the energy storage inductor $L$, and a part of the electrical energy from the power supply $V_d$ flows through $S_1$ to charge the inductor $L$. At this time the inductance $L$ stores energy.

Method 2: when $S_1$ is turned off and $S_2$ is turned off, the inductor $L$ is no longer an energy storage device, but a discharging device. Because the inductor current cannot change suddenly, the current flows through the capacitor $C_d$, the freewheeling diode $V_{D2}$ and the inductor $L$ form a loop, and the energy stored in the inductor $L$ is transferred to the decoupling capacitor $C_d$, and the voltage $V_{cd}$ across the decoupling capacitor gradually increases.

Method 3: when $S_1$ is turned off and $S_2$ is turned on, capacitor $C_d$ acts as a discharge device, and current flows through inductors $L$, $S_2$, and capacitor $C_d$ to form a loop. At this time, inductor $L$ acts as an energy storage device. The voltage across the decoupling capacitor gradually drops.

Method 4: when $S_1$ is turned off and $S_2$ is turned off, the inductor $L$ acts as a discharge device. Since the inductor current cannot change suddenly, the current circuit is formed by the inductor $L$, the freewheeling diode $V_{D1}$, and the DC input source $V_d$.

According to the operating states of the four circuits, the voltage of the decoupling capacitor rises first and then falls within one cycle, and the voltage of the DC bus will also change accordingly. Therefore, only by controlling the duty cycle of the switching tube, the voltage on the decoupling capacitor and the DC bus side voltage can be controlled to compensate the instantaneous unbalanced power of the AC side and the DC side of the inverter, so that the instantaneous power can reach balance to achieve power decoupling.

![Figure 2. Control strategy of decoupling inverter circuit.](image_url)

4. Control strategy of power decoupling circuit

The structure of the proposed PDC inverter control strategy is shown in Figure 2. The control structure is divided into three parts. The first part is grid-connected phase-locked loop detection, mainly to
provide the grid voltage and input current required for inverter control and decoupling circuit control; the second part is the inverter control part, using traditional PWM control, due to space limitations, I will not introduce it here; The third part is the closed-loop control of the power decoupling circuit, which mainly controls the decoupling and balance of the instantaneous pulsating power on the AC and DC sides of the inverter.

4.1. Grid-connected phase-locked loop detection

The function of the grid-connected phase-locked loop circuit is to obtain the input current $i_{Lfq}$ and $i_{Lfd}$ of the inverter control part, the input voltage $v_{od}$, $v_{oq}$ and the input current $i_{od}$, $i_{oq}$ and voltage $v_o$ of the decoupling circuit control part. It should be noted that the phase-locked loop here is different from the ordinary phase-locked loop, it is a phase-locked loop based on the second-order generalized integrator (SOGI-PLL) [7]. Because in the power decoupling control strategy, the $d$-$q$ transformation of the grid voltage/current ($v_o/i_o$) as feedback is required, and the $d$-$q$ transformation usually requires at least two orthogonal variables, but only one variable is available in a single-phase inverter, it cannot meet the needs of $d$-$q$ transformation. Therefore, adding a SOGI-PLL before the $d$-$q$ conversion link can solve this problem well. Due to space limitations, I don’t introduce it in detail here.

4.2. Control strategy of decoupling circuit

The closed-loop feedforward control strategy is adopted for the control of the power decoupling circuit. The main purpose of the decoupling circuit is to transfer the unbalanced double frequency instantaneous pulsating power on the AC side of the inverter to the decoupling capacitor $C_d$. According to Equations (2) - (3), in order to compensate for the unbalanced pulsating power generated on the AC and DC sides of the inverter, the instantaneous power of the decoupling capacitor should be:

$$p_{cd} = v_{od}i_{od} = \frac{V_d}{2} \cos (2\omega t + \varphi) - \frac{V_o}{2} \sin (2\omega t)$$

Therefore, the voltage of the decoupling capacitor should be set to the value shown in Equation (5):

$$V_{cd}^* = \sqrt{V_d^2 + \frac{V_d i_{od}}{2\omega C_d} \sin (2\omega t) + \frac{V_o i_{oq}}{2\omega C_a} \cos (2\omega t) + \frac{C_f}{2C_a} V_o^2 \cos (2\omega t)}$$

It can be seen from the Equation (5) that the parameter size of the components in the circuit will also affect the effect of power decoupling, and the efficiency of power decoupling function is different for components with different parameters. In order to solve this problem, and make the voltage of the decoupling capacitor $C_d$ accurately track the calculated voltage, a closed-loop feedforward control strategy is adopted here, and the actual value of the decoupling capacitor voltage $V_{cd}$ is used as the feedback value and the theoretical value $V_{cd}^*$ for comparison, the generated error $e$ is added to $V_{cd}$ after being adjusted by the PI controller, and then divided by the DC bus voltage to obtain the modulated wave signal. Compared with the triangular carrier, the switching tube $S_1$ is controlled $S_2$ on and off (see Figure 2).

Table 1. Simulation parameters.

| Parameter               | Symbol | Value |
|-------------------------|--------|-------|
| DC voltage source       | $V_d/V$| 100   |
| Grid voltage            | $v_o/V$| 160   |
| Grid current            | $i_o/A$| 5     |
| Filter inductance       | $L/f/M$| 2     |
| Energy storage          | $L/\mu H$| 220   |
| Filter capacitor        | $C_d/\mu F$| 10    |
| Decoupling capacitor    | $C_d/\mu F$| 150   |
| AC frequency            | $f_n/Hz$| 50    |
5. Simulation verification of power decoupling control
In order to verify the effectiveness of the decoupling control strategy, a simulation was carried out in Matlab simulation software. Among them, the simulation parameters are shown in Table 1.

5.1. Working analysis under unit power factor
When the inverter's grid-connected output power factor is 1, that is, $\cos \varphi = 1$, the grid voltage $v_o$ only has voltage component $v_{od}$ on the $d$-axis of the rotating coordinate system, in this time, the inverter only feeds active power to the grid. The simulation waveform is shown in Figure 3 - Figure 5.

![Figure 3](image1)

(a) DC bus voltage $V_{\text{link}}$

(b) Decoupling capacitor voltage $V_{Cd}$

**Figure 3.** $V_{\text{link}}$ and $V_{Cd}$ at unit power factor.

![Figure 4](image2)

(a) With decoupling circuit

(b) Without decoupling circuit

**Figure 4.** The comparison of DC bus current waveform at unit power factor.

![Figure 5](image3)

(a) DC side power waveform

(b) AC side power waveform

**Figure 5.** Power of inverter with decoupling circuit at unit power factor.

As shown in Figure 3(a), the DC bus voltage is a sine wave with an average value of about 250V, while the decoupling capacitor voltage waveform in Figure 3(b) is about 150V with an average value, which is consistent with the theoretical analysis; the DC bus current in Figure 4(a) is about 4.5A, compared with Figure 4(b), the waveform is relatively stable, and the double frequency is basically eliminated ripple; As shown in Figure 5(a) and Figure 5(b), the instantaneous power waveform on the DC side is similar to a triangular wave, and the average power is about 1100W, while the average power on the AC side is about 1125W, and the instantaneous power waveform on the DC side is similar to that on the AC side. The compensation of the unbalanced pulsating power on the AC and DC sides of the inverter is realized, and the decoupling efficiency reaches 97.7%, which proves the feasibility of the closed-loop feedforward power decoupling control strategy.
5.2. Work analysis under non-unity power factor
When the inverter is working in a non-unit power factor environment, \( \cos \phi \neq 1 \). At this time, the AC side of the inverter feeds both active power \( P \) to the grid and reactive power \( Q \) to the grid. Figure 6 - Figure 8 are the simulation results of the inverter working in a non-unit power factor environment.

![Figure 6. \( V_{\text{link}} \) and \( V_{\text{Cd}} \) at non unit power factor.](image1)

![Figure 7. The comparison of DC bus current waveform at non unit power factor.](image2)

![Figure 8. Power of inverter with decoupling circuit at non unit power factor.](image3)

It can be seen from Figure 6(a) that the DC bus side voltage is a sine wave with an average voltage of about 195V, while the decoupling capacitor average voltage in Figure 6(b) is 95V, which is consistent with the theoretical analysis; as shown in Figure 7(a), the current on the DC bus side with decoupling circuit is about 3.8A, compared with the DC bus current waveform without decoupling circuit in Figure 7(b), the waveform is still relatively stable, and the double frequency ripple on the DC side of the inverter is basically eliminated; As shown in Figure 8(a) and Figure 8(b), the instantaneous power waveform on the DC side is similar to triangular wave, and the average power is about 700W, while the average power of the AC side is about 725W, and the instantaneous power waveform of the DC side and the instantaneous power waveform of the AC side are almost the same, and the unbalanced pulsating power on the AC and DC sides of the inverter is compensated. After compensation, the decoupling efficiency reaches 96.5%, which proves the feasibility of the closed-loop feedforward power decoupling control strategy.

6. Conclusions
This paper proposes a power decoupling control strategy based on single-phase photovoltaic inverters. The power decoupling circuit adopts closed-loop feedforward control, replacing large-capacity electrolytic capacitors with small-capacity decoupling capacitors, extending the service life of the inverter. The simulation results show that the proposed decoupling control strategy can smooth the DC
side bus current waveform well regardless of whether the inverter is working in a unit power factor environment, so that the instantaneous power on the DC side and the instantaneous power on the AC side of the inverter can basically reach balance. This kind of inverter with power decoupling circuit can also be used in battery energy storage, wind power generation and other electric energy conversion systems, and has good application prospects.

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