Letters

A Lossless Turn-ON Snubber for Reducing Diode Reverse Recovery Losses in Bidirectional Buck/Boost Converter

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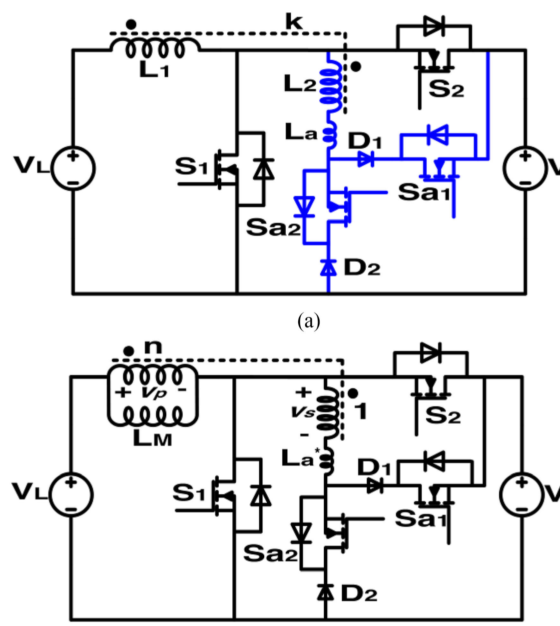
***Abstract*—In this letter, we introduce a simple turn-ON snubber for the conventional bidirectional converter. This snubber notably reduces the current reduction rate of the converter main diodes at turn-OFF. Hence, the reverse recovery losses, which are the dominant losses in the bidirectional converter, are almost eliminated. These features are achieved with a minimum circulating current and no extra voltage or current stress. The conventional bidirectional converter with the proposed snubber is analyzed, and to confirm the analysis, the experimental results are presented.**

***Index Terms*—Bidirectional buck/boost converter (BBC), lossless snubber, soft switching.**

I. Introduction

The bidirectional buck/boost converter (BBC) is comprised of two basic buck and boost converters. This converter is among the most widely used type of the bidirectional converters and recognizes as being the basic structure of the bidirectional converters. The leading problem with this converter is the excessive reverse recovery time of the main diodes. The reason for this problem is that the slow body diode of each switch serves as the converter rectifying diode in the opposite operation. On the whole, the body diodes of the conventional power switches, compared to the existing power diodes, suffer from a substantial reverse recovery time. For this reason, during the turn-ON instant of the main switches, a vast amount of the reverse recovery losses is imposed on the converter. These losses are the dominant losses in the bidirectional converters [1]. This drawback reduces the overall efficiency of the converter, particularly at high switching frequencies. To overcome the abovementioned problem, the soft switching condition should be provided for the BBC. In the soft-switching bidirectional converters, by limiting the current reduction rate of the converter diodes, the reverse recovery time of the diode and reverse recovery losses are reduced [2]. Consequently, the high-frequency switching of the converter with an excellent efficiency will be feasible. Zero voltage transition (ZVT) and active clamping techniques are the most common strategies to achieve the soft-switching condition in the bidirectional converters [2]–[9]. In these methods, one or two auxiliary switches are used, and the zero voltage switching (ZVS) of the main switches at turn-ON is achieved, in addition to the reduction of the diodes current rate at turn-OFF. Albeit the ZVS condition of the main switches is desirable but in these methods, the auxiliary switches turn-ON under zero current switching (ZCS). In fact, the capacitive turn-ON losses of the main switches transfer to the auxiliary switches, especially if the voltage stress of the auxiliary switches is equal [6] or more [7]–[9] than that of the main switches. In addition, in these methods, the current of the diode is reduced to zero in a very short period of time. Hence, the reduction rate of the diode current is not low enough to reduce the diode reverse recovery time efficiently. This point can be clearly seen in the measured waveforms in [2].



(a)

(b)

Fig. 1. Structure of the BBC with the proposed snubber. (a) Proposed converter. (b) Equivalent circuit.

In this letter, a simple lossless snubber is proposed for the BBC. The structure of the BBC with the proposed snubber is illustrated in Fig. 1(a). As can be seen, the proposed snubber is made up of an auxiliary inductor L_a, two auxiliary switches S_{a1} and S_{a2}, two auxiliary diodes D_1 and D_2, and an inductor L_2, which is coupled with the main inductor L_1. In each operation mode, one of the auxiliary switches has always been ON and the other one kept OFF. Hence, in contrast to the soft-switching BBCs in [2]–[9], the auxiliary switches have no switching losses, and there is no need to the additional timing circuits for the auxiliary switches. The proposed snubber provides the minimum current reduction rate for the turn-OFF instants of the diodes. Consequently, the reverse recovery losses of these diodes are almost eliminated. In addition, ZCS condition is provided for the main switches

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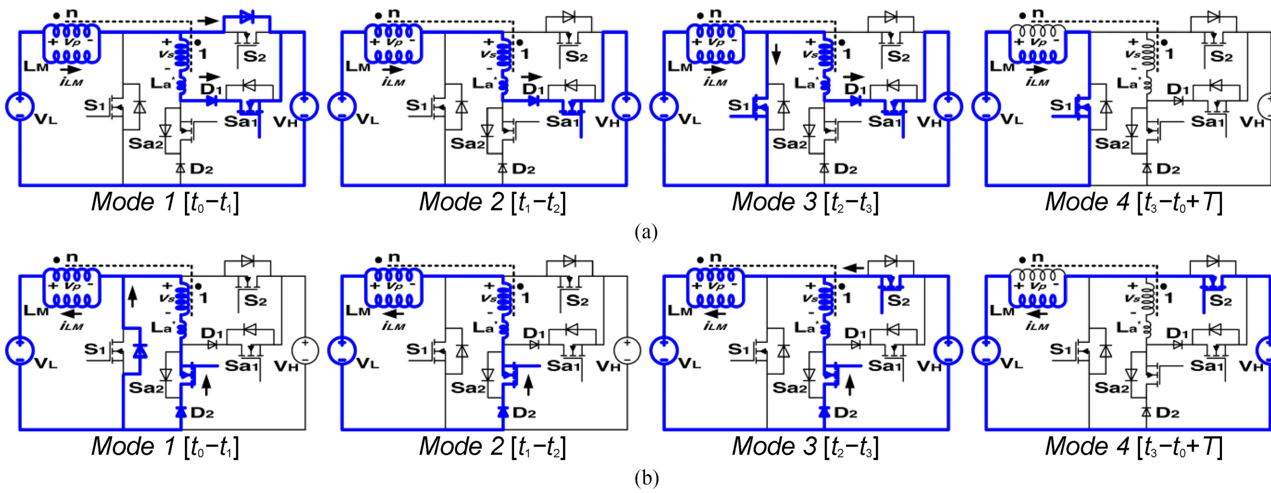

Fig. 2. Operating modes of the proposed converter in (a) boost operation and (b) buck operation.

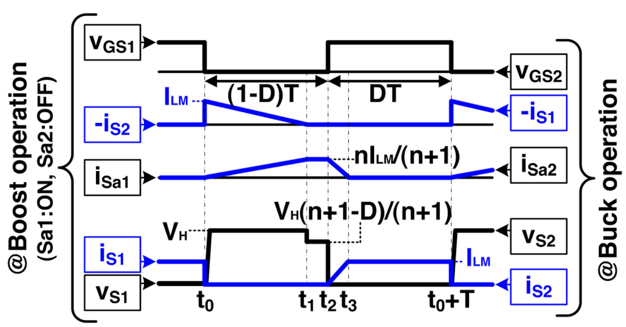

Fig. 3. Converter theoretical waveforms.

at turn-ON. These features are achieved with no additional voltage or current stress and no circulating current. In Section II, the operation of the circuit is described. Design considerations, experimental results, and conclusions are presented in Sections II–IV, respectively.

II. Circuit Operation Analysis

To simplify the analysis, as Fig. 1(b) depicts, the coupled inductors L_1 and L_2 are modeled by a magnetizing inductor L_M $(= L_1)$, a leakage inductor $L_{\rm lk}(= (1 - k^2)L_2)$, and an ideal transformer with a turns ratio $n(= k^{-1}(L_1/L_2)^{1/2})$. Note that, L_a^* is equal to the sum of L_a and $L_{\rm lk}$ $(L_a^* = L_a + L_{\rm lk})$, and L_M is the main converter inductor. The four operating modes of the boost and buck operations are illustrated in Fig. 2. Besides, Fig. 3 depicts the related waveforms. Due to the symmetric operation of the converter in the boost and buck operations, the boost operation is merely discussed. In order to make equations applicable in both the boost and buck operations, all equations are presented based on D. In fact, each equation is true in boost operation if the duty cycle of the main switch S_1 is applied, and similarly, each equation is true in buck operation if the duty cycle of the main switch S_2 is utilized. Note that in a given condition of $V_{\rm L}$ and V_H, the duty cycles of S_1 and S_2 are the complement of each other. In the boost operation, S_{a1} is ON and S_{a2} kept OFF. Besides, S_1 is controlled, S_2 is OFF, and S_2 body diode is the converter main diode. To simplify the analysis, it is assumed that the L_M is large enough and its current $(i_{\rm LM})$ is constant $(i_{\rm LM} = I_{\rm LM})$. Before the mode 1, it is assumed that the converter is at its typical mode when the main switch is ON.

Mode 1 $[t_0–t_1]$*:* At t_0, S_1 turns-OFF. Hence, S_2 body diode turns-ON and $I_{\rm LM}$ flows to V_H. In this condition, the voltages of the primary and secondary sides of the ideal transformer are $–(V_H–V_L)$ and $–(V_H–V_L)/n$, respectively $(v_p = –(V_H–V_L)$ and $v_s = –(V_H–V_L)/n)$. Hence, the voltage $(V_H–V_L)/n$ placed across the L_a^* and its current is linearly increased. Since $V_L = (1–D)V_H$, the current of i_{Sa1} is obtained as

$$i_{Sa1} = \frac{V_H D}{nL_a^*}(t - t_0). \tag{1}$$

In this stage, the current of i_{Sa1} enters the dotted terminal of the secondary side, hence, $(i_{Sa1})/n$ exits the dotted terminal of the primary side. Consequently, the current of the S_2 body diode is as follows:

$$-i_{S2} = I_{\rm LM} - \frac{(n+1)V_H D}{n^2 L_a^*}(t - t_0). \tag{2}$$

According to (2), the current of S_2 body diode is reduced to zero with a limited rate. Hence, at the end of this mode, the S_2 body diode is turned OFF. In this condition, the reverse recovery time of the diode is considerably reduced. From (2), the current reduction rate of the S_2 body diode is obtained as follows:

$$\left|\frac{di_{S2}}{dt}\right| = \frac{(n+1)V_H D}{n^2 L_a^*}. \tag{3}$$

In this mode, the output current is shared between the S_2 body diode and S_{a1}. At the end of this mode, i_{Sa1} is equal to $nI_{\rm LM}/(n+1)$. The duration time of this mode is as follows:

$$t_1 - t_0 = \frac{n^2 L_a^* I_{\rm LM}}{(n+1)V_H D}. \tag{4}$$

Mode 2 $[t_1–t_2]$*:* In this mode, the current of the S_2 body diode has completely diverted to S_{a1} and $I_{\rm LM}$ flows to V_H through S_{a1}. As can be seen from Fig. 3, the sum of the duration times of the modes 1 and 2 is equal to $(1–D)T$. By using (4), the duration time of mode 2 is obtained as follows:

$$t_2 - t_1 = (1 - D)T - \frac{n^2 L_a^* I_{\rm LM}}{(n+1)V_H D}. \tag{5}$$

Mode 3 [t_2–t_3]*:* At t_2, S_1 turns-ON. In this condition, the voltage V_L appears across the primary side of the ideal transformer and so the voltage on the secondary side would be V_L/n. Hence, the voltage $-(V_H + V_L/n)$ is placed across L_a^*, S_{a1} current reduces linearly to zero, and D_1 turns-OFF under the ZCS condition. Recall that $V_L = V_H(1–D)$, the current of i_{Sa1} is obtained as follows:

$$i_{Sa1} = \frac{nI_{\rm LM}}{n+1} - \frac{V_H(n+1-D)}{nL_a^*}(t-t_2). \quad (6)$$

In this mode, similar to stage 1, the current of i_{Sa1} enters the dotted terminal of the secondary side, hence, $(i_{Sa1})/n$ exits the dotted terminal of the primary side. Consequently, the current of the main switch S_1 is as follows:

$$i_{S1} = \frac{V_H(n+1)(n+1-D)}{n^2 L_a^*}(t-t_2). \quad (7)$$

According to (7), the current of S_1 is linearly increased from zero to $I_{\rm LM}$. Consequently, S_1 turns-ON under ZCS.

Mode 4 [t_3–t_0+T]*:* The converter is at its typical mode when the main switch is ON.

III. Design Considerations

In this section, the values of the proposed snubber elements are designed. The inductor $L_{\rm M}$ is the main converter inductor and designed similar to the main inductor of the conventional boost or buck converters. Typically, to operate the converter in continuous conduction mode (CCM), L_M is designed to ensure that the converter operates in CCM at load condition above 20% of full load.

To achieve the minimum rate of the body diode current before the turn-OFF instant, the duration time of mode 1 should be maximized. On the other hand, the diode current must reach zero before the main switch turn-ON instant. Otherwise, a short circuit occurs through the loop of the high-voltage side (V_H), the main switch, and main diode. To avoid this problem, the duration time of mode 2 is considered as the dead time between the main diode turn-OFF and main switch turn-ON. By considering a proper dead time about 10% of switching period (0.1T) for mode 2 and using (5), the following condition must satisfy:

$$(1-D)T - \frac{n^2 L_a^* I_{\rm LM}}{(n+1)V_H D} > 0.1T. \quad (8)$$

Another important issue in the proposed converter is the voltage stress of the auxiliary switches, which in both the boost and buck operations is equal to $(DV_H)/n$. In mode 4, this voltage is placed on the auxiliary switch that is OFF. To limit the voltage stress of the auxiliary switches under 20% of the high-voltage side (V_H), the following condition should satisfy:

$$n > \frac{D}{0.2}. \quad (9)$$

Hence, by selecting n as in (9), it is feasible to utilize the low-voltage switches with a very low ON-state resistance $R_{\rm DS}$(ON) as the auxiliary switches. Hence, the additional conducting losses of the auxiliary switches are negligible. Finally, from (8), the value of L_a^* is designed as follows:

$$L_a^* < \frac{(0.9-D)(n+1)V_H D}{I_{\rm LM} n^2 f} \quad (10)$$

where f is the converter switching frequency. Note, L_a^* should design for the condition that the right-hand side of (10) is minimized. Hence, by selecting the value of L_a^* according to (10), the minimum current rate of the body diode current before the turn-OFF instant is achieved.

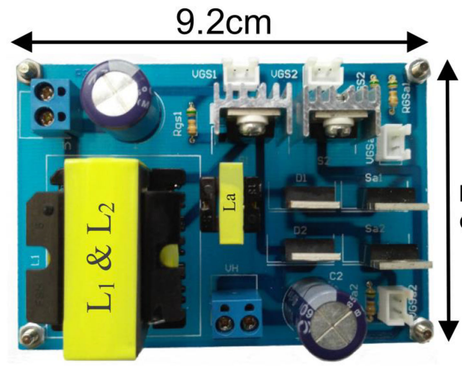

Fig. 4. Photo of the prototype.

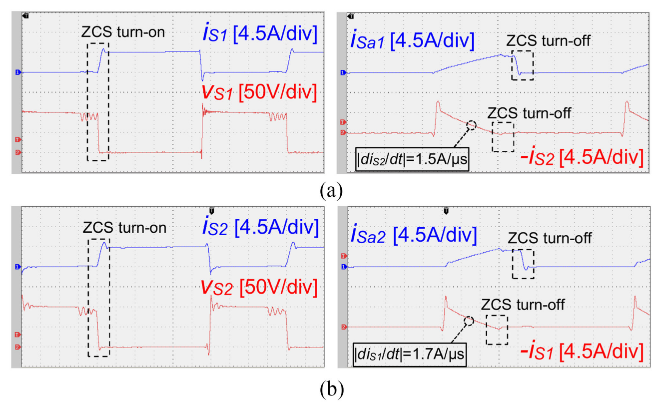

Fig. 5. Experimental waveforms (time scale is 1 μs/div) in (a) boost mode and (b) buck mode.

As mentioned before, the value of L_a^* is equal to $L_a + L_{\rm lk}$. Hence, the value of L_a is selected as follows:

$$L_a = L_a^* - L_{\rm lk}. \quad (11)$$

IV. Experimental Results

To confirm the theoretical analysis, a 200-W prototype of the BBC with the proposed snubber has implemented under the condition of $V_L = 50$ V, $V_H = 100$ V, and $f = 100$ KHz. The values of L_M and n has been selected as 420 μH and 4, respectively. The derived $L_{\rm lk}$ is about 1.3 μH. From (10), the maximum value of L_a^* is obtained 15.6 μH. Hence, from (11), the maximum value of L_a can be 14.3 μH. L_a is selected as 13 μH. The MOSFET IRF640 ($V_{\rm DS} = 200$ V, $R_{\rm DS}(on) = 180$ mΩ) is utilized for the main switches, and for the auxiliary switches, MOSFET IRF3205 ($V_{\rm DS} = 55$ V, $R_{\rm DS}({\rm ON}) = 8$ mΩ) is applied. Besides, for the diodes D_1 and D_2, the ultrafast diode BYV32 is used. Fig. 4 illustrates the implemented prototype. The measured waveforms of the implemented converter are illustrated in Fig. 5. As can be seen, the ZCS condition of the main switches (S_1 in boost mode and S_2 in buck mode) at turn-ON and almost ZVS condition at turn-OFF (due to the intrinsic capacitor of the switch) are achieved. In addition, the reduction rates of the converter main diodes (S_2 body diode in boost mode and S_1 body diode in buck mode) at turn-OFF are considerably low and so the reverse recovery currents of the diodes are almost eliminated. The measured current rates of the main diodes at turn-OFF in boost and buck modes are about 1.5 and 1.7 A/μs, respectively. Besides, there is no circulating current in the circuit and the voltage or current stress of the main switches is at its minimum value. Table I

TABLE I
COMPARISON OF THE CURRENT REDUCTION RATE OF THE CONVERTER MAIN DIODE AT TURN-OFF IN BOOST OPERATION BETWEEN THE PROPOSED CONVERTER AND PREVIOUSLY PROPOSED SOFT-SWITCHED BBCS

	ZVT BBC in [5]	ZVT BBC in [2]	Active clamped BBC in [9]	Proposed converter
Current rate of the main diode at turn-OFF	32* A/μs	26** A/μs	16*** A/μs	1.5 A/μs

* condition of V_L=70 V, V_H=100 V, P=150 W and f=100 KHz
** condition of V_L=135 V, V_H=200 V, P=250 W and f=100 KHz
*** condition of V_L=100 V, V_H=400 V, P=500 W and f=100 KHz

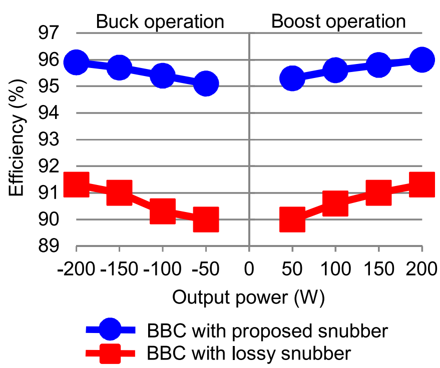

Fig. 6. Efficiency curves of the proposed converter and the BBC with a lossy snubber.

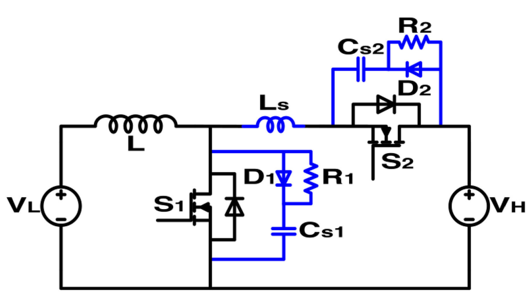

Fig. 7. Structure of a BBC with a lossy snubber.

shows the comparison of the current rates of the main diodes at turn-OFF between the proposed converter and the previously proposed soft-switched BBCs. The efficiency curves of the proposed converter and the conventional BBC with a lossy snubber are demonstrated in Fig. 6. As seen, the proposed snubber provides an excellent efficiency over a wide load range. The structure of the BBC with a lossy snubber is shown in Fig. 7. In this converter, an additional snubber inductor is applied in series with one of the main switches to reduce the reverse recovery current of the slow body diodes. Otherwise, due to the high-frequency operation of the hard-switching converter, the main switches would destroy. Besides, to absorb the energy of the snubber inductor, the resistor–capacitor–diode snubber is utilized.

V. CONCLUSION

A lossless turn-ON snubber for the conventional BBC was introduced, in this paper. By utilizing this snubber, the current rate of the slow diodes of the converter at turn-OFF instants was notably reduced. Hence, the reverse recovery losses of BBC, which were the dominant losses, was almost eliminated. The experimental results of a 200 W-100 KHz prototype showed a current rate of about 1.5 A/μs in the boost mode and 1.7 A/μs in the buck mode for the converter main diodes at turn-OFF.

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