A New Topology of Embedded Z-H Buck-Boost Converter

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ABSTRACT: In this paper, a new embedded Z-H (EZ-H) buck-boost converter is proposed. In this topology, two identical dc voltage sources are embedded in a LC network in a series connection with the inductors. The proposed converter eliminates the shoot-through (ST) switching state and there is no need for a front-end diode. Other advantages of the proposed topology are having capability of buck and boost operations in one structure; reaching the maximum gain in the duty cycle near 0.5; lowering ripples of voltage and current; and particularly reducing the voltage stress on the capacitors. In this paper, the voltage and current equations of all the components are extracted with considering all the operation modes. In addition, a suitable switching method is presented for the proposed converter to generate the desired output voltage. The ripple values of inductors and capacitors are calculated. Simulation results by the PSCAD/EMTDC software show accuracy and performance of the proposed converter.

1- Introduction
The voltage source inverters operate only in buck mode, which makes them unsuitable for renewable energy applications. To increase the voltage magnitude, a dc-dc converter is used. In order to increase or decrease the output voltage, without an additional converter, an X-shaped LC network, namely Z-source inverter can be used [1-3]. The Z-source inverters are used in many applications such as adjustable speed drives [4-5], uninterruptable power supplies (UPS) [6-7], photovoltaics [8-10], wind turbine [11-12], etc. The main features of Z-source inverters are a) the ST zero state makes the magnitude of output voltage lower or higher than the magnitude of a source voltage without any need to buck or boost converters or transformers; b) the LC network enhances the reliability. Adding two inductors and two capacitors to the voltage source inverter increases the size.

In order to increase the power density of the system, the size of capacitors and inductors must be decreased, which can be done by modification in the Z-source inverter structure. Over the recent years, several Z-source inverter structures with different capabilities have been proposed. Embedded Z-source (EZ-source) inverter and series Z-source inverter are two modified structures [13-16]. In the EZ-source inverter, the voltage of capacitor and input current are decreased due to the dc voltage source in series with the inductors. In series Z-source inverter, the voltages of two capacitors are decreased due to the dc voltage source in series with the bridge inverter. In the modified Z-source inverters, the size and cost of capacitors are decreased, which make the size of inductors smaller and therefore power density of the system is increased.

The diode (switch) before LC network (front-end diode) has some disadvantages, a) it makes the current waveform non-continuous, which causes inappropriate condition during non-shoot-through state; b) it prevents flowing reverse currents, which causes to be used in applications that do not require reverse flow of energy capability [1, 17]. In order to overcome the aforementioned problems, the Z-H converter was proposed in [17], which has one structure for buck conversion and another one for boost conversion. Buck and boost Z-H converters eliminate the front-end diode and shoot-through state.

The main disadvantage of this Z-H converter is that to increase or decrease the output voltage, two separate structures must be used [17, 18]. Another structure based on Z-H structure has been presented in [19] as a buck-boost Z-H converter, which has two capabilities of buck and boost conversion in one structure.

In this paper, in order to overcome the problems of the Z-H converter, using the concepts of Z-source inverter, Z-H converters, and an embedded voltage source, a new converter is proposed, which has buck and boost capabilities in one structure and particularly decreases the voltage stress across capacitors. In order to evaluate the proposed structure, the equations of voltage, current waveforms, and voltage gain are obtained and the ripple values of inductors’ and capacitors’ voltage are given. A suitable switching method is presented. Also, the converter is simulated in PSCAD/EMTDC and results are presented.
2- Proposed EZ-H Buck-Boost Converter

Fig. 1 shows the structure of the proposed EZ-H buck-boost converter. Like the Z-source inverter, this structure contains an LC impedance network and similar to the Z-H converter, this structure eliminates the front-end diode of the LC network. This structure differs from those of the Z-source inverter and the Z-H converter in terms of topology but resembles them in terms of operating principles. In the proposed topology, two dc input sources with values of \( V_{1}/2 \) are used in series with inductors of the LC network. The switches in Fig. 1 are of bidirectional types from voltage and current points of view. The inductors \( L_1 \) and \( L_2 \) filter the current drawn from the dc sources which resolves the need for additional filter [15]. In the conventional Z-source, the diode before the LC network creates an unfavorable operation mode during the non-ST state. In addition, it prevents the reverse current, which confines the use of this converter to the applications with no need to energy return to the input source [1, 17-18]. However, in the proposed converter, the front-end diode is eliminated.

The proposed converter can produce lower or higher voltage than the input voltage. Due to the existence of LC network, the reliability of the converter is increased. The proposed structure can be applied for dc-dc, dc-ac and ac-ac conversions without any change in its structure. Moreover, it eliminates ST switching state due to Z-source LC network. In conventional Z-source inverters, the number of the switches is higher than the one in the proposed converter. Also, the conventional Z-source inverter has a front-end diode that adds to the losses of the inverter. Therefore, in the similar conditions, according to [19, Eq. 76], power loss in the conventional Z-source inverter is higher than the power loss in the proposed converter, and this shows the higher efficiency of the proposed converter in comparison with the conventional Z-source inverter.

The proposed converter consists of two operating zones. Over \( D = [0,0.5) \), the converter operates in buck-boost mode and over \( D = (0.5,1] \), it operates in boost mode. In Fig. 1, \( S_1 \) is turned on complementary with \( S_2 \) and \( S_3 \) is turned on complementary with \( S_4 \) (when \( S_1 \) and \( S_4 \) are on \( S_2 \) and \( S_3 \) are off and vice versa). The duty cycle for \( S_2 \) and \( S_3 \) are used in series with \( c_A \) and the voltage \( V_o \) is compared with the reference signal \( V_r \). Considering the voltage balancing law, the average voltage of \( V_i \) and \( V_o \) are given by:

\[
V_{i1} = V_{o2} = V_c, \tag{1}
\]

\[
v_{L1} = v_{L2} = v_L, \tag{2}
\]

where \( V_c \) and \( v_L \) are the voltage across capacitors and inductors, respectively. In \( T_o \) (Fig. 3(a)), the following equations can be written:

\[
v_{L,T_o} = 0.5 V_i + V_c \tag{3}
\]

\[
v_{o,T_o} = V_c \tag{4}
\]

where \( V_i \) and \( V_o \) are the input and output voltages of the converter, respectively.

For \( T_1 \) (Fig. 3(b)), the following equations are obtained:

\[
v_{L,T_1} = 0.5 V_i - V_c \tag{5}
\]

\[
v_{o,T_1} = V_c \tag{6}
\]

According to (4) and (6), the values of output voltage are equal in \( T_o \) and \( T_1 \).

2-1- Extraction of Voltages' Equations and Voltage Gain

Considering the voltage balancing law, the average voltage of an inductor is zero. Thus, from (3) to (6), the average voltage across capacitors (\( V_c \)) and the average output voltage (\( V_o \)) in the both operating zones and the both time intervals \( T_o \) and \( T_1 \) are given by:

\[
V_o = V_c = \begin{cases} \frac{1}{1-2D}V_i & \text{for } D = [0, 0.5) \\ \frac{1}{1-2D}V_i & \text{for } D = (0.5, 1] \end{cases}
\tag{7}
\]

Considering (7), the voltage gain (\( B \)) of the converter can be defined as:

\[
B = \frac{V_o}{V_i} = \begin{cases} \frac{0.5}{1-2D} & \text{for } D = [0, 0.5) \text{ & } D = (0.5, 1] \end{cases}
\tag{8}
\]
As Fig. 4(a) shows, in $D = [0, 0.5)$ the converter operates as buck where $0 \leq D < 0.25$ and $0 \leq B \leq 1$ and as boost where $0.25 < D < 0.5$ and $1 \leq B \leq +\infty$. In $D = (0.5, 1]$, the converter operates as boost where $-\infty < B \leq -1$. Fig. 4(b) compares the voltage stress across capacitors for the Z-H converter [17] and the proposed EZ-H converter. The output voltage is positive in the first operating zone and is negative in the second operating zone. Figs. 4(a) and 4(b) also show that in comparison with the Z-H converter, EZ-H converter has buck-boost characteristics in one structure.

2-2- Extraction of Currents’ Equations

For the time interval $T_0$ (Fig. 3(a)), the following equations are obtained:

\[ i_{c,1,T0} = i_{o,T0} - i_{l,1,T0}, \]  
\[ i_{c,2,T0} = -i_{l,2,T0}, \]  
where $i_c$ and $i_l$ are the instantaneous currents through the capacitors and the inductors, respectively. Also, $i_o$ is the output current of the converter.

For the time interval $T_1$ (Fig. 3(b)), the following equations are obtained:

\[ i_{c,1,T1} = i_{l,1,T1}, \]  
\[ i_{c,2,T1} = -i_{l,2,T1}. \]  

Assuming that the load is purely resistive, the instantaneous output current ($i_o$) and the average output current ($i_{o,av}$) in the both operating zones and the both time intervals can be given by:

\[ i_o = i_{o,av} = \frac{V_o}{R}. \]  

Assuming that the initial current of the inductor at the beginning of the time interval $T_0$ is equal to $I_1$, the instantaneous current through the inductor ($i_l$) in the time interval $T_0$ can be given by:

\[ i_{l,T0} = \frac{0.5V_o + V_c}{L} - I_1, \]  
for $0 \leq t \leq T_0$

In order for instantaneous current through the inductor in the time interval $T_0$ to be ascending in the first operating zone and descending in the second operating zone, the following
conditions must be satisfied:
\[
\frac{di_{L,1}}{dt} > 0 \quad \& \quad V_C > -0.5V_i \quad \text{for} \quad D = [0, 0.5),
\]
(15)  
\[
\frac{di_{L,2}}{dt} < 0 \quad \& \quad V_C < -0.5V_i \quad \text{for} \quad D = (0.5, 1].
\]
(16)  

Considering the inequalities (15), (16), (19), and (20), the conditions for controllable power transfer in the first and second operating zones are given as follows,
\[
V_C > -0.5V_i \quad \& \quad 0.5V_i < V_C \quad \text{for} \quad D = [0, 0.5),
\]
(21)  
\[
V_C < -0.5V_i \quad \& \quad 0.5V_i > V_C \quad \text{for} \quad D = (0.5, 1].
\]
(22)  

According to (21), in the first operating zone, the voltage across the capacitor must be positive and ±0.5 times more than the input voltage. Regarding (22), in the second operating zone, in order for the power to be transferred from the input voltage source to the output, the voltage across capacitor must be negative and the input voltage must be times as much as the capacitor voltage.

By letting \( t = T_f = (1-D)T \) in (18), the current through the inductor at the end of the time interval \( T_1 \), i.e. \( i_{L,1} \), can be obtained as:
\[
i_{L,1} \big|_{t = T_1} = I_1 = \frac{0.5V_i - V_C}{L}T_1 + I_2
\]
(23)  

Using (17) and (23), the average value of the current through each of the inductors in both the operating zones can be given by
\[
I_{L,av} = \frac{1}{T} \int_0^T i_L \, dt = \frac{1}{2Lf} \left[ (0.5V_i + V_C)D^2 + (0.5V_i - V_C)(1-D)^2 + DI_1 + (1-D)I_2 \right],
\]
(24)  
where \( f = 1/T \) denotes the switching frequency of the converter.

Considering (17), (23) and (7), the current ripples of the inductors can be obtained as:
\[
\Delta I_{L,1} = \Delta I_{L,2} = \left| I_{L,1} - I_{L,2} \right| = \frac{0.5V_i - V_C}{L}DT = \frac{D(1-D)V_i}{(1-2D)Tf}
\]
(25)  

According to the current balance law on the capacitor \( C_1 \), the average current through the inductors \( \frac{1}{L} \) and \( \frac{2}{L} \), say \( i_{L,av} \) and \( i_{L,2,av} \) respectively, can be given by
\[
I_{L,1,av} = \frac{1-D}{2R_L} \int_0^T \left( \frac{1-D}{2R_L} \right) V_i \, dt
\]
(26)  
\[
I_{L,1,av} = \frac{D}{(1-2D)^2} \int_0^T \left( \frac{D}{(1-2D)^2} \right) V_i \, dt
\]
(27)  

The average value of inductor current, say \( I_{L,av} \), can be defined by
\[
I_{L,av} = \frac{1}{2} i_{L,1} + i_{L,2}
\]
(28)  

The following equation defines the current ripple of the inductor ( \( \Delta I_L \) ),
\[
\Delta I_L = I_2 - I_1
\]
(29)  

Considering (28) and (29), the values of \( I_1 \) and \( I_2 \) can be calculated as it follows,
The instantaneous currents through the capacitors $C_1$ and $C_2$, at the end of the time intervals $T_0$ and $T_1$, $I'_{2,x}$ and $I'_{x,2}$, can be given by:

$$I'_{2,c1} = I'_{c,2,c1} = I'_{2,x} = -I_{2,1},$$

$$I'_{x,1} = I'_{x,2} = I'_{x,1} = I_{x,2}.$$  

(32)

(33)

Considering (32) and (33), the allowable voltage ripple across the capacitors $\Delta V_{c1}$, $\Delta V_{c2}$, in both the operating zones can be calculated as it follows,

$$\Delta V_{c1} = \Delta V_{c2} = \Delta V_c = \pm \frac{D(I_{1,av})}{C f}.$$  

(34)

According to (1)-(34), Fig. 5 shows the voltage and the current waveforms of the proposed EZ-H converter in the first operating zone.

According to (26) and (27), it can be observed that the average currents flowing through the inductors of the proposed converter are not equal. It is due to the fact that the series connection of the inductor and the dc input source of the upper and the lower parts of the converter are not symmetrical. This causes different powers to be taken from the input sources. Therefore, this will harden the control of the input powers for achieving maximum power. However, this problem can be solved by changing the structure of the proposed circuit.

3- Designing Values of $L$ and $C$

Ripples of capacitor voltage and inductor current affect the stability of the converters. To properly design the values of $C_1$ and $C_2$, the allowable voltage ripple $x_c \%$ may be used, which is defined as it follows [20],

$$x_{c1} \% = x_{c2} \% = x_{c} \% = \frac{\Delta V_c}{V_c}. $$

(35)

Considering (26) and by inserting the values of $V_c$ and $\Delta V_c$ from (7) and (34) into (35), the rated value of $C_1$ and $C_2$ are calculated as it follows,

$$C_1 = C_2 = C = \frac{D(1-D)}{R (1-2D)x_c \%}.$$  

(36)

To properly design the values of $L_1$ and $L_2$, the allowable current ripples $x_{l1} \%$ and $x_{l2} \%$ may be used, which are defined as it follows,

$$x_{l1} \% = \frac{\Delta I_{l1}}{I_{l1,av}},$$

$$x_{l2} \% = \frac{\Delta I_{l2}}{I_{l2,av}}.$$  

(37)

(38)

By inserting the values of $\Delta I_{l1}$ and $I_{l1,av}$, given by (25) and (26), into (37), and by replacing the values of $\Delta I_{l2}$ and $I_{l2,av}$ from (25) and (27) with (38), the rated values of $L_1$ and $L_2$ are calculated as it follows,

$$L_1 = \frac{2D(1-2D)R_L}{f x_{l1} \%},$$

$$L_2 = \frac{(1-D)(1-2D)R_L}{f x_{l2} \%}.$$  

(39)

(40)

4- Imulation Results

In order to evaluate accurate operation of the proposed EZ-H converter, simulations are performed in PSCAD/EMTDC software. Table 1 gives the values of the parameters used in the simulations. Fig. 6 illustrates the simulation results in the first operating zone for the buck operation by assuming $B = 0.625$ and $D = 2.5$ and for the boost operation by assuming $B = 2.5$ and $D = 0.4$.

<table>
<thead>
<tr>
<th>Table 1. The values of the parameters used in the simulations.</th>
</tr>
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<tbody>
<tr>
<td>Switching frequency $(f)$</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>50 kHz</td>
</tr>
</tbody>
</table>

4-1- Calculating Values of Capacitors and Inductors

Based on the discussions given in Section 3, the values of capacitors and inductors can be obtained as it follows.

Assume that $D = 0.4$, $\Delta I_{l1} = \Delta I_{l2} = 1.15 A$, $V_c = 120 V$ and $\Delta V_{c1} = \Delta V_{c2} = 1.15 V$. From (35), the allowable voltage ripple $x_c \%$ is given by:

$$x_{c1} \% = x_{c2} \% = \frac{\Delta V_c}{V_c} = \frac{1.15}{120} = 0.0095.$$  

(41)

From (36), the rated values of the capacitances $C_1$ and $C_2$ are

$$C_1 = C_2 = \frac{D(1-D)}{R (1-2D)x_c \%} = 25 \mu F.$$  

(42)

From (37) and (38), the allowable current ripples $x_{l1} \%$ and $x_{l2} \%$ are given by

$$x_{l1} \% = \frac{\Delta I_{l1}}{I_{l1,av}} = 0.32,$$

$$x_{l2} \% = \frac{\Delta I_{l2}}{I_{l2,av}} = 0.48.$$  

(43)

(44)

From (39) and (40), the rated values of the inductances $L_1$ and $L_2$ are obtained from the following relations,

$$L_1 = \frac{2D(1-2D)R_L}{f x_{l1} \%} = 1 mH,$$

$$L_2 = \frac{(1-D)(1-2D)R_L}{f x_{l2} \%} = 1 mH.$$  

(45)

(46)

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Fig. 5. Voltage and current waveforms of the proposed EZ-H converter in the first operating zone, where $D = [0, 0.5]$; (a) buck; (b) boost.
The proposed Z-H dc-dc buck-boost converter

- $V_{L1} = V_{L2}$ [V]
- $i_{C1} = i_{C2}$ [A]
- $V_{C1} = V_{C2}$ [V]
- $i_{L1}$ [A]
- $v_{L1}$ [V]
4-2 Calculation of Voltages and Currents Values
From (7) and (13), the output voltage and current of the converter in the time intervals $T_0$ and $T_1$ are $V_o = 120V$ and $i_o = 1.2A$, respectively. Considering (7), the average voltage across capacitors $C_1$ and $C_2$ in both the time intervals is $V_C = 120V$. From (3) and (5), the voltages across inductors $L_1$ and $L_2$ in the time intervals $T_0$ and $T_1$ are as $v_{L1,T0} = 144V$ and $v_{L2,T1} = -96V$, respectively. According to (25), the value of current ripples of inductors is $\Delta I_{L1} = \Delta I_{L2} = I_{L1} = 1.15A$. From (26), (30) and (31), the average current through the inductor $L_1$ and the values of its current at the end of the time intervals $T_0$ and $T_1$ are $I_{L1,T0} = 3.6A$, $I_{L1,T1} = 3.02A$ and $I_{L2,T2} = 4.17A$, respectively. Using (27), (30) and (31), the average current of the inductor $L_2$ and its current at the end of the time intervals $T_0$ and $T_1$ are $I_{L2,T0} = 2.4A$, $I_{L2,T1} = 1.82A$ and $I_{L2,T2} = 2.97A$, respectively. Considering (32) and (33), the currents through the capacitors $C_1$ and $C_2$ at the end of the time intervals $T_0$ and $T_1$ are $I_{C1,T1} = I_{C1,T2} = -4.17A$ and $I_{C2,T1} = I_{C2,T2} = -1.82A$, respectively. From (34), the voltage ripples of the capacitors are $\Delta V_{C1} = \Delta V_{C2} = 1.15V$. The results obtained from the simulations as in Fig. 6(b), confirm the accuracy of the theoretical calculations and correspond to the waveforms illustrated in Fig. 5(b). The above calculations are for the boost operation and in the same way can be repeated for the buck operation.

4-3 Variations Analysis of the Current and Voltage Ripples
In order to show the variations of the inductor current ripple, capacitor voltage ripple, duty cycle, frequency, inductance and capacitance with respect to each other, Figs. 7 and 8 are given.

Fig. 7(a) shows the variations of the current ripple of the inductor versus the inductance and the duty cycle for specific values of the input voltage and the frequency. As the figure shows, the current ripple of the inductor increases by approaching the duty cycle $D = 0.5$ from both ends of the duty cycle. In addition, it is observed that for a specified duty cycle, the value of the current ripple of the inductor decreases as the value of the inductance increases. Fig. 7(b) shows the variations of the current ripple of the inductor versus the frequency and the duty cycle for specific values of the input voltage and the inductance. As the figure shows, the current ripple of the inductor increases by approaching the duty cycle $D = 0.5$ from both ends of the duty cycle. In addition, it is observed that for a specified duty cycle, the value of the current ripple of the inductor decreases as the value of the frequency increases. Fig. 7(c) shows the variations of the current ripple of the inductor versus the frequency and the inductance for specific values of the input voltage and the duty cycle $D = 0.6$. As can be seen, the value of the current ripple of the inductor increases by decreasing the values of both the frequency and the inductance. Fig. 8(a) shows the variations of the voltage ripple of the
maximum voltage gain by duty cycle near 0.5, and lower ripples of voltage and current waveforms are the advantages of the proposed topology. The operating principles of the proposed converter were discussed and equations of voltage and current of all the elements of the proposed converter were obtained. Also, the optimum values of the inductors and the capacitors were given. The results obtained from the theoretical calculations and simulations in PSCAD/EMTDC showed the performance and effectiveness of the proposed converter.

References


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