Research on the Three-phase Cascaded Dual-buck Grid-connected Inverter

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Abstract. The inhibition of common-mode leakage current is the key problem to be solved in cascaded photovoltaic grid-connected inverter. To eliminate the common-mode leakage current of cascaded dual-buck grid-connected inverter, a three-phase cascade double-buck photovoltaic grid-connected inverter (TPCDBGCI) topology is proposed in this paper. Meanwhile, a new phase-shifting carrier SPWM (PSCSWPM) control strategy that can make the single phase common-mode voltage and three phase differential-mode voltage constant in the half cycle is presented. Then, the simplified model and operating modes of TPCDBGCI are analyzed, which show that common-mode leakage current of TPCDBGCI is effectively suppressed. Finally, the experimental results verified the correctness of TPCDBGCI.

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]. Compared with the isolated photovoltaic grid-connected inverter, non-isolated photovoltaic grid-connected inverter has the advantages of small size, light weight and low cost. However, due to the lack of transformer isolation in practical applications, high-frequency variation of common mode voltage will cause leakage current [2]. Leakage current will not only lead to the distortion of grid-connected current and cause electromagnetic interference problems, but also has some security risks [3]. The VDE-0126-1-1 standard requires that the GCI must be removed from the power grid when the leakage current is higher than 300mA [4]. An three-phase cascaded H4 PV grid-connected inverter in Fig.1 (a) is proposed in reference [5]. As is shown in Fig.1 (a), adopt the thought of inductance placed symmetrically. The single phase differential-mode voltage can be ignored. But it is still hard to keep three variables constant. Besides, it need to be set dead-time to avoid the shoot-through problem. Dual-buck full-bridge grid-connected inverter (DFGI) is shown in Fig.1 (b). The reference [6] has proven DFGI is extensively investigated due to its no shoot-through problem, high efficiency and reliability. However, the conventional DFGI don't separate the DC power from a grid during freewheeling time, which needs to employ either line-frequency or high-frequency isolation transformers. But line-frequency transformers are large and heavy, making the whole system bulky and hard to install.

To solve aforementioned problem, a three-phase cascade double-buck photovoltaic grid-connected inverter and a new phase-shifting carrier SPWM control strategy is put forward in this paper to solve the three phase photovoltaic grid-connected inverter common mode leakage current problem.
Figure 1. Topologies of conventional grid-connected inverter. (a) Three-phase cascaded H4 PV grid-connected inverter, (b) Dual-buck full-bridge grid-connected inverter.

2. Three-phase cascaded dual-buck grid-connected inverter

2.1. Topology

The topology of the three-phase cascaded dual-buck grid-connected inverter are shown in Fig. 1(a). Which is divided into phase a, phase b and phase c. S1–S15 are power switches of IGBT. D1–D12 are high-performance diodes. L1–L4 are filter inductances of phase a. L5–L8 are filter inductances of phase b. L9–L12 are filter inductances of phase c.
b. $L_{c1}-L_{c4}$ are filter inductances of phase c. Which is defined $i=a,b,c$. $L_2$ and $L_3$ can effectively prevent the phenomenon of through bridge arm. Therefore, a setting of dead-time is not necessary for power switches. $u_i$ is grid voltage $u(t)=U_m \times \sin(2\pi ft)$, where $U_m$ and $f$ are the amplitude and frequency of $u_i$, respectively. $U_{dc}$ is DC voltage of the photovoltaic cell. $C_i$ is filter capacitor. $C_{gi1}$ and $C_{gi2}$ is the parasitic capacitance of the DC photovoltaic panels. $i_a, i_b$ and $i_c$, are the three-phase grid-connected current.

Compared to non-cascaded three-phase cascaded H4 PV grid-connected inverter, an additional switch is added in series at the every phase positive terminal of DC voltage. Three-phase photovoltaic DC side and AC network are separated by these switches. In this way, the common-mode circuit can be prevented between the photovoltaic DC side, the AC power grid and the ground.

![Figure 2. Topology of the Proposed TPCDBGCI](image)

2.2. Modulation strategy

Compared with traditional non-cascaded photovoltaic grid-connected inverter, TPCDBGCI has more recirculation circuits. Meanwhile, to reduce switching loss and conduction loss and improve efficiency of the inverter to suppress common mode leakage current effectively. Therefore, a unipolar phase-shifting carrier sinusoidal pulse width modulation (PSCSPWM) strategy is proposed to solve above problems. Fig. 3 shows the ideal waveforms of the proposed TPCDBGCI with unipolar PSCSPWM. $V_{c1+}$, $V_{c2+}$, $V_{c3+}$, $V_{c1-}$, $V_{c2-}$ and $V_{c3-}$ are unipolar triangular carrier wave, which determines switching cycle $T_s$. $V_{c1+}$, $V_{c2+}$, $V_{c3+}$ are above the x-axis in the positive half cycle, whose phase difference is 120 degrees. $V_{c1-}$, $V_{c2-}$, $V_{c3-}$ are below the x-axis in the negative half cycle, whose phase difference is 120 degrees. $V_m$ is the modulation signal. $S_1$-$S_{15}$ are the driving signals of each power switch. Among them, the driving signals of $S_1$-$S_3$ is obtained by comparing $V_m$ with carrier wave $V_{c1+}$ and $V_{c1-}$. The driving signals of $S_4$-$S_{10}$ is obtained by comparing $V_m$ with carrier wave $V_{c2+}$ and $V_{c2-}$. The driving signals of $S_{11}$-$S_{15}$ is obtained by comparing $V_m$ with carrier wave $V_{c3+}$ and $V_{c3-}$.
2.3. Simplified model circuit equivalent

According to the reference [7] analyze the leakage current reduction of three-phase cascaded PV grid-connected inverter, the simplified model of TPCDBGCI can be established. From the Fig.1, $C_{gi}$ is defined as the parasitic capacitances between PV system and ground. When the voltage of $C_{gi}$ is high-frequency, which will generate large common mode leakage current. $U_{A_i-N_i}$ is the single phase voltage between A and N, $U_{B_i-N_i}$ is the single phase voltage between B and N. The common-mode voltage (CMV) and differential-mode voltage (DMV) can be defined as follow from the reference [5]. Which are represented as $U_{cmi}$ and $U_{DMI}$:

$$U_{cmi} = \left( U_{A_i-N_i} + U_{B_i-N_i} \right) / 2$$  \hspace{1cm} (1)

$$U_{DMI} = \left( U_{A_i-N_i} - U_{B_i-N_i} \right) / 2$$  \hspace{1cm} (2)

From the formula (1) and formula (2), the single phase midpoint voltage of bridge arm $U_{A_i-N_i}$ and $U_{B_i-N_i}$ are:

$$U_{A_i-N_i} = U_{cmi} + 0.5U_{DMI}$$  \hspace{1cm} (3)

$$U_{B_i-N_i} = U_{cmi} - 0.5U_{DMI}$$  \hspace{1cm} (4)

The low-frequency grid voltage has little effect on leakage current, so the effect of grid voltage is ignored. On this basis, the TPCDBGCI simplified model of mode 1 and mode 2 can be established in Fig.4. Meanwhile, the formula conditions are satisfied: $C_{gi} = C_{g1} + C_{g2}$.
Assuming the follow conditions: \( L_1 = L_a = L_b = L_c = L_m \), \( L_2 = L_3 = L_n \).

Considering the relationship of \( L_m >> L_n \) in the circuit design process. Where the equivalent resistance \( L_{ei} \) satisfies:

\[
L_{ea} = L_{aa} + L_{a3} \approx L_{aa} \tag{5}
\]
\[
L_{eb} = L_{bb} + L_{b3} \approx L_{bb} \tag{6}
\]
\[
L_{ec} = L_{c1} + L_{c2} \approx L_{c1} \tag{7}
\]

**Figure 4.** TPCDBGCI simplified model of mode 1 and mode 2

For the simplified model in figure 3, kirchhoff’s law can be applied to obtain:

\[
\frac{U_{AO} - 0.5U_{dma}}{Z_{La1}} + \frac{U_{AO} - U_{NO} + 0.5U_{dma}}{Z_{Lea}} + \frac{U_{AO} + U_{cma}}{Z_{ga}} = 0 \tag{8}
\]
\[
\frac{U_{BO} - 0.5U_{dmb}}{Z_{Lb1}} + \frac{U_{BO} - U_{NO} + 0.5U_{dmb}}{Z_{Leb}} + \frac{U_{BO} + U_{emb}}{Z_{gb}} = 0 \tag{9}
\]
\[
\frac{U_{CO} - 0.5U_{dmc}}{Z_{Lc1}} + \frac{U_{CO} - U_{NO} + 0.5U_{dmc}}{Z_{Leb}} + \frac{U_{CO} + U_{cmc}}{Z_{gc}} = 0 \tag{10}
\]
\[
\frac{U_{AN} + 0.5U_{dma}}{Z_{Lea}} + \frac{U_{BN} + 0.5U_{dmb}}{Z_{Leb}} + \frac{U_{CN} + 0.5U_{dmc}}{Z_{Lec}} = 0 \tag{11}
\]

\[
U_{AN} = U_{AO} - U_{NO}; \ U_{BN} = U_{BO} - U_{NO}; \ U_{CN} = U_{CO} - U_{NO} \tag{12}
\]
For the sake of analysis, assume that $C_{ga}=C_{gb}=C_{gc}=C_g$, $L_{a1}=L_{b1}=L_{oac}=L/2$, $L_{oa}=L_{eb}=L_{oe}=L/2$.

It can be easily seen that $Z_{ga}=Z_{gb}=Z_{gc}=Z_{g}=1/(2sC_g)$, $Z_{la1}=Z_{b1}=Z_{lc1}=Z_{l}/2=sL/2$, $Z_{Loa}=Z_{Leb}=Z_{Loe}=Z_{L}/2=sL/2$.

Known from formula (8) to (12), the single phase common-mode leakage current is:

$$I_{cmi} = -\frac{0.25 Z_l + Z_g}{0.5 Z_l U_{cm} + (3Z_l + 6Z_g)U_{cmi}}$$

(13)

Where $U_{cm}$ and $U_{dm}$ are satisfied:

$$U_{cm} = U_{cma} + U_{cmb} + U_{cmc}$$

(14)

$$U_{dm} = U_{dmd} + U_{dmb} + U_{dmc}$$

(15)

Known from formula (13)-(15), the common-mode leakage current of $i$ phase is depend on the three-phase common-mode voltage, the three-phase differential-mode voltage and the single phase common-mode voltage. So the common-mode leakage current of mode 1 and mode 2 can be suppressed validly as follow conditions: $U_{cm}=constant$, $U_{dm}=constant$.

In the same way, the simplified model of other modes can be established. According to the verification, which are satisfied the same conditions.

3. TPCDBGCI operation characteristics analysis

According to the topology and modulation strategy of TPCDBGCI, the proposed TPCDBGCI can be divided into 8 operating modes, which are shown in Fig. 5(a)-(h), respectively. The detailed working conditions of each mode as follows:

**Mode 1:** As shown in Fig. 5(a), the power switches $S_1$, $S_4$, $S_5$, $S_6$, $S_9$, $S_{10}$, $S_{12}$, $S_{13}$, $S_{14}$ turn on and others turn off. The phase a, phase b and phase care in a positive charging state. $U_{Ab-Na}=U_{Ab-Nb}=0$, $U_{Ba-Na}=U_{Bb-Nb}=U_{dc}$, $U_{Ac-Nc}=U_{dc}$, $U_{Bc-Nc}=0$. According to Eqs.(), CMV: $U_{cm}=U_{cma}=U_{cmb}=U_{cme}=U_{de}/2$. DMV: $U_{dmd}=U_{dmb}=U_{de}/2$, $U_{dmc}=U_{de}/2$.

**Mode 2:** As shown in Fig. 5(b), the power switches $S_1$, $S_4$, $S_5$, $S_6$, $S_{13}$ turn on and others turn off. The phase a is in a positive charging state. $U_{Ab-Na}=0$, $U_{Bb-Na}=U_{dc}$, $U_{Ab-Nb}=U_{Bb-Nb}=U_{Ac-Nc}=U_{Bc-Nc}=U_{de}/2$. According to Eqs.(), CMV: $U_{cm}=U_{cma}=U_{cmb}=U_{cme}=U_{de}/2$. DMV: $U_{dmd}=U_{de}/2$, $U_{dmc}=U_{de}=0$.

**Mode 3:** As shown in Fig. 5(c), the power switches $S_1$, $S_4$, $S_5$, $S_6$, $S_{10}$, $S_{11}$, $S_{14}$, $S_{15}$ turn on and others turn off. The phase a, phase b and phase care in a positive charging state. $U_{Ab-Na}=0$, $U_{Ab-Nb}=U_{dc}$, $U_{Bb-Na}=U_{dc}$, $U_{Bb-Nb}=0$, $U_{Ac-Nc}=0$, $U_{Bc-Nc}=U_{dc}$. According to Eqs.(), CMV: $U_{cm}=U_{cme}=U_{cme}=U_{de}/2$. DMV: $U_{dmd}=U_{de}/2$, $U_{dmc}=U_{de}/2$, $U_{dmc}=-U_{de}/2$.

**Mode 4:** As shown in Fig. 5(d), the power switches $S_4$, $S_6$, $S_{10}$, $S_{11}$, $S_{14}$, $S_{15}$ turn on and others turn off. The phase c is in a positive charging state. $U_{Ab-Na}=U_{de}/2$, $U_{Ab-Nb}=U_{de}/2$, $U_{Bb-Na}=U_{dc}$, $U_{Bb-Nb}=U_{dc}$, $U_{Ac-Nc}=0$, $U_{Bc-Nc}=U_{dc}$. According to Eqs.(), CMV: $U_{cm}=U_{cmb}=U_{cme}=U_{de}/2$. DMV: $U_{dmd}=0$, $U_{dmb}=0$, $U_{dmc}=-U_{de}/2$.

**Mode 5:** As shown in Fig. 5(e), the power switches $S_2$, $S_3$, $S_5$, $S_6$, $S_{10}$, $S_{11}$, $S_{14}$, $S_{15}$ turn on and others turn off. The phase a, phase b and phase care in a positive charging state. $U_{Ab-Na}=U_{de}$, $U_{Ab-Nb}=U_{dc}$, $U_{Bb-Na}=0$, $U_{Bb-Nb}=0$, $U_{Ac-Nc}=U_{dc}$, $U_{Bc-Nc}=U_{dc}$. According to Eqs.(), CMV: $U_{cm}=U_{cmb}=U_{cme}=U_{de}/2$. DMV: $U_{dmd}=0$, $U_{dmb}=0$, $U_{dmc}=U_{de}/2$.

**Mode 6:** As shown in Fig. 5(f), the power switches $S_1$, $S_4$, $S_{10}$, $S_{14}$ turn on and others turn off. The phase b is in a positive charging state. $U_{Ab-Na}=U_{de}/2$, $U_{Ab-Nb}=U_{dc}$, $U_{Bb-Na}=U_{de}/2$, $U_{Bb-Nb}=0$, $U_{Ac-Nc}=U_{dc}$, $U_{Bc-Nc}=U_{dc}$. According to Eqs.(), CMV: $U_{cm}=U_{cmb}=U_{cme}=U_{de}/2$. DMV: $U_{dmd}=0$, $U_{dmb}=U_{de}/2$, $U_{dmc}=0$.

**Mode 7:** As shown in Fig. 5(g), the power switches $S_2$, $S_3$, $S_5$, $S_6$, $S_{10}$, $S_{12}$, $S_{13}$, $S_{15}$ turn on and others turn off. The phase a, phase b and phase care in a positive charging state. $U_{Ab-Na}=U_{dc}$, $U_{Ab-Nb}=0$, $U_{Bb-Na}=U_{dc}$, $U_{Bb-Nb}=0$, $U_{Ac-Nc}=U_{dc}$, $U_{Bc-Nc}=U_{dc}$.
According to Eqs.(), CMV: \( U_{cma} = U_{cmb} = U_{cmc} = U_{dc}/2 \). DMV: \( U_{dma} = U_{dc}/2, U_{dmb} = -U_{dc}/2, U_{cmc} = 0 \).

**Mode 8**: As shown in Fig. 5 (h), the power switches \( S_3, S_9, S_{13} \) turn on and others turn off. No phase is in a positive charging state. \( U_{Aa-Na} = U_{dc}, U_{Ab-Nb} = U_{dc}/2, U_{Ba-Na} = 0, U_{Bb-Nb} = U_{dc}/2, U_{Ac-Nc} = U_{dc}/2, U_{Bc-Nc} = U_{dc}/2 \). According to Eqs.(), CMV: \( U_{cma} = U_{cmb} = U_{cmc} = U_{dc}/2 \). DMV: \( U_{dma} = U_{dc}/2, U_{dmb} = U_{cmc} = 0 \).
(c) Mode 3

(d) Mode 4
(e) Mode 5

(f) Mode 6
Figure 5. Operating circuit of each Mode and its equivalent circuit.
(a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4, (e) Mode 5, (f) Mode 6, (g) Mode 7, (h) Mode 8.
From the above analysis, it’s easy to see that at the whole cycle, $U_{cmi}$ remains a constant $U_{dc}/2$, $U_{dm}$ remains a constant $-U_{dc}/2$ in the positive half cycle and remains a constant $U_{dc}/2$ in the negative half cycle. According to the equations (13), the condition of eliminating common-mode leakage current is satisfied. 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 Tab. 1.

The waveform of parasitic capacitor voltage is shown in Fig. 6(a), which indicates that leakage current of the system decreases obviously because it only contains low-frequency components, not high-frequency components. The leakage current is shown in Fig. 6(a). The maximum of leakage current equal to 60mA approximately, which proofs common-mode leakage current of the TPCDBGCI is eliminated in the line cycle, meeting the VDE-0126-1-1 standard. The waveforms of $u_g$ and $i_g$ of TPCDBGCI are shown in Fig. 6(b) and (c), respectively. $i_g$ is highly sinusoidal synchronized with $u_g$, and power factor is close to 1. The output line voltage is shown in Fig. 6(d). It is observed that the proposed TPCDBGCI outputs at five levels, which are 240V, 120V, 0V, -120V, -240V. The three-phase voltage waveforms of TPCDBGCI’s bridge arms phase a of $u_{Aa-Na}$, $u_{Ba-Na}$, $u_{Aa-Na} + u_{Ba-Na}$, phase b of $u_{Ab-Nb}$, $u_{Bb-Nb}$, $u_{Ab-Nb} + u_{Bb-Nb}$, phase c of $u_{Ac-Nc}$, $u_{Bc-Nc}$, $u_{Ac-Nc} + u_{Bc-Nc}$, and their amplifying waveforms of the dotted box in a voltage cycle are shown in Fig. 6(e) to (f), respectively. From Fig. 6(e) to (f), the single-phase voltage of bridge arms $u_{A1-N1}$, $u_{B1-N1}$ change according to a certain rule. Meanwhile, within a switching cycle, $u_{A1-N1}$ and $u_{B1-N1}$ complement each other and $u_{A1-N1} + u_{B1-N1}$ is a constant 120V approximately. Which verify the correctness of theoretical analysis. The sum of three-phase difference-mode voltage and its amplifying waveforms of the dotted box are shown in Fig. 6(i) and Fig. 6(j), respectively. From Fig. 6(i) and Fig. 6(j), $U_{dm}$ alternates between -120V and 120V in the entire power frequency cycle.

Combined the experimental results of $U_{cmi}$ with the waveforms of $U_{dm}$, the single phase common-mode leakage current $I_{cmi}$ is variation in the positive half voltage cycle to the negative half voltage cycle.

| Table 1. Circuit parameters. |
|-----------------------------|
| parameters | value | parameters | value |
| $U_{dc}$/V | 120 | $U_m$/V | 220 |
| $Z_l$/Ω | 1.2 | $T_s$/μs | 20 |
| $f$/Hz | 50 | $L_Ω=L_{ij}$/μH | 0.6 |
| $L_{m}=L_{bb}=L_{cc}$/μH | 450 | $L_{i1}$/μH | 250 |

![Waveform of parasitic capacitor voltage](a)
Figure 6. Experimental results of the proposed TPCDBGCI. (a) Parasitic capacitor voltage and the leakage current of TPCDBGCI, (b) $i_g$, (c) $u_g$, (d) Output line voltage, (e) $u_{Aa-Na}$ and $u_{Ba-Nb}$, (f) $u_{Ab-Nb}$ and $u_{Bb-Nb}$, (g) $u_{Ac-Nc}$, $u_{Bc-Nc}$ and $u_{Ac-Nc + u_{Bc-Nc}}$, (h) Amplifying waveform of the dotted box in Fig.6(f), (i) The three-phase differential mode current, (j) Amplifying waveform of the dotted box in Fig.6(i).

5. Conclusion

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

1) Compared with three-phase cascaded H5 topology, due to the structure of dual-buck type, the freewheeling current doesn’t flow through the body diodes of the switches. Therefore, TPCDBGCI needn’t set the dead time, and it has higher reliability and power density.

2) The common-mode voltage $u_{cm}$ are all $U_{dc}/2$ in the entire power frequency cycle. Meanwhile, the differential-mode voltage are always -$U_{dc}/2$ in the positive half voltage cycle and change into $U_{dc}/2$ in the negative half voltage cycle. A new strategy PSCSWPM is suited to the proposed TPCDBGCI,
which can keep the each phase common-mode voltage and the sum of three-phase difference-mode voltage satisfying the constraint condition in the line cycle. Therefore, the condition of eliminating common-mode leakage current is met completely.

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References
[1] Lin Mao, Li Ying-hui, Wu Chen, “Improved predictive current control of NPC multilevel inverters,” IEICE Electronics Express, vol. 13, no. 23, pp. 1349 - 2543, Sep. 2016.
[2] Li Wuhua Li, Gu Yunjie, Luo Haoze, et al.“Topology review and derivation methodology of single-phase transformerless photovoltaic inverters for leakage current suppression [J],” IEEE Transactions on Industrial Electronics., vol. 62, no. 7, pp. 4537 - 4551, 2015.
[3] Gu Y J, Li W H, Zhao Y, et al.“Transformerless inverter with virtual DC bus concept for cost-effective grid-connected PV power systems [J],” IEEE Transactions on Power Electronics., vol. 28, no. 2, pp. 793-805, 2013.
[4] VDE-0126-1-1-2006: ‘Automatic disconnection device between a generator and the public low-voltage grid’, DIN_VDE Normo, 2008.
[5] WU Ting, XIAO Lan, YAO Zhi-lei. ‘Dual Buck Full-bridge Inverter’, Proceedings of the CSEE, 2009, vol. 25, no. 5, pp. 22 – 27.
[6] A. A. Khan, H. Cha, and H. F. Ahmed, “A Highly Reliable and High-Efficiency Quasi Single-Stage Buck–Boost Inverter,” IEEE Trans. Power Electron., vol.3, no.26, pp. 4185 - 4198, Jun. 2017.
[7] Xiaojiang Guo, Xiaoyu Jia. “Analysis of Common Mode Leakage Current for Transformerless Cascaded H5 PV Inverter,” TRANSACTIONS OF CHINA EFFCTROTECHNICAL SOCIETY. vol. 33, no.2, pp. 361-369, Jan. 2018.