Impact of Component Losses on the Voltage Boost Properties and Efficiency of the qZS-Converter Family

Dmitri Vinnikov, Indrek Roasto
Department of Electrical Drives and Power Electronics, Tallinn University of Technology (Tallinn, Estonia)
dmitri.vinnikov@ieee.org

Abstract- This paper is devoted to the quasi-Z-source (qZS) converter family. Recently, the qZS-converters have attracted high attention because of their specific properties of voltage boost and buck functions with a single switching stage, which could be especially advantageous in renewable energy applications. As main representatives of the qZS-converter family, the traditional quasi-Z-source inverter as well as two novel extended boost quasi-Z-source inverters are discussed. Steady state analysis of three main topologies operating in the continuous conduction mode is presented. Input voltage boost properties of converters are compared for an ideal case. Mathematical models of converters considering losses in components are derived. Practical boost properties of converters are compared to idealized ones and the impact of losses on the voltage boost properties of each topology is justified. Finally, the impact of losses in the components on the boost conversion efficiency is analyzed.

I. INTRODUCTION

Recently, the quasi-Z-source inverter (qZSI) topology (Fig. 1a) has attracted high attention because of its specific properties of voltage boost and buck functions with a single switching stage [1-3]. The qZSI also features such advantages as continuous input current, low or no inrush current during start-up, high immunity against EMI noise and misgating. Because of that the qZSI became a very attractive choice for renewable and alternative energy applications, where the reliability and reduced number of energy conversion stages could play a vital role.

The conception of extending the qZSI boost capability without increasing the number of active switches has been recently proposed by several authors [4-9]. These new converters are known as cascaded (or extended boost) qZSIs and are generally classified as capacitor assisted and diode assisted. The topology of a capacitor assisted extended boost qZSI (CAEB qZSI, Fig. 1b) was derived by the adding of one diode (D2), one inductor (L3) and two capacitors (C3 and C4) to the traditional qZSI [7, 8]. The topology of a diode assisted extended boost qZSI (DAEB qZSI, Fig. 1c) was derived by the adding of one capacitor (C3), one inductor (L3) and two diodes (D2 and D3) to the traditional qZSI.

These three topologies (Fig. 1) have a common property - the input inductor L1 that buffers the source current. It means that during the continuous conduction mode (CCM) the input current of the converter never drops to zero, thus featuring the reduced stress of the input voltage source.

Since all these three topologies have a different number of passive components in the qZS-networks, a detailed analysis of component losses and their impact on a converter’s operating properties are especially topical issues to be addressed in order to obtain higher energy efficiencies.

Fig. 1. Representatives of the qZS-converter family: traditional qZSI (a), capacitor assisted cascaded qZSI (b) and diode assisted cascaded qZSI (c).
II. STEADY STATE ANALYSIS OF INVESTIGATED TOPOLOGIES

The topologies shown in Fig. 1 could be simply represented by the PWM inverter coupled with the appropriate qZS-network. Similarly to the traditional qZSI, the extended boost qZSI has two main types of operational states at the dc side: non-shoot-through states (i.e. the six active states and two conventional zero states of the traditional three-phase voltage source inverter (VSI)) and the shoot-through state (i.e. both switches in at least one phase leg conduct simultaneously). To simplify our analysis the inverter bridge was replaced by a switch $S$ (Fig. 2). When the switch $S$ is closed, the shoot-through state occurs and the converter performs the voltage boost action. When the switch $S$ is open, the active (non-shoot-through) state emerges and previously stored magnetic energy in turn provides the boost of voltage seen on the load terminals.

The operating period of the qZS-converter in the CCM basically consists of a shoot-through state $t_a$ and an active state $t_b$:

$$T = t_a + t_b.$$  

Equation (1) could also be represented as

$$\frac{t_a}{T} + \frac{t_b}{T} = D_a + D_s = 1,$$

where $D_a$ and $D_s$ are the duty cycles of an active and shoot-through states, correspondingly.

In order to simplify the analysis it was assumed that all the capacitors, inductors, and diodes of the qZS-networks of the investigated topologies are identical and lossless.

A. qZS-converter

Fig. 3 shows the equivalent circuits of the traditional qZS-converter operating in the CCM for the shoot-through (a) and active (b) states. At the steady state the average voltage of the inductors over one operating period is zero:

$$U_{L1} = \frac{1}{T} \int u_{L1} dt = 0; \quad U_{L2} = \frac{1}{T} \int u_{L2} dt = 0.$$  

Considering the above and defining the shoot-through duty cycle as $D_s$ and the non-shoot-through duty cycle as $(1-D_s)$, the inductors’ voltages over one operating period could be represented as

$$U_{L1} = \bar{u}_{L1} = D_s (U_{IN} + U_{C1}) + (1 - D_s) (U_{IN} - U_{C1}) = 0,$$

$$U_{L2} = \bar{u}_{L2} = D_s (U_{C1}) - (1 - D_s) (U_{C1}) = 0.$$  

(4)

The peak DC-link voltage is

$$\hat{u}_{DC} = U_{C1} + U_{C2} = U_{IN} \frac{1}{1 - 2D_s},$$

where $U_{C1} = U_{IN} \frac{1 - D_s}{1 - 2D_s}$ and $U_{C2} = U_{IN} \frac{D_s}{1 - 2D_s}$.

B. CAEB qZS-converter

Fig. 4 shows the equivalent circuits of the CAEB qZS-converter operating in the CCM for the shoot-through (a) and active (b) states.

At the steady state the average voltage of the inductors over one operating period is zero:
The peak DC-link voltage is
\[
\hat{u}_{\text{DC}} = U_{c_1} + U_{c_2} = U_{\text{IN}} \frac{1}{D_S^2 - 3D_S + 1} + \frac{1}{D_S^2 - 3D_S + 1}.
\]
where \( U_{c_1} = U_{\text{IN}} \frac{D_S^2 - 2D_S + 1}{D_S^2 - 3D_S + 1} \) and \( U_{c_2} = U_{\text{IN}} \frac{2D_S - D_S^2}{D_S^2 - 3D_S + 1} \).

D. Comparison of idealized boost properties of the qZS-converter family

To evaluate the boost properties of the discussed qZS-converter topologies the boost ratio of the input voltage \( B \) was introduced:

\[
B = \frac{\hat{u}_{\text{DC}}}{U_{\text{IN}}},
\]

where \( \hat{u}_{\text{DC}} \) is the amplitude value of the dc-link voltage \( U_{\text{DC}} \) and \( U_{\text{IN}} \) is the input voltage of the converter. Fig. 5 shows the boost ratio comparison chart of the three discussed topologies. It is seen that the CAEB and DAEB qZS-converters could provide up to 2 and 1.6 times higher input voltage gain, respectively, than the traditional qZS-converter.

III. IMPACT OF COMPONENT LOSSES ON THE VOLTAGE BOOST PROPERTIES OF THE qZS-CONVERTER FAMILY

In the previous section the lossless models of the qZS-converter family were discussed. In real practice the voltage boost properties of the qZS-converters could be seriously affected by the losses in components. For more careful estimation of the operating characteristics of the converter the loss elements, such as winding resistances of inductors and voltage drops in semiconductors, should be added to the model. In our analysis the losses in inductors \( L_1 \ldots L_3 \) as well as in \( L_o \) are represented by the resistances \( r_L \) and losses in diodes during the conduction state are controlled by the voltage drop \( U_d \). Moreover, it was assumed that the IGBT with the saturation voltage of \( U_s \) was used for switch \( S \). To simplify the analysis it was stated that the capacitors and inductors of all the compared topologies are identical.
A. \textit{qZS-converter}

An extended equivalent circuit of the traditional \textit{qZS-converter} considering losses in the components is presented in Fig. 7.

![Equation (12)](image)

Equation (4) written for the lossless system could be extended to (12). Considering losses in the components the peak dc-link voltage of the traditional \textit{qZS-converter} could be expressed by (13).

B. \textit{CAEB qZS-converter}

An extended equivalent circuit of the CAEB \textit{qZS-converter} considering component losses is presented in Fig. 8.

![Equation (14)](image)

Equation (7) written for the lossless system could be extended to (14). Considering losses in the components the peak dc-link voltage of the CAEB \textit{qZS-converter} could be expressed by (15).

C. \textit{DAEB qZS-converter}

An extended equivalent circuit of the DAEB \textit{qZS-converter} considering component losses is presented in Fig. 9.

![Equation (15)](image)

In order to demonstrate the impact of losses in the components on the input voltage boost properties of the investigated topologies the lossless and lossy models were compared mathematically with the following parameters:

\begin{align*}
U_{IN} &= 40 \text{ V}; \quad U_S = 1.7 \text{ V}; \quad U_D = 1.6 \text{ V}; \\
R_O &= 4.5 \Omega; \quad r_L = 4 \text{ m}\Omega; \quad D_S = 0 \ldots 0.25.
\end{align*}
\[
U_{L1} = \pi_{L1} = D_s(U_{IN} + U_{C2} - I_{DS}r_L - U_S) + (1 - D_s)(U_{IN} - U_{C1} - I_{DS}r_L - U_D) = 0 \\
U_{L2} = \pi_{L2} = D_s(U_{C1} - U_D - I_{DS}r_L - U_S) + (1 - D_s)(U_{C1} - U_{C2} - I_{DS}r_L - U_D) = 0 \\
U_{L3} = \pi_{L3} = D_s(U_{C3} - I_{DS}r_L - U_S) + (1 - D_s)(U_{C3} - U_{C2} - U_D) = 0 \\
U_{L4} = \pi_{L4} = D_s(U_{S} - I_{DS}r_L - U_C0) + (1 - D_s)(U_{C1} - I_{DS}r_L - U_C0 + U_D) = 0 .
\]  
(16)

\[
I_{C1} = \pi_{C1} = -D_s I_{L2} + (1 - D_s)(I_{L1} + I_{L3} - I_0 - I_{L2}) = 0 \\
I_{C2} = \pi_{C2} = -D_s I_{L3} + (1 - D_s)(I_{L1} - I_0) = 0 \\
I_{C3} = \pi_{C3} = -D_s I_{L3} + (1 - D_s)(I_{L2} - I_{L3}) = 0
\]

\[
U_{DC} = \frac{a D_s^2 + \beta D_s^2 + \gamma D_s^2 + \lambda D_s^2 + 3 R_u U_D - R_u U_{IN} + 6 U_D r_L - U_{IN} r_L}{(- R_u - 2 r_L) D_s^2 + (6 R_u + 10 r_L) D_s + (- 11 R_u - 19 r_L) D_s^2 + (6 R_u + 14 r_L) D_s - R_u - 4 r_L},
\]
(17)

where \( \alpha = R_u U_D^2 R_u + 2 U_D r_L - 2 U_S r_L \);
\( \beta = 6 R_u U_D - 6 R_u U_D - 10 U_D r_L + 9 U_S r_L \);
\( \gamma = 13 R_u U_D^2 - 10 R_u U_D + 21 U_D r_L - U_{IN} r_L + 15 U_S r_L \);
\( \lambda = 3 R_u U_D^2 - 12 R_u U_D^2 - 20 U_D r_L + 3 U_{IN} r_L + 6 U_S r_L \).

Figs. 10, 11 and 12 show the impact of losses on the input voltage boost factor of the traditional, CAEB and DAEB qZS-converters, respectively. The diagrams show that at the maximal studied shoot-through duty cycle \( D_s = 0.25 \) the traditional, CAEB and DAEB qZS-converters have demonstrated the 9%, 14% and 13% reduction of the targeted DC-link voltage amplitude, respectively.

**IV. IMPACT OF COMPONENT LOSSES ON THE EFFICIENCY OF THE QZS-CONVERTER FAMILY**

In order to demonstrate the impact of component losses on the overall efficiency of the qZS-converters a number of experiments were performed. First, the impact of inductor winding resistance was studied. Figs. 13, 14 and 15 show that at maximal shoot-through duty cycle \( D_s = 0.25 \) and selected inductor’s resistance \( r_L = 4 \) mAΩ, the efficiency variation of the investigated topologies lies in the range of 87...94%.

![Fig. 10. Comparison of idealized and practical boost properties of the traditional qZS-converter.](image10)

![Fig. 11. Comparison of idealized and practical boost properties of the CAEB qZS-converter.](image11)

![Fig. 12. Comparison of idealized and practical boost properties of the DAEB qZS-converter.](image12)

![Fig. 13. Impact of the inductor’s winding resistance on the efficiency of the traditional qZS-converter.](image13)
In the second experiment, the impact of the forward voltage drop of diodes $D_1 \ldots D_3$ on the converter’s efficiency was studied. Figs. 16, 17 and 18 show that at maximal shoot-through duty cycle ($D_D = 0.25$) and selected fast recovery epitaxial diodes ($U_D = 1.6$ V) the maximal efficiency that could be obtained with traditional, CAEB and DAEB qZS-converters is 94%, 87% and 88%, respectively. If the diodes are replaced with high-power Schottky rectifiers with a low forward voltage drop ($U_D = 0.6$ V), the effective efficiency rise by at least 5% could be expected for all three topologies.

Fig. 15. Impact of the inductor’s winding resistance on the efficiency of the DAEB qZS-converter.

Fig. 16. Impact of diode forward voltage drop on the efficiency of the traditional qZS-converter.

Fig. 17. Impact of diode forward voltage drop on the efficiency of the CAEB qZS-converter.

Fig. 18. Impact of diode forward voltage drop on the efficiency of the DAEB qZS-converter.

V. CONCLUSIONS

This paper is devoted to the analysis of the voltage boost capability of three different quasi-Z-source converters. Special attention is paid to the impact of losses in passive components on the boost properties and boost conversion efficiency of the investigated topologies. It was found that for the same operating parameters ($U_{IN} = 40$ V; $R_O = 4.5$ Ω) and component values ($U_S = 1.7$ V; $U_D = 1.6$ V; $r_L = 4$ mΩ) the twofold boost of the input voltage could be realized at the efficiency of 93.9%, 89.2% and 89.3% for the traditional, CAEB and DAEB qZS-converters, respectively.

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