New Family of Zero-Voltage-Transition PWM Bidirectional Converters With Coupled Inductors

Mohammad Reza Mohammadi and Hosein Farzanehfard, Member, IEEE

Abstract—In this paper, a new family of zero-voltage-transition bidirectional converters using coupled inductors is introduced. By applying two auxiliary switches and coupled inductors, soft-switching condition is achieved for all semiconductor elements regardless of the power flow direction. Moreover, the presence of coupled inductors provides significant reduction in the converter volume, since all the converter inductors are implemented on a single core. Also, all semiconductor elements benefit from soft-switching condition in full duty cycle range, and thus, high efficiency is achieved for full line voltage range. No extra voltage and current stresses on the main switches and the ease of control are the other properties of the proposed converters. The proposed bidirectional buck and boost converter is fully analyzed for both buck and boost operating modes. The validity of the theoretical analysis is justified using the experimental results of a 240-W 50–100-V prototype converter.

Index Terms—Bidirectional dc–dc converter (BDC), pulsewidth modulation (PWM) dc–dc converter, zero-voltage transition (ZVT).

I. INTRODUCTION

NOWADAYS, the development of bidirectional dc–dc converters (BDCs) has become an important topic in power electronics. BDCs are capable of reversing the direction of current flow and thereby the power flow between two dc sources while maintaining the voltage polarity of both dc sources. Considering the mentioned points, these converters are widely used in many industry applications. BDCs are key components of industrial equipment with energy storage devices (e.g., battery or supercapacitor). In equipment such as uninterruptible power supplies [1], [2], fuel cell power systems [3], [4], hybrid electric/fuel cell vehicles [5]–[8], solar cell power systems [9], and dual voltage automotive systems [10], [11], BDCs are applied to manage power flow and maintain energy storage device health. Moreover, BDCs can play the role of converting voltage level between an energy storage device and the dc bus, and thus, there is flexibility in the choice of energy storage device voltage level.

Various BDCs can be divided into nonisolated and isolated BDCs. The isolated type is necessary when both sides cannot be grounded simultaneously and high voltage gain is required [8]. In this case, a transformer is needed, which adds extra cost and losses. If high-voltage ratio and isolation are not required, nonisolated BDCs are always employed for their simple structure and control scheme [1]–[11]. Four basic nonisolated BDCs are derived by the combination of converters (buck, boost, buck–boost, Cuk, SEPIC, and Zeta). These converters are buck and boost, buck–boost/buck–boost, SEPIC/Zeta, and Cuk/Cuk, as shown in Fig. 1.

In order to significantly reduce reactive component size and cost, high-frequency operation of BDCs is desirable. However, in a hard-switching converter, as the switching frequency increases, switching losses and electromagnetic interference increase. To resolve this problem, soft-switching converters are employed.

Zero-voltage transition (ZVT) and zero-current transition (ZCT) are two techniques which incorporate a soft-switching function into conventional pulsewidth modulation (PWM) converters [12]–[17] in order to reduce switching losses. In ZVT and ZCT BDCs, to avoid complexity, using the same auxiliary elements which provide soft commutation in both modes of operation of BDC is desirable. However, due to the bidirectional characteristic of BDCs, using two auxiliary switches is inevitable [18]–[24]. In [18]–[21], several ZVT BDCs are proposed with reduced number of components (one inductor, two auxiliary switches, and a snubber capacitor). In [18] and [19], the auxiliary switches turn off under hard-switching condition. In [20], although soft-switching condition is provided for all switches in both turn-on and turnoff instants, soft-switching condition is lost at operating duty cycles lower than 0.5. In addition, the soft-switching range of this converters is limited in practice to duty cycles approximately higher than 0.6. In [21], soft-switching range increases with the same number of components. However, in every switching cycle, the main switches and the auxiliary switch are switched, which results in higher switching losses and complexity of the control circuit.

Manuscript received December 8, 2010; revised March 5, 2011; accepted March 27, 2011. Date of publication April 29, 2011; date of current version October 18, 2011.

The authors are with the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran (e-mail: mohammadi@cc.iut.ac.ir; hosein@cc.iut.ac.ir).

Digital Object Identifier 10.1109/TIE.2011.2148681
ZVT BDCs are proposed in [22] and [23], where all switches are soft switched and duty cycle is not limited. However, in [22], two split input voltages are required by means of inserting two equal capacitors between the input line and ground. Moreover, in order to balance the capacitors, the auxiliary circuit is applied two times in a switching cycle, resulting in more complex control circuit and switching losses. Furthermore, in [23], auxiliary elements are not identical for both modes of operation of BDC, which thus results in higher number of components and circuit complexity. In [24], a soft-switching BDC is proposed, but it suffers from too many auxiliary elements. Turn-on capacitive losses and extra voltage and current stresses on the main switches are the other drawbacks of this converter.

In this paper, a new family of ZVT bidirectional converters with coupled inductors is introduced. In the proposed converters, the idea of coupled inductors to create soft switching [25] is developed for BDCs, and consequently, soft-switching condition for all semiconductors elements in full duty cycle range is achieved regardless of the power flow direction. Also, by employing the leakage inductor as the resonant inductor, all converter inductors can be implemented on a single core, and thus, minimum volume is achieved. No extra voltage and current stresses on the main switches and the ease of control are the other properties of the proposed converters.

The proposed ZVT bidirectional buck and boost converter is analyzed, and its operation is described in Section II. Design considerations, control circuit, and experimental results are presented in Sections III–V, respectively. Other family members of the proposed ZVT BDCs are introduced in Section VI.

II. CIRCUIT DESCRIPTION AND OPERATION

As shown in Fig. 2(a), the proposed converter is composed of two main switches $S_1$ and $S_2$, two auxiliary unidirectional switches $S_{a1}$ and $S_{a2}$, a snubber capacitor $C_s$, and two coupled inductors $L_1$ and $L_2$ with a turn ratio of $n_2/n_1(L_2 = (n_2/n_1)^2L_1)$. The coupled inductors can be modeled as a combination of a magnetizing inductance ($L_M$), an ideal transformer with corresponding turn ratio ($n_2/n_1$), and a leakage inductance ($L_{lk}$). The equivalent circuit of the proposed circuit is shown in Fig. 2(b). Note that the magnetizing inductance $L_M$ is employed as the converter filter inductor. The proposed converter has two modes of operations and seven operating intervals in each mode. The equivalent circuits of the seven operating intervals in the boost mode of operation are shown in Fig. 3, and the key waveforms of the converter in this mode are shown in Fig. 4. Also, the equivalent circuit of each operating interval in the buck mode of operation and the key waveforms of the converter in this mode are shown in Figs. 5 and 6, respectively. Since the operation of the auxiliary circuit and the theoretical equations in both boost and buck modes are similar, only the boost mode is discussed. Note that, in each interval, the theoretical equations for $S_1$, $S_{a1}$, and $S_2$ in boost mode are true in buck mode for $S_2$, $S_{a2}$, and $S_1$, respectively.

In order to simplify the theoretical analysis, the following assumptions are made.

1) All elements are ideal, and the converter is operating at steady-state condition.
2) Magnetizing inductor $L_M$ is large enough to assume that its current ($I_{LM}$) is constant in a switching cycle.
3) The input and output voltages are constant and modeled by two voltage sources $V_1$ and $V_2$, respectively.
4) The turn ratio of coupled inductors is $n (n_2/n_1 = n)$.

A. Boost Mode of Operation

In this mode, $S_1$ and $S_{a1}$ are the main and auxiliary switches, respectively. Before the first interval, it is assumed that all switches are off and the magnetizing inductor current ($I_{LM}$) is transferred to the $V_2$ through the body diode of $S_2$. Also, it is assumed that no current flows in the windings of the ideal transformer in the model and the $C_S$ voltage is $V_2$.

Interval 1: $[t_0–t_1]$ [Fig. 3(a)]: At $t_0$, the auxiliary switch $S_{a1}$ turns on under almost zero-current switching (ZCS) condition due to the series inductor $L_{lk}$. By turning this switch on, according to (1), the $S_{a1}$ current starts to increase linearly. Thus, the current through the body diode of $S_2$ starts to reduce until it reaches zero, and therefore, this diode turns off under ZCS condition

$$I_{Sa1} = \frac{V_2(1 + nD)}{L_{lk}}(t - t_0). \tag{1}$$

The current $I_{Sa1}$ enters the dotted terminal of the ideal-transformer secondary side, and thus, $nI_{Sa1}$ flows out of the undotted terminal of the primary side. Therefore, $I_{S2}$ and $I_{in}$ equations are as follows:

$$I_{S2} = -\left(\frac{V_2(1 + nD)(n + 1)}{L_{lk}}\right)(t - t_0) \tag{2}$$
$$I_{in} = I_{LM} - nI_{Sa1}. \tag{3}$$

Also, the duration of this interval is

$$t_1 - t_0 = \frac{I_{LM}L_{lk}}{V_2(1 + nD)(n + 1)}. \tag{4}$$

At the end of this interval, $S_{a1}$ current is $I_{LM}/(n + 1)$.
Fig. 3. Equivalent circuit for each operating interval of the proposed converter in boost mode of operation. (a) Interval 1. (b) Interval 2. (c) Interval 3. (d) Interval 4. (e) Interval 5. (f) Interval 6. (g) Interval 7.

Interval 2: \([t_1-t_2]\) [Fig. 3(b)]: At \(t_1\), the body diode of \(S_2\) turns off, and resonance starts between \(L_{lk}\) and \(C_s\). During this resonance, \(C_s\) discharges from \(V_2\) to zero and provides zero-voltage switching (ZVS) condition for \(S_1\) turn-on. The \(S_1\) voltage and \(S_{a1}\) current are

\[
V_{S1} = \frac{nV_2(1-D)}{n+1} + \left(\frac{V_2(1+nD)}{n+1}\right) \cos(\omega_0(t - t_1)) \tag{5}
\]

\[
I_{Sa1} = \frac{I_{LM}}{n+1} + \left(\frac{V_2(1+nD)}{Z_0(n+1)^2}\right) \sin(\omega_0(t-t_{c1})) \tag{6}
\]

where

\[
\omega_0 = \frac{n+1}{\sqrt{L_{lk}C_s}} \quad Z_0 = \frac{\sqrt{L_{lk}}}{n+1} \tag{7}
\]

The duration of this interval is

\[
t_2 - t_1 = \frac{1}{\omega_0} \cos^{-1}\left(\frac{-n(1-D)}{nD+1}\right) \tag{8}
\]

At the end of this interval, the \(L_{lk}\) current is \(I_0\). From (6) and (8), \(I_0\) is as follows:

\[
I_0 = \frac{I_{LM}}{n+1} + \frac{V_2}{Z_0(n+1)^2} \sqrt{n(2D-1) + 1} \tag{9}
\]

Interval 3: \([t_2-t_3]\) [Fig. 3(c)]: At \(t_2\), the body diode of the main switch \(S_1\) is turned on under ZVS condition. When this diode is conducting, the main switch \(S_1\) can be turned on under ZVS condition. During this interval, the voltage across the primary windings of the ideal transformer in the model is \(V_1\). Therefore, the voltage across the secondary winding is \(nV_1\). The negative voltage across the leakage inductor \(L_{lk}\) would
reduce the inductor current linearly to zero. The important equations of this interval are

\[ I_{Sa1} = I_0 - \frac{n(1-D)V_2}{L_{lk}}(t-t_2) \]  
\[ (10) \]

\[ I_{S1} = -(n+1)I_0 + I_{LM} + \frac{n(n+1)(1-D)V_2}{L_{lk}}(t-t_2). \]  
\[ (11) \]

This interval ends when the \( I_{S1} \) current reaches zero and the body diode of \( S_1 \) can be turned off under ZCS condition. The duration of this interval is

\[ t_3 - t_2 = \frac{(n+1)I_0 - I_{LM}}{n(n+1)(1-D)V_2}L_{lk}. \]  
\[ (12) \]

At the end of this interval, the \( S_{a1} \) current is \( I_{LM}/(n+1) \). 

**Interval 4: \([t_3 - t_4]\) [Fig. 3(d)]:** In this interval, the \( S_1 \) current direction changes, and \( I_{S1} \) increases from zero. The \( I_{Sa1} \) current reduces and reaches zero at the end of this interval. The \( S_{a1} \) current equation is as follows:

\[ I_{Sa1} = \frac{I_{LM}}{n+1} - \frac{n(1-D)V_2}{L_{lk}}(t-t_3). \]  
\[ (13) \]

Resetting the auxiliary-switch current to zero guarantees ZCS condition for auxiliary switch at turnoff; thus, the duration of this interval is

\[ t_4 - t_3 = \frac{I_{LM}L_{lk}}{n(n+1)(1-D)V_2}. \]  
\[ (14) \]
Interval 5: \([t_4-t_5]\) [Fig. 3(e)]: During this interval, \(I_{LM}\) flows through \(S_1\). This operating interval is identical to a regular PWM boost converter when the main switch is on.

Interval 6: \([t_5-t_6]\) [Fig. 3(f)]: This interval begins by turning the main switch off. Due to snubber capacitor \(C_s\), the voltage across \(S_1\) changes slowly, and \(S_1\) is turned off under almost ZVS condition. At the end of the interval, \(C_s\) is charged to \(V_2\), and the body diode of the main switch \(S_2\) begins to conduct.

Interval 7: \([t_6-t_0+T]\) [Fig. 3(g)]: This operating stage is identical to a regular PWM boost converter when the main switch is off, and the magnetizing inductor current \(I_{LM}\) is transferred to the output through the body diode of \(S_2\).

### III. Design Considerations

The main buck and boost converter is designed like a regular PWM buck and boost converter. Therefore, it is important to select \(C_s, L_{lk}, n\) and semiconductor devices. Note that \(L_M\) is employed as the converter filter inductor, and thus, it is designed as the inductor filter in a regular buck and boost converter. \(C_s\) provides ZVS condition for the main switches at turnoff instant. Therefore, its value can be selected similar to any snubber capacitor as follows [26]:

\[
C_s > C_{s,\text{min}} = \frac{I_{sw} t_f}{2 V_{sw}}
\]  

(15)

where \(t_f\) is the switch current fall time, \(I_{sw}\) is the switch current before turnoff, and \(V_{sw}\) is the switch voltage after turnoff. In practice, \(C_s\) is considered much larger than \(C_{s,\text{min}}\) to guarantee soft switching.

\(L_{lk}\) provides ZCS condition for the auxiliary switches at turn-on instant. This inductor can be selected according to [26] as follows:

\[
L_{lk} > L_{lk,\text{min}} = \frac{I_{sw} t_r}{V_{sw}}
\]

(16)

where \(t_r\) is the switch current rise time, \(I_{sw}\) is the switch current after turn-on, and \(V_{sw}\) is the switch voltage before turn-on. In practice, \(L_{lk}\) should be larger than \(L_{lk,\text{min}}\) to guarantee soft switching. Note that the snubber values obtained are the minimum values. Using these values may result in very high resonant frequency of auxiliary circuit, which is not practical. In this case, the values should be overdesigned in order to have a reasonable resonant period larger than 1/20 of the switching period.

From (8), it can be observed that, to ensure complete discharge of \(C_s\) to zero in boost mode of operation or charge \(C_s\) to \(V_2\) in buck mode of operation for full duty cycle range, \(n\) must be smaller than or equal to one. So, in order to achieve ZVS condition for the main switches at turn-on in both buck and boost modes of operations, \(n\) must be selected as follows:

\[
n \leq 1.
\]  

(17)

Another consideration for designing \(n\) is the additional stress of auxiliary switches. The additional stress of auxiliary switches in both boost and buck modes is equal to \(n D V_2\). In order to limit this additional voltage stress to 20% of their voltage stress in a regular ZVT converter [13], the following equation should be satisfied:

\[
n D V_2 < 0.2 V_2
\]

(18)

therefore, we have

\[
n < \frac{0.2}{D}.
\]  

(19)

However, a small value of \(n\) would increase the duration of intervals 3 and 4 in both buck and boost modes and increase the auxiliary-switch current stress. Therefore, \(n\) can be selected as follows:

\[
n = \frac{0.2}{D_{\text{max}}}
\]

(20)

where \(D_{\text{max}}\) is the converter maximum duty cycle. From (7), it can be seen that \(n\) affects the resonant frequency \(w_0\). For this reason, the inductor seen by \(C_s\) is equal to \(L_{lk}/(n+1)^2\). Thus, the term \((n+1)\) appears in the resonant frequency \(w_0\). However, according to (20), the value of \(n\) is selected small enough so that the resonant frequency is not affected significantly. The compensation for this value is considered in the overdesign of resonant period.

To ensure that the auxiliary switches are turned off under zero-current condition, they must be unidirectional.

### IV. Implementation of the Control Circuit

Fig. 7 shows the block diagram and the key waveform of the proposed converter control circuit. The converter operation mode is determined by the enable signal \(V_{\text{Enable}}\). When \(V_{\text{Enable}}\) is low, the BDC operates in boost mode, and when \(V_{\text{Enable}}\) is
Fig. 8. (Top waveform) Voltage and (bottom waveform) current of main switch $S_1$ when converter is operating in boost mode. The vertical scale is 50 V/div or 6 A/div, and the time scale is 1 $\mu$s/div.

Fig. 9. (Top waveform) Voltage and (bottom waveform) current of auxiliary switch $S_{a1}$ when converter is operating in boost mode. The vertical scale is 50 V/div or 9 A/div, and the time scale is 1 $\mu$s/div.

Fig. 10. (Top waveform) Voltage and (bottom waveform) current of main switch $S_2$ when converter is operating in buck mode. The vertical scale is 50 V/div or 9 A/div, and the time scale is 1 $\mu$s/div.

Fig. 11. (Top waveform) Voltage and (bottom waveform) current of auxiliary switch $S_{a2}$ when converter is operating in buck mode. The vertical scale is 50 V/div or 9 A/div, and the time scale is 1 $\mu$s/div.

Fig. 12. Efficiency comparison of the proposed soft-switching converter and a hard-switching buck converter versus output power in (a) boost and (b) buck modes.

V. EXPERIMENTAL RESULTS

A prototype of the proposed bidirectional buck and boost converter is implemented at 50 V for $V_1$ and 100 V for $V_2$. The converter operates at 100 kHz and an output power of 240 W.

According to the discussions in the previous section, the designed values for $n$, $L_{lk}$, and $C_s$ are $1/3$, 2 $\mu$H, and 10 nF, respectively. Also, the value of $L_{M1}$ is selected as 360 $\mu$H. For all switches, IRF640 is used. To implement the unidirectional switches, BYV32 is added in series with the auxiliary switches.
Fig. 13. Proposed family of ZVT bidirectional converters with coupled inductors: (a) Buck–boost/buck–boost, (b) Cuk/Cuk, and (c) SEPIC/Zeta.

The experimental results are shown in Figs. 8–11. Figs. 8 and 9 show the voltage and current of the main and auxiliary switches in boost mode of operation, respectively. Also, Figs. 10 and 11 show the voltage and current of the main and auxiliary switches in buck mode of operation, respectively. It can be observed that ZVS condition at turn-on, as well as almost ZVS condition at turnoff, is provided for the main switches. Unlike the soft-switching BDCs in [22] and [24], it can be seen that there are no extra voltage and current stresses on the main switches in both buck and boost modes. Moreover, it can be observed that the ZCS condition at turnoff, as well as almost ZCS condition at turn-on, is provided for the auxiliary switches, in contrast to the soft-switching BDCs in [18] and [19] where the auxiliary switches are turned off under hard-switching condition. The converter efficiency curve is shown in Fig. 12 for both buck and boost modes. The efficiency of the converter at 100 kHz is implemented. Also, other family members of the proposed bidirectional converters have been presented.

VI. OTHER ZVT BDCS WITH COUPLED INDUCTORS

Similar to the bidirectional buck and boost converter, this ZVT technique can be applied to other basic nonisolated bidirectional converters to improve their efficiency, as shown in Fig. 13. In all topology variations, the theoretical operating modes are very similar to the operation of the bidirectional buck and boost converter explained in Section II, and thus, further explanation is neglected.

VII. CONCLUSION

In this paper, a new family of ZVT bidirectional converters with coupled inductors has been introduced. In these converters, soft-switching condition for all semiconductor elements is achieved only by adding two auxiliary switches and coupled inductors for full duty cycle range. The theoretical analysis for a bidirectional buck and boost converter is presented in details. To validate the theoretical analysis, a 240-W prototype of the converter at 100 kHz is implemented. Also, other family members of the proposed bidirectional converters have been presented.

REFERENCES


Mohammad Reza Mohammadi was born in Isfahan, Iran. He received the B.S. degree in electrical engineering from Amir Kabir University of Technology, Tehran, Iran, in 2007 and the M.S. degree in electrical engineering from Isfahan University of Technology, Isfahan, in 2011, where he is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering. His current research interest is soft-switching techniques in bidirectional converters.

Hosein Farzanehfard (M’08) was born in Isfahan, Iran, in 1961. He received the B.S. and M.S. degrees in electrical engineering from the University of Missouri, Columbia, in 1983 and 1985, respectively, and the Ph.D. degree from Virginia Polytechnic Institute and State University, Blacksburg, in 1992. Since 1993, he has been a Faculty Member of the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan. He is the author or coauthor of more than 100 technical papers published in journals and conference proceedings. His current research interests include high-frequency soft-switching converters, pulsed-power applications, power factor correction, active power filters, and high-frequency electronic ballasts.