Research Article

An Enhanced Half-Quasi-Z-Source Inverter for Wind Energy Conversion System with D-PMSG

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To solve the problem of the traditional quasi-Z-source inverters with low voltage gain, an enhanced half-quasi-Z-source inverter (E-HQZSI) is proposed and applied to direct-drive permanent-magnet wind power generation systems in this paper. The expression of the boosting factor is deduced, which shows that E-HQZSI has higher voltage gain compared with the QZSI and HQZSI. However, the higher voltage gain of the E-HQZSI will lead to the large distortion of the generator stator current necessarily. In this paper, a periodic shoot-through duty ratio control scheme is proposed to reduce the stator current harmonics for E-HQZSI. According to the change rule of the single-phase stator current, the shoot-through duty ratio is compromised to make that the three-phase stator currents are as close as possible to the sine wave. Finally, the correctness of the theoretical analysis is verified by simulation and experiment.

1. Introduction

In recent years, wind power generation has developed rapidly due to the advantages of green, clean, and pollution-free [1–5]. According to the statistics of the Global Wind Energy Council [6], by the end of 2017, the cumulative installed capacity of wind power generation has reached 539.58 GW around the world, and the added installed capacity has reached 52.57 GW.

At present, domestic wind power generation system (WPGS) is mainly developing towards large-scale, while the small- and medium-sized WPGS have been highly regarded in European and American countries at the same time [7, 8]. In the United States and Germany, the added installed capacity of small- and medium-sized WPGS in 2017 increased by 25% and 33%, respectively, compared with the previous year. Compared with MW-class WPGS, small- and medium-sized WPGS have the following advantages:

(1) Three-phase diode rectifier is utilized in small- and medium-sized WPGS generally, and the cost of converter is lower
(2) The cutting in and out of a single small- and medium-sized wind turbine has less impact on the large power grid
(3) The adjustment of small- and medium-sized WPGS is more flexible, which is helpful for peak load shifting of the power grid

The types of generators used in WPGS mainly include doubly fed induction generator (DFIG) and permanent-magnet synchronous generator (PMSG) [9–12]. Compared with the DFIG, the PMSG has the advantages of light weight, small volume, high power factor, and good reliability and thus has become the mainstream choice of current WPGS gradually.

The topology with three-phase diode rectifier, boost converter, and three-phase six-switch PWM inverter is often
used in the small- and medium-sized WPGS with PMSG. This topology has the advantages of simple structure and controllable generator speed, but the topology needs to be controlled by two stages, and the control is complicated [13–16].

With the continuous development of power electronics topology, a power conversion topology with the three-phase diode rectifier and three-phase impedance source inverter (ISI) has emerged. This topology has the advantages of single-stage control and no need to insert dead time, which reduces the complexity of the control system and further improves the reliability of the inverter. In addition, the shoot-through state of the three-phase impedance source inverter can derive a degree of freedom, thereby realizing the controllable generator speed. However, the three-phase diode rectifier is still utilized between PMSG and ISI; it is bound to produce a large stator current harmonics of the generator [17–21].

To solve the problems shown above, a half- quasi-Z-source inverter (HQZSI) is proposed in [22] and applied to the WPGS with PMSG. When the inverter is in the shoot-through state, the rate of change of the generator stator current is only related to the stator voltage of the generator, which provides a possibility for the output power factor correction of the PMSG. However, HQZSI has lower boosting capability, which is due to the high switching voltage stress. It will increase the probability of device damage.

In this paper, an enhanced half- quasi-Z-source inverter (E-HQZSI) is proposed for direct-drive permanent-magnet wind power systems in Section 2, which have higher voltage gain compared with the QZSI and HQZSI. Then, the input current change rate of the E-HQZS wind power conversion system (WPCS) is deduced in Section 3. In addition, the input power factor is analyzed in Section 4. Furthermore, a periodic shoot-through duty ratio control scheme is proposed to reduce the stator current harmonics of the generator in Section 5. Finally, experimental verification is presented in Section 6.

2. Proposed E-HQZSI

The topology of E-HQZSI is shown in Figure 1, which includes DC power supply, impedance source network, and three-phase inverter bridge. The impedance source network is composed of four diodes, two capacitors, and three inductors.

To simplify the analysis, it is assumed that all switching devices, capacitors, and inductors are ideal components. And, inductors \( L_1 \), \( L_2 \), and \( L_3 \) have an inductance of \( L \). When the E-HQZSI is in the shoot-through state, the three-phase inverter bridge can be equivalent to the short circuit; the diodes \( D_1 \) and \( D_3 \) are turned off, and diodes \( D_2 \) and \( D_4 \) are turned on, as shown in Figure 2. In the shoot-through state, the inductor \( L_1 \) is charged by DC power supply through the diodes \( D_2 \) and \( D_4 \) and the shoot-through loop; the inductor \( L_2 \) is charged by the capacitor \( C_1 \) through the diode \( D_4 \) and the shoot-through loop, and the inductor \( L_3 \) is charged by the capacitor \( C_2 \) through the shoot-through loop.

From Figure 2, the following equations are obtained:

\[
\begin{align*}
-V_{DC} + L \frac{di_{L1}}{dt} &= 0, \\
-V_{DC} + L \frac{di_{L2}}{dt} &= 0, \\
-V_{DC} + L \frac{di_{L3}}{dt} &= 0,
\end{align*}
\]

where \( V_{DC} \) is the voltage of the DC power supply and \( i_{L1} \), \( i_{L2} \), and \( i_{L3} \) are the currents of the impedance source inductors \( L_1 \), \( L_2 \), and \( L_3 \), respectively.

When the E-HQZSI is in the nonshoot-through state, the three-phase inverter bridge can be equivalent to a current source; the diodes \( D_1 \) and \( D_3 \) are turned off, and diodes \( D_2 \) and \( D_4 \) are turned on, as shown in Figure 3. In the nonshoot-through state, the inductor \( L_1 \), \( L_2 \), and \( L_3 \) and the DC power supply are discharged for the load and the capacitors \( C_1 \) and \( C_2 \).

From Figure 3, the following equations are obtained:

\[
\begin{align*}
-V_{DC} + L \frac{di_{L1}}{dt} + V_{C1} &= 0, \\
-V_{C1} + L \frac{di_{L2}}{dt} + V_{C2} &= 0, \\
-V_{C2} + L \frac{di_{L3}}{dt} + v_i &= 0,
\end{align*}
\]

where \( V_{C1} \) and \( V_{C2} \) are the voltages of the impedance source capacitors \( C_1 \) and \( C_2 \), respectively, and \( v_i \) is the output voltage of the impedance source network.

It is noticed that the average voltage of the inductors \( L_1 \), \( L_2 \), and \( L_3 \) is zero in one switching cycle. According to equations (1) and (2), it can be obtained as

\[
\begin{align*}
\frac{T_0}{T} V_{DC} + \frac{T_1}{T} (V_{DC} - V_{C1}) &= 0, \\
\frac{T_0}{T} V_{C1} + \frac{T_1}{T} (V_{C1} - V_{C2}) &= 0, \\
\frac{T_0}{T} V_{C2} + \frac{T_1}{T} (V_{C2} - v_i) &= 0,
\end{align*}
\]

where \( T_0 \) and \( T_1 \) are the switching periods.
where $T_0$ and $T_1$ are the times of the shoot-through state and nonshoot-through state in one switching cycle.

It can be derived from equation (3) that

\[
\begin{align*}
V_{C1} &= \frac{1}{1 - d_0} V_{DC}, \\
V_{C2} &= \frac{1}{1 - d_0} V_{C1} = \frac{1}{(1 - d_0)^2} V_{DC}, \\
v_i &= \frac{1}{1 - d_0} V_{C2} = \frac{1}{(1 - d_0)^3} V_{DC},
\end{align*}
\]

where $d_0$ is the shoot-through duty ratio of the E-HQZSI.

Thus, the average output voltage of the impedance source network can be expressed as follows:

\[
V_{\text{avg}} = \frac{(0T_0 + v_iT_1)}{T} = \frac{1}{(1 - d_0)^3} V_{DC} = V_{C2}. 
\]

It can be seen from [17] that the relationship between the boost factor and the shoot-through duty ratio of the quasi-Z-source inverter (QZSI) can be expressed as

\[
B_0 = \frac{1}{1 - 2d_0},
\]

where $B_0$ is the boost factor of the impedance source inverter.

It can be obtained from [22] that the relationship between the boost factor and the shoot-through duty ratio of the half-quasi-Z-source inverter (HQZSI) can be expressed as

\[
B_0 = \frac{1}{(1 - d_0)^3}. 
\]

According to equation (4), the relationship between the boost factor and the shoot-through duty ratio of the E-HQZSI can be written as

\[
B_0 = \frac{1}{(1 - d_0)^3}. 
\]

The voltage gain of E-HQZSI can be expressed as

\[
G = \frac{M}{(1 - d_0)^3},
\]

where $M$ is the modulation index of the E-HQZSI.

The comparison of boost factor $B_0$ between the QZSI and the HQZSI is shown in Figure 4. It can be seen that the QZSI has the greater boost capacity compared to the HQZSI.

The comparison of boost factor $B_0$ between the QZSI and the E-HQZSI is shown in Figure 5. It can be obtained that the E-HQZSI has the greater boost capacity compared to the QZSI.

It can be seen from Figures 6–8 that, under the same voltage gain, the HQZSI requires the largest shoot-through duty ratio, the QZSI is the second, and the E-HQZSI requires the smallest shoot-through duty ratio. In addition, the maximum modulation degree can be achieved under the same boosting factor; the E-HQZSI is the largest, the QZSI is the second, and the HQZSI is the smallest.

However, under the same system parameters, the input current waveform sinusoid of the rectifier is inversely proportional to the boost factor of the impedance source inverter, when the input voltage of the impedance source inverter is provided by a three-phase diode rectifier. So the input current harmonic of the E-HQZSI is larger compared to the HQZSI.

### 3. Input Current Change Rate of E-HQZS WPCS

Because E-HQZSI has higher voltage gain, it is suitable for the wind power conversion system. The input current change rate of the E-HQZS WPCS will be analyzed in this section.

The voltage waveform of the three-phase AC power supply is shown in Figure 9. According to its polarity, the half AC period of the three-phase power supply can be divided into six sectors. The following research of E-HQZSI is analyzed in the case of the sector II. Since the AC period of the three-phase power supply is much longer than the switching cycle, the voltage of three-phase AC power supply can be approximated as a constant value in one switching cycle. When the E-HQZSI is in the shoot-through state, the equivalent function $V_Z = 1$; when the E-HQZSI is in the nonshoot-through state, the equivalent function $V_Z = 0$.

Figure 10 is the waveform of three-phase input current during one switching cycle in sector III.
A switching cycle is divided into three operation modes during sector III, as shown in Figures 9 and 10. E-HQZSI operates in the Mode 1 from $t_0$ to $t_1$. In this case, the diodes $D_2$, $D_4$, $D_6$, and $D_{10}$ are in the ON state, while the diodes $D_1$, $D_3$, $D_5$, $D_7$, and $D_9$ are in the OFF state. Inductor $L_1$ is charged by three-phase AC power supply, and inductor $L_2$ is charged by capacitor $C_1$. At the same time, the inductor $L_3$ is charged by capacitor $C_2$.

From Figure 11(a), it can be obtained that
It can be seen from equation (13) that the derivative of $i_{sa}$, $i_{sb}$, and $i_{sc}$ is only related to the three-phase stator emf of PMSG in Mode 1.

E-HQZSI operates in the Mode 2 from $t_1$ to $t_2$. In this case, the diodes $D_1$, $D_3$, $D_6$, $D_8$, and $D_9$ are in the ON state, while the diodes $D_2$, $D_4$, $D_5$, $D_7$, and $D_9$ are in the OFF state. The load and capacitors $C_1$ and $C_2$ are charged by three-phase AC power supply and inductors $L_1$, $L_2$, and $L_3$.

From Figure 11(b), it can be obtained that

\[
\begin{align*}
\frac{d}{dt} e_{sa} - L \frac{d}{dt} i_{sa} & = v_{NO}, \\
\frac{d}{dt} e_{sb} - L \frac{d}{dt} i_{sb} - L_i \frac{d}{dt} i_{sb} & = v_{NO}, \\
\frac{d}{dt} e_{sc} - L \frac{d}{dt} i_{sc} & = v_{NO},
\end{align*}
\] (10)

The three equations in equation (14) can be added to obtain that

\[
v_{NO} = \frac{1}{3} \left( e_{sa} + e_{sb} + e_{sc} \right) - \frac{L}{3} \left( \frac{d}{dt} i_{sa} + \frac{d}{dt} i_{sb} + \frac{d}{dt} i_{sc} \right) - \frac{L_i}{3} \frac{d}{dt} i_{sb}.
\] (11)

Equation (12) can be obtained because of Kirchhoff’s law and symmetry of $e_{sa}$, $e_{sb}$, and $e_{sc}$:

\[
v_{NO} = -\frac{L_i}{3} \frac{d}{dt} i_{sb},
\] (12)

Bringing equation (12) into equation (10), the change rate of $i_{sa}$, $i_{sb}$, and $i_{sc}$ can be expressed as

\[
\begin{align*}
\frac{d}{dt} i_{sa} & = \frac{L_1 e_{sb}}{3L^2 + 2LL_1} + \frac{e_{sa}}{L}, \\
\frac{d}{dt} i_{sb} & = \frac{3e_{sb}}{3L + 2L_1}, \\
\frac{d}{dt} i_{sc} & = \frac{e_{sb}}{3L^2 + 2LL_1} + \frac{e_{sc}}{L}.
\end{align*}
\] (13)

It can be seen from equation (17) that the derivative of $i_{sa}$, $i_{sb}$, and $i_{sc}$ is related to the three-phase stator emf of PMSG and the voltage of capacitor $C_1$ in Mode 2.

E-HQZSI operates in the Mode 3 from $t_2$ to $t_3$. In this case, the diodes $D_1$, $D_3$, $D_6$, and $D_9$ are in the ON state, while the diodes $D_2$, $D_4$, $D_5$, $D_7$, and $D_8$ are in the OFF state.

From Figure 11(c), it can be obtained that

\[
\begin{align*}
\frac{d}{dt} e_{sa} - L \frac{d}{dt} i_{sa} & = v_{NO}, \\
\frac{d}{dt} e_{sb} - L \frac{d}{dt} i_{sb} - L_1 \frac{d}{dt} i_{sb} - V_{C1} & = v_{NO}, \\
\frac{d}{dt} e_{sc} - L \frac{d}{dt} i_{sc} & = v_{NO}.
\end{align*}
\] (14)

Equation (16) can be obtained because of Kirchhoff’s law and symmetry of $e_{sa}$, $e_{sb}$, and $e_{sc}$:

\[
v_{NO} = -\frac{L_1}{3} \frac{d}{dt} i_{sb} - \frac{V_{C1}}{3}.
\] (16)

Bringing equation (16) into (14), the change rate of $i_{sa}$, $i_{sb}$, and $i_{sc}$ can be expressed as

\[
\begin{align*}
\frac{d}{dt} i_{sa} & = \frac{3L e_{sa} + 2L_1 e_{sa} + L_1 e_{sb} + LV_{C1}}{3L^2 + 2LL_1}, \\
\frac{d}{dt} i_{sb} & = \frac{3e_{sb} - 2V_{C1}}{3L + 2L_1}, \\
\frac{d}{dt} i_{sc} & = \frac{3L e_{sc} + 2L_1 e_{sc} + L_1 e_{sb} + LV_{C1}}{3L^2 + 2LL_1}.
\end{align*}
\] (17)

It can be seen from equation (17) that the derivative of $i_{sa}$, $i_{sb}$, and $i_{sc}$ is related to the three-phase stator emf of PMSG and the voltage of capacitor $C_1$. The load and capacitors $C_1$ and $C_2$ are charged by three-phase AC power supply and inductors $L_1$, $L_2$, and $L_3$.
\[
\begin{align*}
\begin{cases}
i_{sa} = 0, \\
e_{sb} - e_{sc} - L_s (\frac{di_{sb}}{dt} - \frac{di_{sc}}{dt}) - L_1 \frac{di_{sb}}{dt} - V_{C1} = 0, \\
i_{sc} = -i_{sb}. 
\end{cases}
\end{align*}
\]

The change rate of \(i_{sa}, i_{sb},\) and \(i_{sc}\) can be expressed as
\[
\begin{align*}
\frac{di_{sa}}{dt} = 0, \\
\frac{di_{sb}}{dt} = \frac{e_{sb} - e_{sc} - V_{C1}}{2L + L_1}, \\
\frac{di_{sc}}{dt} = \frac{e_{sb} - e_{sc} - V_{C1}}{2L + L_1}.
\end{align*}
\]

It can be seen from equation (19) that the derivative of \(i_{sa}, i_{sb},\) and \(i_{sc}\) is related to the three-phase stator electromotive force of PMSG and the voltage of capacitor \(C_1\) in Mode 3.

### 4. Analysis of Input Power Factor

Considering that the phase current of the three-phase AC power supply is 1/4 cycle symmetry, the average expression of the current of phase \(b\) in the interval \([0, \pi/2]\) is derived. The \(b\)-phase current of the three-phase AC power supply in the interval \([\pi/3, \pi/2]\) can be expressed as
\[
\begin{align*}
i_{sbav} = \frac{1}{T} \left( \int_{t_0}^{t_1} i_{sb}(\xi)d\xi + \int_{t_1}^{t_2} i_{sb}(\xi)d\xi + \int_{t_2}^{t_3} i_{sb}(\xi)d\xi \right).
\end{align*}
\]

From equation (13), it can be seen that
\[
\begin{align*}
\int_{t_0}^{t_1} i_{sb}(\xi)d\xi = \int_{t_1}^{t_2} \frac{3e_{sb}}{3L + 2L_1} d\xi.
\end{align*}
\]

Since the switching period is much smaller than the period of AC power supply, it can be considered that \(e_{sa}, e_{sb},\) and \(e_{sc}\) are constant from \(t_0\) to \(t_1;\) then, equation (21) can be expressed as
\[
\begin{align*}
\int_{t_0}^{t_1} i_{sb}(\xi)d\xi = \frac{3e_{sb}}{3L + 2L_1} d_{sb} T.
\end{align*}
\]

From equation (17), it can be seen that
\[
\begin{align*}
\int_{t_1}^{t_2} i_{sb}(\xi)d\xi = \int_{t_1}^{t_2} \frac{3e_{sb} - 2V_{C1}}{3L + 2L_1} d\xi = \frac{3e_{sb} - 2V_{C1}}{3L + 2L_1} (t_2 - t_1).
\end{align*}
\]

It can be seen from Figure 10 that \(t_2 - t_1\) is the time for the \(a\)-phase current to drop from \(t_1\) to \(t_2,\) so \(t_2 - t_1\) can be expressed as
\[
\begin{align*}
t_2 - t_1 = \frac{L_1 e_{sb} + 3e_{sa} L + 2e_{sc} L_1}{3L e_{sa} + 2e_{sa} L_1 + L_1 e_{sb} + LV_{C1}} d_{sb} T.
\end{align*}
\]

Bringing equation (24) into equation (23), it can be obtained that
\[
\begin{align*}
\int_{t_1}^{t_2} i_{sb}(\xi)d\xi = \frac{(3e_{sb} - 2V_{C1}) (L_1 e_{sb} + 3e_{sa} L + 2e_{sc} L_1)}{(3L + 2L_1) (3L e_{sa} + 2e_{sa} L_1 + L_1 e_{sb} + LV_{C1})} d_{sb} T.
\end{align*}
\]

From equation (19), it can be seen that
\[
\begin{align*}
\int_{t_1}^{t_2} i_{sb}(\xi)d\xi = \int_{t_1}^{t_2} \frac{e_{sb} - e_{sc} - V_{C1}}{2L + L_1} d\xi = \frac{e_{sb} - e_{sc} - V_{C1}}{2L + L_1} (t_3 - t_2).
\end{align*}
\]
It can be seen from Figure 10 that $t_3 - t_2$ can be expressed as

$$t_3 - t_2 = T - (t_1 - t_0) - (t_2 - t_1)$$

Bringing equation (27) into equation (26), it can be obtained that

$$= T - d_0 T - \frac{L_1 e_{ib} + 3e_{sa} L + 2e_{sa}L_1}{3L e_{sa} + 2e_{sa} L_1 + L_1 e_{ib} + LV_{C1}} d_0 T$$

$$= \left(1 - \frac{6Le_{sa} + 4e_{sa} L_1 + 2L_1 e_{ib} + LV_{C1}}{3Le_{sa} + 2e_{sa} L_1 + L_1 e_{ib} + LV_{C1}} d_0 \right) T.$$  

(27)

$$\int_{t_1}^{t_2} i_{sb}(\xi)d\xi = \frac{e_{sb} - e_{sc} - V_{C1}}{2L + L_1} - \frac{(e_{sb} - e_{sc} - V_{C1})(6Le_{sb} + 4e_{sa} L_1 + 2L_1 e_{ib} + LV_{C1})}{(2L + L_1)(3Le_{sa} + 2e_{sa} L_1 + L_1 e_{ib} + LV_{C1})} d_0 T.$$

(28)

Bringing equations (22), (25), and (28) into equation (20), the $b$-phase current of the three-phase AC power supply in the interval $[\pi/3, \pi/2]$ can be expressed as

$$i_{sbav} = \frac{3e_{sb}d_0 + 3L + 2L_1}{3L + 2L_1}$$

$$+ \frac{(3e_{sb} - 2V_{C1})(L_1 e_{sb} + 3e_{sa} L + 2e_{sa}L_1)}{(3L + 2L_1)(3Le_{sa} + 2e_{sa} L_1 + L_1 e_{ib} + LV_{C1})} d_0$$

$$- \frac{6Le_{sa} + 4e_{sa} L_1 + 2L_1 e_{ib} + LV_{C1}}{3Le_{sa} + 2e_{sa} L_1 + L_1 e_{ib} + LV_{C1}} d_0.$$  

(29)

In a similar way, the $b$-phase current of the three-phase AC power supply in the interval $[0, \pi/6]$ can be expressed as

$$i_{sbav} = \frac{e_{sb}(6L + L_1) - e_{sb}(3L + L_1)}{3L^2 + 2LL_1}$$

$$+ \frac{[e_{sb}(3L + L_1) - L_1 e_{sa} - LV_{C1}][e_{sb}(6L + L_1) - e_{sb}(3L + L_1)]}{[3L^2 + 2LL_1][e_{sb}(3L + L_1) - L_1 e_{sa} - LV_{C1}]} d_0.$$  

(30)

The $b$-phase current of the three-phase AC power supply in the interval $[\pi/6, \pi/3]$ can be expressed as

$$i_{sbav} = \frac{e_{sb}(6L + L_1) - e_{sa}(3L + L_1)}{3L^2 + 2LL_1}$$

$$+ \frac{[e_{sa}(3L + L_1) - L_1 e_{sa} - LV_{C1}][e_{sb}(6L + L_1) + e_{sc}L_1]}{[e_{sb}(3L + L_1) - e_{sc}L_1 - LV_{C1}][3L^2 + 2LL_1]} d_0.$$  

(31)

From equations (29)–(31), the $b$-phase current of the three-phase AC power supply in the interval $[0, \pi/2]$ can be expressed as

$$i_{sbav} = k_1 d_0^2 + k_2,$$

where $k_1$ and $k_2$ can be calculated as
obtained as power factor correction with the constant shoot-through duty state, the converter system cannot realize input is equivalent to only one additional degree of freedom in the Sincethe impedancesourceinverterincludingtheE-HQZSI

Periodic Shoot-Through Duty Ratio

where

\[ k_1 = \begin{cases} 0, & \left[ 0, \frac{\pi}{6} \right], \\ \left[ \frac{\pi}{6}, \frac{\pi}{3} \right], \\ 1, & \left[ \frac{\pi}{3}, \frac{\pi}{2} \right]. \end{cases} \] (33)

So the input power factor of E-HQZS WPCS can be obtained as

\[ \text{PF}_{\text{DHQSZS}} = \frac{P_{\text{shav}}}{E_S I_{\text{sharms}} = \frac{(4/T) \int_0^{T/4} e_{\text{sh}} i_{\text{shav}} \, dt}{E_S \sqrt{\int_0^{T/4} (i_{\text{shav}})^2 \, dt}}} = \frac{(2/\sqrt{\pi}) \int_0^{\pi/2} \cos(\omega t - (2\pi/3))(k_1 d_0 + k_2) dt}{\sqrt{\int_0^{\pi/2} (k_1 d_0 + k_2)^2 \, dt}}, \] (34)

where \( P_{\text{shav}} \) is the average input power of phase \( b \), \( I_{\text{sharms}} \) is the root mean square (RMS) of \( b \)-phase input current, and \( E_S \) is the RMS of \( e_{\text{sh}} \).

5. Periodic Shoot-Through Duty Ratio Control Method

Since the impedance source inverter including the E-HQZSI is equivalent to only one additional degree of freedom in the shoot-through state, the converter system cannot realize input power factor correction with the constant shoot-through duty ratio. Consider \( d_0 \) in equation (35) as the periodic shoot-through duty ratio as follows:

\[ d_{\text{sh}} = D_0 \cos(\omega t - (2\pi/3)) \frac{k_1}{k_2}, \] (35)

where \( D_0 \) is a constant.

Bringing equation (35) into equation (32), the \( b \)-phase current of the three-phase AC power supply can be expressed as

\[ i_{\text{shav}} = D_0 \cos(\omega t - (2\pi/3)) + k_2. \] (36)

It can be seen from equation (36) that the \( b \)-phase current is closer to the ideal sine wave when the shoot-through duty ratio of E-HQZSI is changed in accordance with equation (35).

In a similar way, the equivalent periodic shoot-through duty ratio of \( a \)-phase current can be expressed as

\[ d_{a\text{sh}} = D_0 \cos \omega t \frac{k_3}{k_3}, \] (37)

where \( k_3 \) can be calculated as
The equivalent periodic shoot-through duty ratio of a phase current can be expressed as
\[
d_{dc} = D_0 \frac{\cos(\omega t + (2\pi/3))}{k_4},
\]
where \(k_4\) can be calculated as
\[
k_4 = \frac{e_{sa}(3L - L_1) + e_{sb}L_1}{3L^2 + 2LL_1} - \frac{e_{sa} - e_{sc} - V_{C1}}{2L + L_1} \left[ \frac{e_{sc}(6L + L_1) - L_1e_{sc} - LV_{C1}}{3Le_{sa} + 2e_{sa}L_1 + L_1e_{sb} + LV_{C1}} \right]
\]
\[
+ \left. \frac{\bigg[ e_{sa}(3L + L_1) - e_{sb}L_1 - LV_{C1} \bigg] \bigg[ e_{sa}(6L + L_1) - e_{sb}(3L + L_1) \bigg]}{3L^2 + 2LL_1} \right|_{0, \frac{\pi}{6}}.
\]

The equivalent periodic shoot-through duty ratio curve, which can be obtained according to equations (35), (37), and (39). Due to the lack of degrees of freedom, a constant shoot-through duty ratio cannot be
found to realize the PFC of the input current of the E-HQZS WPCS. Therefore, in order to make the three-phase input current of the E-HQZS WPCS as close as possible to the sine wave, it is necessary to compromise the shoot-through duty ratio of the E-HQZSI. Then, the weighted equivalent periodic shoot-through duty ratio of E-HQZSI can be obtained as

$$d_{0Z} = y_1 d_{0a} + y_2 d_{0b} + y_3 d_{0c}, \quad (41)$$

where $y_1$, $y_2$, and $y_3$ are the weighting coefficient of $d_{0a}$, $d_{02}$, and $d_{03}$, respectively.

### 6. Experiment Verification

The RT-Lab OP5600 is adopted to simulate the converter and PMSG. TMS320F2812 is selected as the DSP controller for E-HQZSI. The hardware-in-the-loop simulation (HILS) of WPCS can be realized by downloading the compiled code from PMSG and converter model in OP5600 and by downloading the C-code generated from the designed controller model in DSP. The average output voltage of the impedance source network is 560 V, and the rated power of the system is 2.2 kW. The inductance of impedance source inductors $L_1$, $L_2$, and $L_3$ is 1.5 mH, and the capacitance of impedance source capacitors $C_1$ and $C_2$ is 900 μF. The main parameters of PMSG used in the experiment are shown in Table 1, and the experimental results are shown in Figures 13–18.

In Figure 13, the voltage stress of the E-HQZSI is compared with that of the QZSI and the HQZSI when the PMSG rotates at 1500 RPM. Figure 13(a) shows that the output voltage peck of the impedance source network is 610 V, when the voltage of the QZS capacitor $C_1$ is set to 560 V. Figure 13(b) shows that the output voltage peck of the impedance source network is 586 V, when the voltage of the E-HQZS capacitor $C_2$ is set to 560 V. It can be seen that compared to the QZSI and the HQZSI, the voltage stress of the E-HQZSI is minimum.

In Figure 14, the voltage stress of the E-HQZSI is compared with that of the QZSI and the HQZSI when the PMSG rotates at 1200 RPM. Figure 14(a) shows that the output voltage peck of the impedance source network is 710 V, when the voltage of the QZS capacitor $C_1$ is set to 560 V. Figure 14(b) shows that the output voltage peck of the impedance source network is 769 V, when the voltage of the HQZS capacitor $C_1$ is set to 560 V. Figure 14(c) shows that the output voltage peck of the impedance source network is 656 V, when the voltage of the E-HQZS capacitor $C_2$ is set to 560 V. It can be seen that compared to the QZSI and the HQZSI, the voltage stress of the E-HQZSI is decreased by 7.6% and 14.7%, respectively. The results reflect that the E-HQZSI has higher boost capacity compared to the QZSI and the HQZSI.

In Figures 15 and 16, the stator current and spectrum of the PMSG with the E-HQZSI are compared to that with the QZSI and the HQZSI at the 1500 RPM. It can be seen that compared to the HQZSI, the THD of the stator current with the E-HQZSI and the periodic shoot-through duty ratio control scheme is decreased by 27.7% and 34.1%, respectively.

In Figures 17 and 18, the stator current and spectrum of the PMSG with the E-HQZSI are compared to that with the QZSI and the HQZSI at the 1200 RPM. It can be seen that the THD of the stator current is only 11.43% with the E-HQZSI and the periodic shoot-through duty ratio control method, which is much smaller than that with the HQZSI and the E-HQZSI.

![Figure 12: Three-phase equivalent periodic shoot-through duty ratio.](image-url)

### Table 1: Main parameters of PMSG.

| Parameters                  | Value        |
|-----------------------------|--------------|
| Stator phase resistance     | 1.162 Ω      |
| Number of pole pairs        | 2            |
| Rated speed of PMSG         | 1500 RPM     |
| d-axis inductances          | 0.00196 H    |
| q-axis inductances          | 0.00196 H    |
| Flux linkage of permanent magnets | 0.205 Wb    |
Figure 13: Experimental comparison of the three topologies when the PMSG rotates at 1500 RPM. (a) Quasi-Z-source WPCS. (b) Half-quasi-Z-source WPCS. (c) Enhanced half-quasi-Z-source WPCS.

Figure 14: Continued.
Figure 14: Experimental comparison of the three topologies when the PMSG rotates at 1200 RPM. (a) Quasi-Z-source WPCS. (b) Half-quasi-Z-source WPCS. (c) Enhanced half-quasi-Z-source WPCS.

Figure 15: Experimental results of the stator voltage and stator current when the PMSG rotates at 1500 RPM. (a) With half-quasi-Z-source inverter. (b) With enhanced half-quasi-Z-source inverter. (c) With enhanced half-quasi-Z-source inverter and the periodic shoot-through duty ratio control scheme.
Figure 16: Experimental results of the stator current frequency spectrum when the PMSG rotates at 1500 RPM. (a) With half-quasi-Z-source inverter. (b) With enhanced half-quasi-Z-source inverter. (c) With enhanced half-quasi-Z-source inverter and the periodic shoot-through duty ratio control method.

Figure 17: Continued.
In this paper, an enhanced half-quasi-\(Z\)-source inverter has been proposed, which has higher boost capacity due to the lower voltage stress of the inverter bridge. In this paper, the system configuration, operating principle, and voltage gain of the proposed E-HQZSI were analyzed in detail. However, the THD of stator current is increased along with the higher boost capacity of E-HQZSI. So a periodic shoot-through duty ratio control scheme is proposed to reduce the THD of the stator current in this paper. In this part of the paper, input current change rate, input power factor, and periodic shoot-through duty ratio of the proposed E-HQZSI were analyzed in detail. It can be seen that the THD of stator current with the proposed scheme was significantly reduced compared to the traditional scheme according to the experimental results.

**7. Conclusion**

In this paper, an enhanced half-quasi-\(Z\)-source inverter has been proposed, which has higher boost capacity due to the lower voltage stress of the inverter bridge. In this paper, the system configuration, operating principle, and voltage gain of the proposed E-HQZSI were analyzed in detail. However, the THD of stator current is increased along with the higher boost capacity of E-HQZSI. So a periodic shoot-through duty ratio control scheme is proposed to reduce the THD of the stator current in this paper. In this part of the paper, input current change rate, input power factor, and periodic shoot-through duty ratio of the proposed E-HQZSI were analyzed in detail. It can be seen that the THD of stator current with the proposed scheme was significantly reduced compared to the traditional scheme according to the experimental results.
Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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