Research on common-mode leakage current for a novel non-isolated dual-buck photovoltaic grid-connected inverter

Yunzhong Dai\textsuperscript{a),} Zichao Guan, Rongfei Zhang, Shengxian Zhuang, and Yan Wang

Electrical Engineering and Information, Southwest Petroleum University, Chengdu 610500, Sichuan Province, China
\textsuperscript{a)} daiyunzhong@126.com

Abstract: The inhibition of common-mode leakage current is the key problem to be solved in non-isolated photovoltaic grid-connected inverter (NPGCI). To eliminate the common-mode leakage current of dual-buck grid-connected inverter, a novel non-isolated dual-buck photovoltaic grid-connected inverter (NDPGCI) topology is proposed in this paper. Meanwhile, a unipolar sinusoidal pulse width modulation (USPWM) strategy that can make the common-mode voltage constant is presented. Then, operating modes and common-mode leakage current of NDPGCI are analyzed, which show that NDPGCI modulated by USPWM has advantages of no shoot-through problem, three-level output characteristic and high reliability, as well as common-mode leakage current elimination. Finally, the experimental results verified the correctness of NDPGCI.

Keywords: non-isolated dual-buck photovoltaic grid-connected inverter, no shoot-through problem, common-mode voltage, common-mode leakage current

Classification: Power devices and circuits

References

1 Introduction

With the development of photovoltaic (PV) generation system, the requirements of high power quality, reliability and efficiency of grid-connected inverter (GCI) are
increasingly improved [1, 2]. Compared with the isolated photovoltaic grid-connected inverter, non-isolated photovoltaic grid-connected inverter (NPGCI) has the advantages of small size, low cost and high efficiency [3, 4, 5]. To ensure the electrical safety, the VDE-0126-1-1 standard sets strict limits on the common-mode leakage current of PV system. The standard requires that the GCI must be removed from the power grid in 0.3 s when the leakage current is higher than 300 mA [6]. Therefore, the suppression of leakage current of GCI is one of the hot spots in recent years. H-bridge GCIs are applied widely for its simple structure and low cost in [7, 8, 9]. By adding the auxiliary switch, the common-mode leakage current is eliminated effectively. However, H-bridge grid-connected inverters need to be set dead-time to avoid the shoot-through problem, but the dead-time effect will cause the distortion of grid-connected current, which would decrease the power quality of PV system [10]. In addition, during the dead-time, the inductor current flows through the body diode, which has long reverse recovery time and large reverse recovery losses. Therefore, the shoot-through problem is a major killer of the reliability, power quality and efficiency. Dual-buck grid-connected inverter is extensively investigated due to its no shoot-through problem, high efficiency and reliability [11, 12, 13, 14, 15]. A basic dual-buck full-bridge grid-connected inverter is presented in [16]. $S_1$, $S_2$ operate in high frequency at each half-line cycles, and $S_3$, $S_4$ operate in grid period with zero-current switching (ZCS) when the inverter is modulated by USPWM, thus, the common-mode voltage has no high frequency components. However, there is still a shoot-through problem of switches $S_3$ and $S_4$ at the AC side, and the dead-time needs to be set. Based on basic dual-buck full-bridge grid-connected inverter, reference [17] proposed a new dual-buck grid-connected inverter. In this inverter, inductors are linked between every bridge arm, so there is no shoot-through problem. However, this inverter needs 6 switching tubes and 4 inductors. Reference [18] proposed a dual-buck full-bridge photovoltaic grid-connected inverter. The research result shows that the inverter has the advantages of no shoot-through problem, high-efficiency and optimum selection of the freewheeling diodes.

However, the above dual-buck full-bridge grid-connected inverters have a serious disadvantage: the inverters don’t separate the DC power from a grid during freewheeling time, which needs to employ either line-frequency or high-frequency isolation transformers when dual-buck full-bridge grid-connected inverter (DFGI) is connected with power grid. But line-frequency transformers are large and heavy, making the whole system bulky and hard to install. Topologies with high-frequency transformers commonly include several power stages, which increase the system complexity and reduce the system efficiency [19].

To solve the aforementioned problems, inspired by the newly-developed embedded-switch H5 topology and basic dual-buck full-bridge grid-connected inverter, a novel non-isolated dual-buck photovoltaic grid-connected inverter (NDPGCI) is put forward in this paper.
2 Non-isolated dual-buck photovoltaic grid-connected inverter

2.1 Topology

The topologies of the grid-connected inverter with H5-type (TGCI-H5) and dual-buck full-bridge grid-connected inverter (DFGI) are shown in Fig. 1(a) and Fig. 1(b), respectively. Based on TGCI-H5 and DFGI, the NDPGCI is proposed, which is shown in Fig. 2. $S_1$–$S_5$ are power switches. $D_1$–$D_4$ are high-performance diodes. $L_1$–$L_4$ are filter inductances. $u_g$ is grid voltage $u_g = U_m \times \sin(100\pi f t)$, where $U_m$ and $f$ are the amplitude and frequency of $u_g$, respectively. $u_{dc}$ is DC voltage of the photovoltaic cell. $C_{pv}$ is the parasitic capacitance of the DC photovoltaic panels. $i_g$ is the grid-connected current. Similar to TGCI-H5, an additional switch $S_5$ is added in series at the positive terminal of DC voltage. $L_A$ and $L_B$ are the grid filter inductance, which play the role of eliminating the differential mode voltage. Due to the existence of $L_1$–$L_4$, the shoot-through problem can be avoided. $D_3$ and $D_4$ can prevent that the freewheeling current flows through body diodes with poor performances of $S_3$ and $S_1$, respectively. Though six inductors are used in NDPGCI, the coupling of the 4 independent inductances $L_1$–$L_4$ can be achieved by decoupling and integrating, so the size and weight of the core and winding of the inductance won’t be increased. Because the inductance current can’t be changed suddenly, when $S_1$ and $S_2$ turn on in the positive period and $S_3$, $S_4$ turn on in the negative period, the switches won’t be damaged.

Fig. 1. Topologies of grid-connected inverter. (a) Grid-connected inverter with H5-type, (b) Dual-buck full-bridge grid-connected inverter.

Fig. 2. Topology of the Proposed NDPGCI
2.2 Modulation strategy
The full-bridge grid-connected inverter with bipolar sinusoidal pulse width modulation (SPWM) has the characteristics of low leakage current. However, the ripple current of inductor is double unipolar SPWM. The switching and filter inductance loss are larger and the efficiency is lower than unipolar SPWM. Therefore, the unipolar SPWM is adopted for the proposed NDPGCI. To reduce switching loss and conduction loss and improve efficiency of the inverter and keep common-mode voltage constant in the operating cycle to suppress common mode leakage current effectively, NDPGCI operates in the half cycle mode. $S_1$ and $S_4$ work in the positive period and $S_2$ and $S_3$ work in the negative period. Fig. 3 shows the ideal waveforms of the proposed NDPGCI with unipolar SPWM. $u_{\text{control}}$ is the modulation signal. $u_{\text{carrier}}$ is unipolar triangular carrier wave, which determines switching cycle $T_s$. Compared with the bipolar modulation, the volume and weight of the output filter can be decreased. From Fig. 3, in the positive half cycle, $S_3$ and $S_4$ have the same commutation orders. In the negative half cycle, $S_5$ and $S_2$ have the same commutation orders. In the positive period, $S_1$ always turns on, so $L_1$ doesn’t need freewheeling circuit. Similarly, in the negative period, $S_3$ always turns on, and $L_3$ doesn’t need freewheeling circuit as well.

![Fig. 3. Ideal waveforms of the proposed NDPGCI with unipolar SPWM](image)

2.3 Common-mode circuit equivalent
According to the reference [20] analyze the common-mode leakage current of transformerless grid-connected inverter, the common-mode equivalent circuit can be established. DC power is quarantined by $C_{PV}$, so the common mode leakage current just has something to do with AC power. From Fig. 3, when ignoring the influence of $u_{dk}$, $S_1$, $S_4$, $S_5$ operate in the positive half cycle and $S_2$, $S_3$ turn off. According to Fig. 2, the common-mode equivalent circuits of the positive half cycle and the negative half cycle are shown in Fig. 4(a) and Fig. 4(b), respectively. $u_{AN}$ is the voltage between A and N. $u_{BN}$ is the voltage between B and N. $u_{CN}$ is the voltage between C and N. $u_{DN}$ is the voltage between D and N. $Z_G$ is the earthed impedance of the inverter. The inductive and capacitive component of $Z_G$ are much
smaller than \((L_1 + L_A)/2\) and \(C_{PV}\), respectively. \(Z_G\) plays a role of resistive attenuation, so \(Z_G\) can be ignored in the analysis of leakage current [7, 20, 21].

According to the derivation of \(u_{ecm}\) of the double inductance topology from the reference [21], \(u_{ecm}\) in the Fig. 4(a) is:

\[
u_{ecm} = u_{cm} + \frac{u_{dm} L_A - L_B}{2 L_A + L_B}
\]

(1)

Where \(u_{ecm}\) is the effective common-mode voltage, \(u_{cm}\) is the common-mode voltage, \(u_{dm}\) is the differential mode voltage:

\[
u_{cm} = 0.5 \times (u_{AN} + u_{BN})
\]

(2)

\[
u_{dm} = u_{AB} = u_{AN} - u_{BN}
\]

(3)

Known from formula (1), when \(L_1 + L_A \neq L_4 + L_B\), the common mode leakage current will be increased by \(u_{dm}\). Therefore, to eliminate the effect from \(u_{dm}\), assume that \(L_1 = L_2 = L_3 = L_4\), \(L_A = L_B\) and rewrite formula (1):

\[
u_{ecm} = u_{cm} = 0.5 \times (u_{AN} + u_{BN})
\]

(4)

Shown in Fig. 4, the common-mode leakage current is:

\[
i_{cm} = C_{PV} \frac{du_{ecm}}{dt} = C_{PV} \frac{du_{cm}}{dt}
\]

(5)

Known from formula (4) and (5), if \(u_{AN} + u_{BN}\) is kept as a constant, the common-mode leakage current can be suppressed validly. Similarly, in the negative half period, if \(u_{CN} + u_{DN}\) is kept as a constant, the common mode leakage current also can be suppressed effectively.

3 Operating modes and common-mode leakage current analysis

If \(i_g\) flows from A to B, \(i_g\) is positive. According to the direction of \(i_g\) and conduction conditions of \(S_1\)–\(S_5\), the proposed NDPGCI can be divided into 4 operating modes, which are shown in Fig. 5(a)–(d), respectively.

Mode 1: As shown in Fig. 5(a), when \(i_g > 0\), \(S_1, S_4, S_5\) turn on and \(S_2, S_3\) turn off. \(u_{dc}, S_2, S_1, L_1, L_A, u_g, L_B, L_4\) and \(S_4\) constitute a positive charging circuit. \(i_g\) is increasing. According to the condition of elimination of leakage current, the
differential-mode voltage can be eliminated when \( L_1 = L_2 = L_3 = L_4, L_A = L_B \), meanwhile, the common-mode voltage \( u_{cm} \) is

\[
u_{cm} = 0.5 \times (u_{AN} + u_{BN})
\]

Obviously, from Fig. 5(a), \( u_{AN} = +u_{dc}, u_{BN} = 0 \) can be obtained. By substituting \( u_{AN} \) and \( u_{BN} \) into equation (4), \( u_{cm} \) changes into

\[
u_{cm} = 0.5 \times (u_{AN} + u_{BN}) = 0.5 \times (u_{dc} + 0) = 0.5u_{dc}
\]

**Mode 2:** As shown in Fig. 5(b), when \( i_g > 0 \), \( S_1 \) turns on and \( S_2, S_3, S_4, S_5 \) turn off. \( S_1, L_1, L_A, u_B, L_B, L_4 \), and \( D_2 \) constitute a positive freewheel circuit, and \( i_g \) is increasing. 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 NDPGCI can achieve high efficiency, reliability and low the reverse recovery loss. When \( S_4 \) and \( S_5 \) are the same types, \( V_{S4} = V_{S5} \), where \( V_{S4} \) and \( V_{S5} \) are the voltage stresses of \( S_4 \) and \( S_5 \), respectively. Meanwhile, equations (8) can be obtained based on the Kirchhoff’s voltage law.

\[
u_{AN} = u_{dc} - V_{Ss} \quad u_{BN} = V_{S4} \quad u_{AN} = u_{BN}
\]

According to Eqs. (8), \( u_{AN} \) and \( u_{BN} \) can be expressed as

\[
u_{AN} = u_{BN} = 0.5u_{dc}
\]

According to the Eq. (4), \( u_{cm} \) of Mode 2 is given as

\[
u_{cm} = 0.5 \times (0.5u_{dc} + 0.5u_{dc}) = 0.5u_{dc}
\]

**Mode 3:** As shown in Fig. 5(c), when \( i_g < 0 \), \( S_2, S_3 \) and \( S_5 \) turn on and \( S_1, S_4 \) turn off. \( u_{dc}, S_2, S_3, L_3, L_B, L_A, L_2 \) and \( S_2 \) constitute a negative charging circuit. \( i_g \) is increasing. The differential-mode voltage can be eliminated when \( L_1 = L_2 = L_3 = L_4; L_A = L_B \), meanwhile, the common mode voltage \( u_{cm} \) is

\[
u_{cm} = 0.5 \times (u_{CN} + u_{DN})
\]

From Fig. 5(c), it can be easily seen that \( u_{DN} = -u_{CD} = +u_{dc}, u_{CD} = -u_{dc}, u_{CN} = 0 \) and \( u_{cm} \) changes into

\[
u_{cm} = 0.5 \times (u_{CN} + u_{DN}) = 0.5 \times (0 + u_{dc}) = 0.5u_{dc}
\]

**Mode 4:** As shown in Fig. 5(d), when \( i_g < 0 \), \( S_3 \) turns on and \( S_1, S_2, S_4, S_5 \) turn off. \( u_g, L_A, L_2, D_1, S_3, L_3 \) and \( L_B \) constitute a negative discharging freewheel circuit. \( i_g \) is decreasing. Therefore, the isolation of grid and DC voltage is achieved in the negative continuous phase. When \( S_2 \) and \( S_3 \) are the same types, \( V_{S2} = V_{S3} \), where \( V_{S2} \) and \( V_{S3} \) are the voltage stresses of \( S_2 \) and \( S_3 \), respectively. Meanwhile, equations (13) can be obtained based on the Kirchhoff’s voltage law.

\[
u_{CN} = u_{dc} - V_{Ss} \quad u_{CN} = V_{S2} \quad u_{CN} = u_{DN}
\]

According to Eqs. (13), \( u_{CN} \) and \( u_{DN} \) can be expressed as

\[
u_{CN} = u_{DN} = 0.5u_{dc}
\]

And \( u_{cm} \) of Mode 4 is given as

\[
u_{cm} = 0.5 \times (0.5u_{dc} + 0.5u_{dc}) = 0.5u_{dc}
\]
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 NDPGCI has the advantages of high efficiency and high reliability. According to the equation $i_{cm} = C_{pv}d(u_{cm})/dt$, the condition of eliminating common-mode leakage current $i_{cm}$ is met that $u_{cm}$ equals constant. It’s easy to see that at the whole cycle, $u_{cm}$ remains a constant $u_{dc}/2$. So the common-mode leakage current can be eliminated.

4 Experimental results

In order to verify the correctness of theoretical analysis, the experimental prototype is established. The experimental circuit parameters are shown in Table I. The output voltage waveforms of NDPGCI’s bridge arms $u_{AN}$, $u_{BN}$, $u_{AN} + u_{BN}$ and its amplifying waveforms of the dotted box in the positive half voltage cycle are shown in Fig. 6(a) and Fig. 6(b), respectively. From Fig. 6(a) and Fig. 6(b), $u_{AN}$ alternates between 180 V and 360 V and $u_{BN}$ alternates between 0 V and 180 V when $i_g > 0$. Within a switching cycle, $u_{AN}$ and $u_{BN}$ complement each other and $u_{AN} + u_{BN}$ is a constant 360 V approximately. The waveforms of $u_{CN}$, $u_{DN}$, $u_{CN} + u_{DN}$ and its amplifying waveforms of the dotted box in the negative half voltage cycle are shown in Fig. 6(c) and Fig. 6(d). From Fig. 6(c) and Fig. 6(d), $u_{CN}$ alternates between 0 V and 180 V and $u_{DN}$ alternates between 180 V and 360 V when $i_g < 0$. Within a switching cycle, $u_{CN}$ and $u_{DN}$ complement each other and $u_{AN} + u_{BN}$ is a constant 360 V approximately. The waveforms of $i_g$ and $u_g$ are shown in Fig. 6(e). From Fig. 6(e), $i_g$ is highly sinusoidal synchronized with $u_g$. 

Fig. 5. Operating circuit of each Mode and its equivalent circuit. (a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4.
and power factor is close to 1. The waveforms of the common-mode voltage $u_{GN}$ and the common-mode leakage current $i_{tcm}$ of NDPGC1 are shown in Fig. 6(f). From the Fig. 6(f), it can be seen clearly that in the entire power frequency cycle,

<table>
<thead>
<tr>
<th>Circuit parameters</th>
<th>parameters</th>
<th>value</th>
<th>parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{dc}/V$</td>
<td>$u_{dc}/V$</td>
<td>360</td>
<td>$U_m/V$</td>
<td>220</td>
</tr>
<tr>
<td>$P_w/kW$</td>
<td>$P_w/kW$</td>
<td>1.2</td>
<td>$T_s/us$</td>
<td>200</td>
</tr>
<tr>
<td>$f/Hz$</td>
<td>$f/Hz$</td>
<td>50</td>
<td>$L_A=L_B/uH$</td>
<td>450</td>
</tr>
<tr>
<td>$L_1=L_2=L_3=L_4/uH$</td>
<td>$L_1=L_2=L_3=L_4/uH$</td>
<td>250</td>
<td>$C_{pv}/nF$</td>
<td>75</td>
</tr>
</tbody>
</table>

Fig. 6. Experimental results of the proposed NDPGC1. (a) $u_{AN}$, $u_{BN}$ and $u_{AN}+u_{BN}$, (b) Amplifying waveform of the dotted box in Fig. 6(a), (c) $u_{CN}$, $i_{DN}$ and $u_{CN}+i_{DN}$, (d) Amplifying waveform of the dotted box in Fig. 6(c), (e) $u_g$ and $i_g$, (f) $u_{GN}$ and $i_{tcm}$. © IEICE 2018 DOI: 10.1587/elex.15.20180400 Received April 18, 2018 Accepted May 7, 2018 Publicized May 25, 2018 Copyedited June 25, 2018
$u_{GN}$ maintains at 180 V approximately. And the amplitude of the generated leakage current $i_{cm}$ is 50 mA approximately. Therefore, the experimental results verify the correctness of theoretical analysis of $u_{cm}$. And common-mode leakage current of the novel NDPGCI is eliminated in the line cycle, meeting the VDE-0126-1-1 standard.

On the prototype platform, the efficiency comparison test between NDPGCI and DFGI is made. The main parameters are shown in Table I. We would point out that in each working mode of the NDPGCI, the current doesn’t flow through body diodes. Therefore, the reverse recovery loss is low, which is favorable to further improve efficiency. On the same prototype platform and under the parameters of Table I, Fig. 7 shows the result of operation efficiency of NDPGCI and DFGI. It can be seen clearly that the efficiency of NDPGCI is about 2 percent higher than DFGI.

![Efficiency curves comparison between the NDPGCI and DFGI](image)

**Fig. 7.** Efficiency curves comparison between the NDPGCI and DFGI

## 5 Conclusion

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

1) Compared with DFGI, there is no need of the isolation transformer. Meanwhile, the freewheeling current doesn’t flow through the body diodes of the switches. Therefore, NDPGCI needn’t set the dead time, and it has higher reliability and power density.

2) The common-mode voltage $u_{cm}$ of Mode 1, Mode 2, Mode 3 and Mode 4 are all $u_{dc}/2$. The USPWM strategy proposed in the paper can keep the common-mode voltage constant in the line cycle. Therefore, the condition of eliminating common-mode leakage current is met completely.

3) From the efficiency curve comparison, it can be seen clearly that the overall efficiency of NDPGCI is two percent higher than DFGI.

## Acknowledgments

This work was supported by the application fundamental research fund of SiChuan Provincial Science and Technology Department (No. 2014JY0208).