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Research on No-affected Photovoltaic Grid-Connected Inverter by the Inductance Value

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Abstract. In order to solve the low adaptability problem of the common-mode voltage of the existing Non-isolated Photovoltaic Grid-Connected Inverter with H6-type (NPGCI-H6) is affected by the inductance matching factors and causes a large common-mode leakage current. Based on the idea of the parallel bypass switch on grid-connected filter inductor, this article put forward a no-affected photovoltaic grid-connected inverter by the inductance value (NPGCI-IV) circuit that is not affected by the inductance value matching and analyzed its operating modes and control methods. At the same time, this article designed a hysteresis current controller which is suitable for NPGCI-IV. Finally, the article studied the proposed photovoltaic grid-connected inverter circuit that is not affected by inductance matching and its control methods. The results showed the correctness of the proposed circuit and its control methods.

1. Introduction
With the promotion of global green energy concept, photovoltaic (PV) power generation has been paid more and more attention. As an important part of converting PV system of DC into grid-connected AC power, the inverter puts forward higher requirements for reliability and efficiency of PV grid-connected inverter (PGCI)[1, 2, 3, 4]. Meanwhile, the leakage current of PGCI need to meet the VDE-0126-1-1 standard that requires that the GCI must be removed from the power grid in 0.3s when the leakage current is higher than 300mA [5,6]. Therefore, how to suppress leakage current is one of the important research topics of photovoltaic power generation system. To single-phase full bridge grid-connected inverter, auxiliary switches are added to the AC of single-phase full bridge grid-connected inverter (SPFBGCI) to constitute continuous current circuit presented in reference [7], which could eliminate high frequency components and make common mode voltage change at low frequency and then suppress common mode leakage current effectively when the inverter is modulated by USPWM. A highly efficient Non-isolated photovoltaic grid-connected inverter with H6-type (NPGCI-H6) using symmetrical inductor filtering is put forward in reference [8]. It can solve the current leakage problem if the system does not contain transformers, the circuit structure relay circuit does not pass through the body diode with poor performance, so the reverse recovery loss is low. The advantage of system three-level output can be realized by using single-polarity modulation. The research indicates that this circuit structure has the advantages of low leakage current, high efficiency and high reliability, which is more suitable for medium and high power PV grid-connected inverter [8]. However, the above solution is based on the filtering inductance matching, symmetric filtering keeps the voltage constant to eliminate leakage current. The inhibition ability of NPGCI-H6 to leakage current will decrease if the inductance
does not match \((L_1 \neq L_2)\). In practical application, due to the influence of inductance manufacturing process, changes in external environment and working conditions, inductance value will change greatly [9, 10]. It is difficult to achieve a complete matching of inductance value. In addition, high precision inductors would change because of the interference of electromagnetic induction and coupling between different inductors. The mismatch of inductance value will lead to a large high-frequency voltage at both ends of the PV system’s ground capacitance, which will lead to a large common mode leakage current and is difficult to meet the requirements of VDE-0126-1-1.

To solve the above problems, a photovoltaic grid-connected inverter circuit and control method via paralleling bypass switching tube to the grid-connected filter inductor to restrain leakage current of NPGCI caused by mismatching inductance parameter value, is proposed in this paper.

2. Principle Analysis.

2.1. NPGCI-H6 leakage current analysis.

The topology of NPGCI-H6 is shown in figure 1(a). Among \(S_1, S_2, S_3, S_4, S_5, S_6\) is IGBT. \(D_1, D_2\) is high-performance diodes and \(u_0\) is the DC output voltage of the inverter. \(L_1, L_2\) is the filter inductance. \(i_g\) is the grid current, \(u_{grid}\) is the grid voltage and \(u_{grid} = U_m \times \sin(2\pi ft)\), where \(U_m, f\) is the amplitude and frequency of grid voltage. \(u_{AN}, u_{BN}\) is the voltage between N of A, B, which is the middle of the bridge arm. \(C_G\) is parasitic capacitance to earth of \(u_0\).

![Figure 1. NPGCI-H6 circuit topology and its AC equivalent circuit.](image)

The DC source can be isolated by \(C_G\), therefore, item only relates to AC voltage. When ignoring the influence of \(u_0\), the common-mode equivalent current of NPGCI-H6 is shown in figure 1(b). From the figure, the voltage of the CG which is given by \(u_{AN}, u_{BN}, u_{grid}\) can be calculated by superposition principle.

\[
\begin{align*}
\omega_g &= 2\pi f \\
\omega_g &= \frac{L_2 u_{AN} + L_1 u_{BN} + L_2 u_{grid}}{L_1 + L_2 - L_1 L_2 C_G \omega_g} + \frac{L_2 u_{grid}}{L_1 + L_2 - L_1 L_2 C_G \omega_g}
\end{align*}
\]

\(\omega_g=2\pi f\) is the angular frequency of grid voltage. \(C_G\) has something of the environmental and construction of photovoltaic cell panel, and it is about 50~150nF/kW [11]. \(w_g\) is also much less than \(w_s\). Therefore, in practical engineering, the \(L_1L_2C_Gw_g\) of formula (1) is about 0, and formula (1) can be rewrite as.
According to formula (2), the current flowing through $C_G$ which is the leakage current $i_{\text{cm}}$ of NPGCI-H6 can be calculated as:

$$i_{\text{cm}} = C_G \frac{du_G}{dt}$$

Seen from formula (1) and (2), $i_{\text{cm}}$ is not only related to $L_1$ and $L_2$, but also has something connected with $u_{\text{grid}}$, $u_{\text{AN}}$ and $u_{\text{BN}}$. $i_{\text{cm}}$ can be suppressed validly by decrease the voltage gradient of $C_G$.

According to reference [12], the voltage of $C_G$ in four modes is:

$$u_G = \frac{u_0 - u_{\text{grid}}}{L_1 + L_2} = \frac{u_0}{L_1} - \frac{u_{\text{grid}}}{L_2}$$  \hspace{1cm} (4)

$$u_G = \frac{u_0}{L_1 + L_2} L_2 = \frac{u_0}{L_2} - \frac{u_{\text{grid}}}{L_2}$$  \hspace{1cm} (5)

$$u_G = \frac{u_0 L_2 - u_{\text{grid}}}{L_1 + L_2} = \frac{u_0}{L_1} - \frac{u_{\text{grid}}}{L_2}$$  \hspace{1cm} (6)

$$u_G = \frac{u_0}{L_1 + L_2} L_2 - \frac{u_{\text{grid}}}{L_2} = \frac{u_0}{L_1} - \frac{u_{\text{grid}}}{L_2}$$  \hspace{1cm} (7)

Known from formula (4) to (7), when $L_1 \neq L_2$, the $u_G$ is the DC input source to parasitic capacitance to earth, which will change with the operating states. Therefore, the high-frequency component is included in the voltage, and the large leakage current will be caused.

2.2. NPGCI-IV principle analysis.

2.2.1. NPGCI-IV circuit topology. The topology of NPGCI-IV is shown in figure 2(a). $S_1$–$S_8$ are power switches. $D_1$–$D_4$ are high-performance diodes. $L_1$–$L_4$ are filter inductances. $u_{\text{grid}}$ is grid voltage $u_{\text{grid}} = U_m \times \sin(100\pi f)$, where $U_m$ and $f$ are the amplitude and frequency of $u_{\text{grid}}$, respectively. $u_0$ is DC voltage of the photovoltaic cell. $C_G$ is the parasitic capacitance of the DC photovoltaic panels. $i_0$ is the grid-connected current. Compared with the topology of NPGCI-H6, two power switches and diodes are added, respectively. Where $S_1$, $S_2$, $S_3$, $S_4$, $S_5$ and $S_6$ are the main switch tubes, $S_7$ and $S_8$ as auxiliary switch tubes are parallel to the inductance $L_1$ and $L_2$. Meanwhile, in order to effectively reduce the switching loss of the device and improve the efficiency of the inverter, NPGCI-IV adopts half-cycle modulation. Which means that $S_1$, $S_4$, $S_5$, $S_8$ work together in the positive half cycle and $S_2$, $S_3$, $S_6$, $S_7$ work together in the negative half cycle. So the driving waveform of NPGCI-IV is shown in figure 2(b).
2.2.2. NPGCI-IV working mode and leakage current analysis. According to figure 2 and figure 3, the AC equivalent circuit of NPGCI-IV is the same as that of NPGCI-H6 as shown in figure 1(b). Therefore, the expression of the parasitic capacitance’s voltage $u_G$ and leakage current $i_{cm}$ is same with NPGCI-H6. As shown in equations (2) and (3), respectively.

If $i_L$ flows from A to B, $i_L$ is positive. According to the direction of $i_L$ and conduction conditions of $S_1$-$S_8$, the proposed NPGCI-IV can be divided into 4 operating modes, which are shown in figure 3(a)-(d), respectively.

Mode I: As shown in figure 3(a), when $i_L$>0, the power switches of $S_1$, $S_4$, $S_5$, $S_8$ turn on and $S_2$, $S_3$, $S_6$, $S_7$ turn off. $u_0$, $S_1$, $S_5$, $L_1$, $D_3$, $u_{grid}$, $S_8$ and $S_4$ constitute a positive charging circuit. $i_L$ is increasing. From figure 3(a), $u_{AN}$=$u_0$, $u_{BN}$=$0$, $L_2$=$0$ can be obtained. By substituting $u_{AN}$, $u_{BN}$ and $L_2$ into equation (2), $u_G$ changes into

$$u_G = \frac{L_1u_0}{L_1+L_2} + \frac{L_2u_{grid}}{L_1+L_2} = 0$$ (8)

Mode II: As shown in figure 3(b), when $i_L$>0, the power switches of $S_4$, $S_5$, $S_8$ turn on and $S_1$, $S_2$, $S_3$, $S_6$, $S_7$ turn off. $S_5$, $L_1$, $D_3$, $u_{grid}$, $S_8$ and $D_2$ constitute a positive freewheel circuit. $i_L$ is decreasing. Therefore, the isolation of grid and DC voltage is achieved in the positive continuous phase. This freewheel circuit does not pass through the body diodes with poor performances of active switches. So the NPGCI-IV can achieve high efficiency, reliability and low the reverse recovery loss. From figure 3(b), $u_{AN}$=$0$, $u_{BN}$=$0$, $L_2$=$0$ can be obtained. By substituting $u_{AN}$, $u_{BN}$ and $L_2$ into equation (2), $u_G$ changes into

$$u_G = \frac{L_2u_{grid}}{L_1+L_2} = 0$$ (9)

Mode III: As shown in figure 3(c), when $i_L$<0, the power switches of $S_2$, $S_1$, $S_6$, $S_7$ turn on and $S_1$, $S_4$, $S_5$, $S_8$ turn off. $u_0$, $S_2$, $S_6$, $L_2$, $D_4$, $u_{grid}$, $S_7$ and $S_1$ constitute a negative charging circuit. $i_L$ is increasing. From figure 3(c), $u_{AN}$=$0$, $u_{BN}$=$u_0$, $L_1$=$0$ can be obtained. By substituting $u_{AN}$, $u_{BN}$ and $L_1$ into equation (2), $u_G$ changes into

$$u_G = \frac{L_1u_0}{L_1+L_2} + \frac{L_2u_{grid}}{L_1+L_2} = u_{grid}$$ (10)
Mode IV: As shown in figure 3(d), when $i_L<0$, the power switches of $S_3$, $S_6$, $S_7$ turn on and $S_1$, $S_2$, $S_4$, $S_5$, $S_8$ turn off. $S_6$, $L_2$, $D_4$, $u_{grid}$, $S_7$ and $D_1$ constitute a negative freewheel circuit. $i_L$ is decreasing. Therefore, the isolation of grid and DC voltage is achieved in the positive continuous phase. From figure 3(d), $u_{AN}=0$, $u_{BN}=0$, $L_1=0$ can be obtained. By substituting $u_{AN}$, $u_{BN}$ and $L_1$ into equation (2), $u_G$ changes into

$$u_G = \frac{L_1 u_{grid} + u_{grid}}{L_1 + L_2} = u_{grid}$$

From the above analysis, the freewheeling current flows through the independent freewheeling diodes instead of the body diodes of the switches, so the efficiency and reliability can be increased. Therefore, the proposed NPGCI-IV has the advantages of high efficiency and high reliability. Meanwhile, summarize the change of $u_G$. Which keeps constant $0$ and $u_{grid}$ in the positive and negative half cycle, respectively. Considering the frequency of grid voltage $f=50\text{Hz}$ far less than the switching frequency, the high-frequency voltage component does not be included. On this basis, it can be seen from the combination of equation (3) that the leakage current of the PV system can be effectively suppressed by the proposed NPGCI-IV.

In addition, compared with NPGCI-H6 circuit topology. The proposed NPGCI-IV is avoided the problem of $u_G$ changing with working state caused by inductance mismatch in NPGCI-H6. Which greatly improves the adaptability of photovoltaic power generation system in practical industrial application.

2.3. Modulation strategy.

On the basis of effectively suppressing the leakage current of PV grid-connected inverter, in order to realize more efficient function of PV grid-connected power generation system and make the output
current fast and accurately track the reference signal. The hysteresis current control (HCC) is designed because these advantages of high accuracy of current tracking and no transient current overshoot.

As shown in figure 4, the control schematic diagram of NPGCI-IV adopts HCC. Where \( h \) is hysteretic width, \( i_A \) and \( i_B \) are positive half-cycle and negative half-cycle inductive current, respectively. \( i_{\text{ref}} \) is reference signal of grid-connected current \( i_L \). \( I_m \) is the amplitude of \( i_{\text{ref}} \). \( \theta \) is phase angle of \( u_{\text{grid}} \), which can be obtained by applying phase locked loop (PLL) and inquiring the corresponding table of sines \( \sin \theta \). Besides, the current reference signal \( i_{\text{ref}} \) can be obtained by multiplying \( I_m \) and \( \sin \theta \).

According to compared \( i_{\text{ref}} \) and zero-signal, the driving signal of \( S_4, S_5, S_8 \) or \( S_3, S_6, S_7 \) can be obtained. If \( i_{\text{ref}}>0 \), these conditions can be satisfied: \( S_4, S_5, S_8 \) turn on, \( S_3, S_6, S_7 \) turn off and \( i_B \) keeps a constant 0. If \( i_{\text{ref}}<0 \) and \( -i_B<i_{\text{ref}}+h \), \( S_2 \) is switched off by high frequency drive signal, \( i_B \) decreases in the setting reverse direction. If \( i_{\text{ref}}<0 \) and \( -i_B>i_{\text{ref}}+h \), \( S_2 \) is switched on by the same high-frequency drive signal. \( i_B \) increases in the setting reverse direction.

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### Figure 4

The control strategy of NPGCI-IV system is controlled by hysteresis current.

### 3. Simulation and Experimentation

To further analyse the above theory, the experimental platform of MATLAB/Simulink is set up. The simulation parameters are shown in table 1. Considering this condition of inductance mismatch, verify the availability of topology of NPGCI-IV with modulation strategy. Therefore, the filter inductances \( L_1 \) and \( L_2 \) are set to 12mH and 6mH respectively. The results of simulation are shown in figure 5.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( u_o/V \) | 400   | \( U_m/V \) | 220   |
| \( f/Hz \) | 50    | \( L_1/mH \) | 12    |
| \( f_s/kHz \) | 5     | \( L_2/mH \) | 6     |
| \( C_{\phi}/nF \) | 80    |           |       |

According to the waveform of figure 4, the filter inductance \( L_1 \) works in the positive half cycle and disconnect in the negative half cycle. But the filter inductance \( L_2 \) is contrary to \( L_1 \). Inductance \( L_2 \) works in the negative half cycle and disconnect in the positive half cycle. Besides, the parasitic
capacitor voltage $u_0$ keeps a constant 0 in the positive half cycle and changes synchronously with grid voltage $u_{\text{grid}}$ in the negative half cycle.

Summarizing the above analysis, the NPGCI-IV circuit under hysteresis current control is ideally in the half-cycle working state, which ensures further experimental verification of the leakage current of the circuit.

In order to verify the correctness of theoretical analysis, the experimental prototype is established. The model of power switches $S_1$-$S_8$ and diodes $D_1$-$D_4$ are IRG4PH40UD and DSEI30-06, respectively. The experiment parameters is same as table 1.
The NPGCI-IV experimental waveforms of grid voltage $u_{\text{grid}}$ and grid current $i_L$ are shown in figure 6(a). From this figure, $i_g$ is highly sinusoidal synchronized with $u_g$, and power factor is close to 1. Meanwhile, on account of HCC is adopted, which is variable frequency control and makes the inductor current pulsation can be controlled within the hysteresis loop width. So the zero-crossing distortion caused by constant frequency single polarity control current can be avoid. The output voltage waveforms of NPGCI-IV’s bridge arms $u_{AN}$, $u_{BN}$ and its amplifying waveforms of the dotted box are shown in figure 6(b) and figure 6(c), respectively. From figure 6(b) and figure 6(c), the waveforms identify with theoretical analysis. Further, the parasitic capacitor voltage $u_G$ keeps a constant 0 in the positive half cycle and changes synchronously and low-frequency (50Hz) with grid voltage $u_{\text{grid}}$ in the negative half cycle. The waveforms of grid current $i_L$ and leakage current $i_{\text{tcm}}$ are shown in figure 6(d). It can be seen clearly that in the entire power frequency cycle, $i_{\text{tcm}}$ maintains between -100mA and 100mA. Which meet the VDE-0126-1-1 standard. According to the theoretical analysis, when filter inductances $L_1$ and $L_2$ alternatively working the leakage current is caused by the voltage component of low frequency.

4. Conclusion
Based on the theoretical analysis and experimental study of the proposed NPDGI, the following conclusions can be obtained:

(1) Compared with NPGCI-H6, two extra power switches are added to the filter inductance with corresponding driving signals. Which realized the voltage of $C_G$ is not affected in the value of filter inductance. Meanwhile, the voltage of $C_G$ keeps a constant in the half cycle.
(2) According to the simulation and experimentation, the leakage current can be effectively suppressed. Which meets the VDE-0126-1-1 standard, has better security and applies more extensively in the practical photovoltaic system.

(3) A thought of combining the symmetrical inductor filtering with by-pass switches is proposed in this paper. It can increase greatly the adaptation in the DC-AC transform for photovoltaic inverter.

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