A Soft Switching PWM DC-DC Boost Converter with Increased Efficiency by Using ZVT-ZCT Techniques

Yakup Sahin, Naim Suleyman Ting, Ismail Aksoy

***Abstract*—**In this paper, an improved active snubber cell is proposed on account of soft switching (SS) family of pulse width modulation (PWM) DC-DC converters. The improved snubber cell provides zero-voltage transition (ZVT) turn on and zero-current transition (ZCT) turn off for main switch. The snubber cell decreases EMI noise and operates with SS in a wide range of line and load voltages. Besides, all of the semiconductor devices in the converter operate with SS. There is no additional voltage and current stress on the main devices. Additionally, extra voltage stress does not occur on the auxiliary switch and its current stress is acceptable value. The improved converter has a low cost and simple structure. The theoretical analysis of converter is clarified and the operating states are given in detail. The experimental results of converter are obtained by prototype of 500 W and 100 kHz. It is observed that the experimental results and theoretical analysis of converter are suitable with each other perfectly.

***Keywords*—**Active snubber cells, DC-DC converters, zero-voltage transition, zero-current transition.

I. Introduction

PULSE width modulation (PWM) DC-DC converters are widely used in industry because of their wonderful dynamic performance, simplicity, cheapness and easy control [1]. The high switching frequency is required in DC-DC converters. When the switching frequency is high, power density increases, and cost decreases since the size of inductance, capacitor, and transformer decreases in the high frequencies. With the increased switching frequency, the switching losses increase and electromagnetic interference (EMI) happen. These disadvantages decrease the total efficiency and system performance. Therefore, zero voltage switching (ZVS) and zero current switching (ZCS) techniques are improved in order to reduce switching losses.

In the fundamental zero voltage transition (ZVT) converter, while the main switch is in the off state, the voltage of main switch is reduced to zero by aid of snubber cell that it has an active component [2]. Then a turn on signal is applied to the gate of the main transistor while its voltage is zero. Thus, the main switch turns on without loss by ZVS. Additionally, the main diode is turned off with ZCS and the auxiliary switch is turned on with ZCS. On the other hand, the turn off the main transistor is not good enough and the turn off the auxiliary transistor occurs with hard switching (HS). Many studies have been made to overcome these problems [3]-[6].

In the fundamental zero current transition (ZCT) converter, firstly the current of main switch is dropped to zero by aid of snubber cell that has an active component while the main switch is in on state [7]. Then turn on signal applied to the gate of the main transistor is turned off while its current is zero. So, the main switch turns off lossless by ZCS. In addition to, the main diode is turned on with SS and the auxiliary switch is turned on with ZCS. On the other hand, the turning on of the main switch, the turning off for the auxiliary switch and the main diode occurs with HS. The main diode has a high reverse recovery loss. Many studies have been made to overcome these problems in ZCT technique [8]-[11].

The turning off without switching loss is provided owing to ZCT while the turning on without switching loss is provided owing to ZVT. Many studies have been made to eliminate disadvantages in these techniques. However, these studies have many drawbacks as HS, high EMI, current or voltage stress. The best solution of the overcoming these drawbacks is combines ZCT and ZVT techniques. Many studies have been made on the subject of combining ZCT and ZVT [12]-[14].

In [6], it is made a novel study for overcoming disadvantages of ZVT technique. In this study, the main switch is turned on with ZVT and the main diode is turned off with ZCS. Besides, the auxiliary switch is turned on and turned off with ZCS. In the converter, current and voltage stress does not occur on any component except acceptable current stress on the auxiliary switch. However, in this converter, the turning off of main switch is not SS. It is shown on Fig. 1.

In [6], the switching loss occurring during turn off leads to both warming problems and reducing total efficiency. It needs to increase snubber inductance or decrease snubber capacitance for reducing turn off losses in this converter. Nevertheless, increasing the snubber inductance increases the cost and decreases the total power density since in the converter it has enough high value. Likewise, decreasing the snubber capacitor leads to less ZVT interval. In that case, converter cannot provide a sufficient soft switching.

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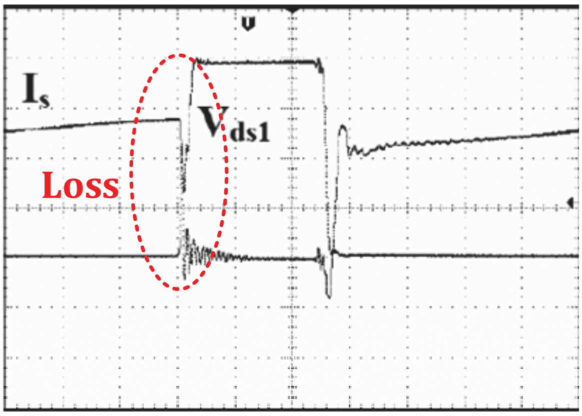

Fig. 1 Voltage and current waveforms of main switch [6]. 100 V/div, 2A/div, 1µs/div

A control method is offered in order to overcome all of these problems. In this converter that control method is changed, ZVT is provided in turn on interval and ZCT is provided in turn off interval. This operating mode of converter is called ZVT-ZCT. The cost is minimized and the power density is increased by reducing value of elements used in snubber cell owing to ZVT-ZCT. Thus, total efficiency of converter is increased. The improved converter is shown on Fig. 2.

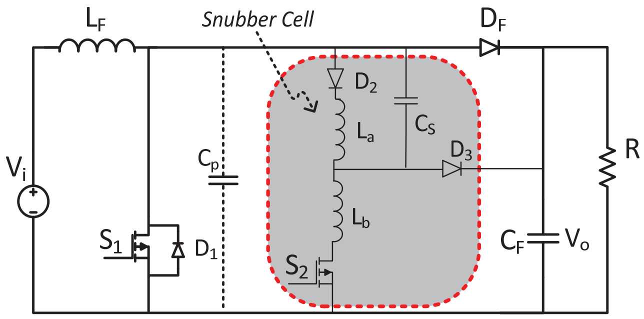

Fig. 2 The proposed improved ZVT-ZCT PWM DC-DC Converter

II. Operating Stages

Twelve stages occur in the steady state operation of the converter in one switching period. The equivalent circuits of these intervals are shown in Fig. 3.

A. Stage 1 [$t_0<t<t_1$- Fig. 3 (a)]

At the $t<t_0$, the main switch S_1 and the auxiliary switch S_2 are in turn off state. The main diode D_F conducts the input current I_i. The voltage of parasitic capacitor V_{Cp} is set to output voltage V_0 and the voltage of snubber capacitor V_{Cs} is zero.

At the beginning of moment $t=t_0$, a turn on signal is applied to auxiliary switch S_2 and a resonance occurs between L_a-L_b-C_s. The current of main diode D_F falls while the current of auxiliary switch S_2 rises simultaneously.

At the $t=t_1$, the current of main diode D_F falls to zero when the current of snubber inductance L_b reaches to input current I_i and this interval is finished. Consequently, the auxiliary switch S_2 is turned on with ZCS because of series resonance inductances L_a and L_b and the main diode D_F is turned off with ZCS. It is noticed that the current of auxiliary switch is equal to the current of snubber inductance L_b during all of intervals.

B. Stage 2 [$t_1<t<t_2$- Fig. 3 (b)]

At the $t=t_1$ the main diode D_F is turned off and this interval begins. Then, a new resonance begins between parasitic capacitor C_p and the snubber cell via C_p-L_a-L_b-C_s. The voltage of parasitic capacitor V_{Cp} is zero when the energy of C_p transfer to snubber cell and the internal diode D_1 of main switch is turned on with ZVS. This interval is finished as soon as D_1 is turned on at the $t=t_2$. In here C_p is parasitic capacitor of the main switch and the sum of other parasitic capacitors.

C. Stage 3 [$t_2<t<t_4$- Fig. 3 (c)]

At the beginning of this interval, internal diode D_1 is turned on under ZVS and the resonance via L_a-L_b-C_s goes on. At the same time, D_1 conducts the excess of input current. It is called ZVT interval where D_1 is turned on and the turn on signal is applied to the main switch S_1 in the middle of this interval. In this way, the main switch S_1 is turned on as lossless with ZVT. D_1 is turned off when the current of snubber inductance L_b falls to the input current level at the $t=t_3$. The main current increases and the current of snubber inductance L_b continues to decrease as soon as D_1 is turned off. At the $t=t_4$, the current of snubber inductance L_b falls to zero when the current of main switch S_1 reaches to input current value and this interval is finished.

D. Stage 4 [$t_4<t<t_5$- Fig. 3 (d)]

At the beginning of this interval that the current of S_1 reaches to the input current value, the auxiliary switch S_2 is turned off because the current of S_2 falls to zero. So, S_2 is turned off with ZCS. The energy stored in upper snubber inductance L_a is transferred to capacitor C_s via L_a-D_3-C_s resonance.

At the $t=t_5$, the voltage of capacitor C_s reaches to maximum voltage value and this interval is finished.

E. Stage 5 [$t_5<t<t_6$- Fig. 3 (e)]

This interval is conventional boost converter, the main switch S_1 conducts the input current I_i.

F. Stage 6[$t_6<t<t_8$- Fig. 3 (f)]

At the $t=t_6$, the turn on signal of the auxiliary switch S_2 is applied and this interval begins. S_2 is turned on with ZCS because of series snubber inductance L_b. A resonance starts between the snubber capacitor C_s and the snubber inductance L_b. The current of the main switch S_1 begins to decrease while the current of snubber inductance L_b is increasing.

At the $t=t_7$, the current of S_1 falls to zero and the interval diode D_1 conducts when the current of L_b reaches to the input current value. D_1 conducts the excess of input current. It is called ZCT interval where D_1 is turned on and the turn on signal of the main switch S_1 is cut off in the middle of this interval. In this way the main switch S_1 is turned off as lossless with ZCT. At the same time, the resonance via C_s-L_b-S_2-D_1 goes on.

At the $t=t_8$, when the voltage of snubber capacitor C_s falls to zero, the current of snubber inductance L_b reaches to maximum value and this interval is finished.

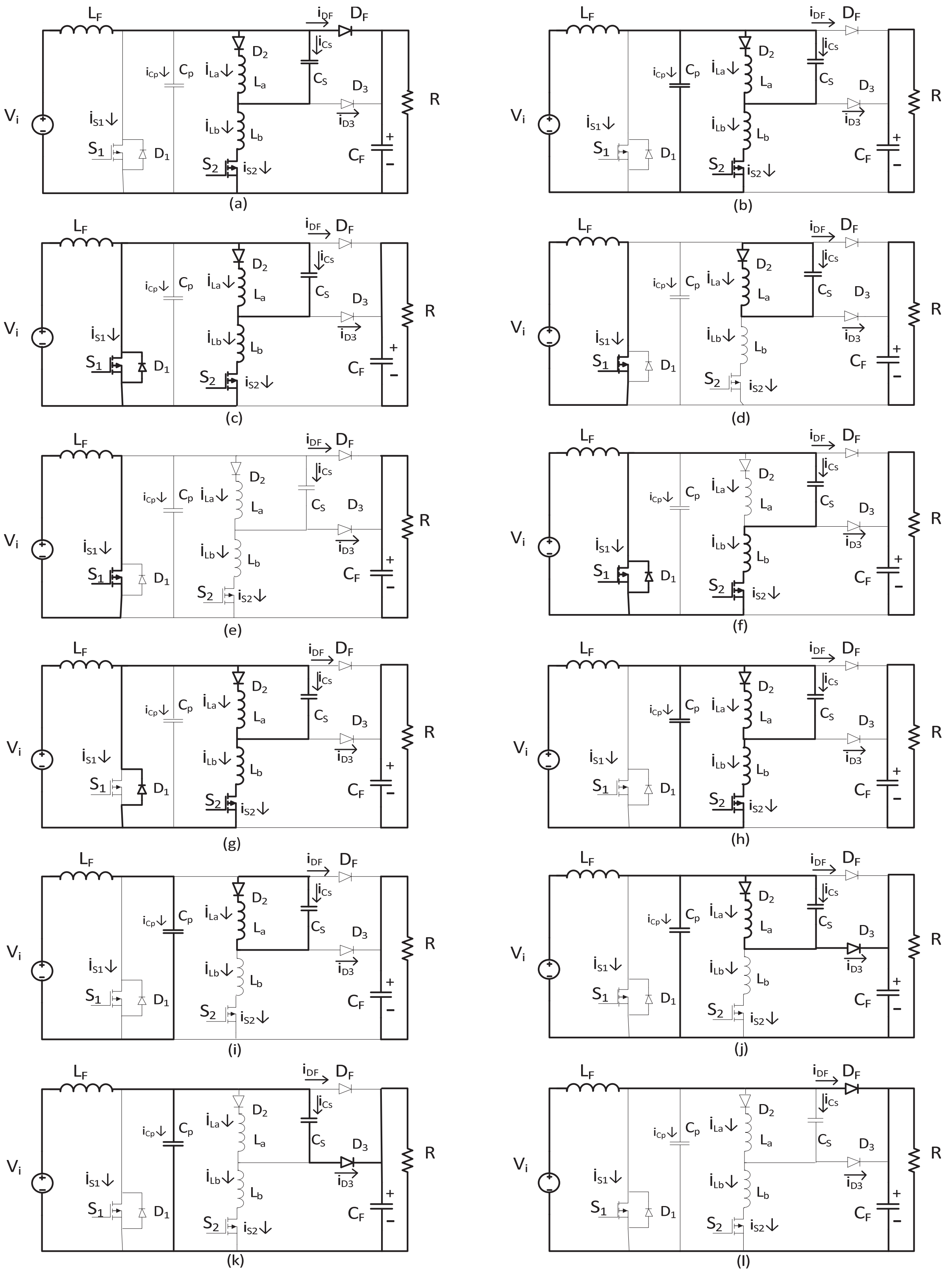

Fig. 3 Equivalent circuit schemes of the operation modes

G. Stage 7[$t_8<t<t_9$- Fig. 3 (g)]

At the $t=t_8$, D_2 is turned on and a resonance occurs via L_a-L_b-C_s-S_2-D_1 when the voltage of snubber capacitor C_s begins to become positive.

At the $t=t_9$, D_1 is turned off as soon as the current of L_b falls to the input current value and this interval is finished.

H. Stage 8[$t_9<t<t_{10}$- Fig. 3 (h)]

At the $t=t_9$ this interval begins when D_1 is turned off, a resonance occurs via C_p-L_a-L_b-C_s under the constant input current. During this interval, the current of snubber inductance L_b decreases and it falls to zero at the $t=t_{10}$. The turn on signal of S_2 is cut off when the current of it falls to zero. So, S_2 is turned off with ZCS and this interval finished.

I. Stage 9[$t_{10}<t<t_{11}$- Fig. 3 (i)]

In this mode, two different circuits occur. The parasitic capacitor C_p is linearly charged under the constant input current and the energy stored in the upper snubber inductance L_a is transferred to the C_s via L_a-D_2-C_s resonance.

At the $t=t_{11}$, the sum of voltage C_p and C_s equal to output voltage and this interval finished.

J. Stage 10[$t_{11}<t<t_{12}$- Fig. 3 (j)]

At the $t=t_{11}$, D_3 is turned on and a resonance via C_p-L_a-C_s occurs under the constant input current. All of the energy stored in the snubber inductance is transferred to C_s and output at the $t=t_{12}$. So, this interval is finished.

K. Stage 11[$t_{12}<t<t_{13}$- Fig. 3 (k)]

At the $t=t_{12}$, the current of L_a falls to zero and this interval begins. In this mode, the parasitic capacitor C_p is linearly charged under the constant input current and C_s is linearly discharged to the output.

At the $t=t_{13}$, the voltage of C_p reaches to the output voltage and the voltage of C_s falls to zero. Consequently, D_F is turned on and this interval finished.

L. Stage 12[$t_{13}<t<t_{14}$- Fig. 3 (l)]

In this interval begins when the main diode D_F is turned on, the input current is transferred to the output through D_F. This mode is conventional PWM boost converter turned off interval. Thus, it is returned to initial conditions and the intervals expressed is repeated in the next switching cycle.

III. Experimental Results

It is realized a prototype of improved ZVT-ZCT PWM DC-DC boost converter with 500 W and 100 kHz at laboratory and the experimental circuit scheme of the improved converter is given in Fig. 4. The experimental results of the converter are shown in between Figs. 5-9.

The main inductance L_F is determined as 1 mH that holds constant the input current in basic converter. The diode D_F is main diode of boost converter. S_1 is main switch and D_1 is internal diode. In the snubber cell, S_2 is auxiliary switch, L_a and L_b are snubber inductances, D_2 and D_3 are auxiliary diodes and C_s is snubber capacitor.

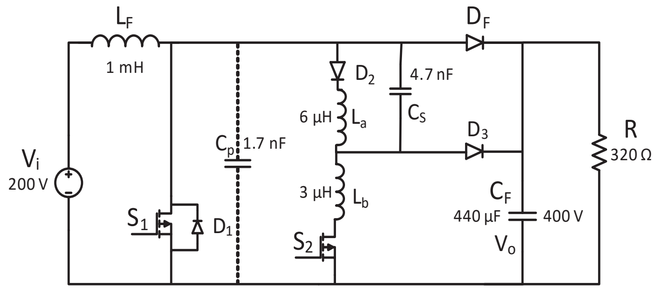

Fig. 4 Prototype of experimental circuit

The experimental current and voltage waveforms of the main switch are given in Fig. 5. The voltage of main switch is fallen to zero with the aid of the snubber cell before the main switch is turned on. Then, the main switch is lossless turned on with ZVT while the internal diode of main switch conducts. Likewise, the current of main switch is fallen to zero with the aid of the snubber cell before the main switch is turned off. Then, the main switch is lossless turned off with ZCT while the internal diode of main switch conducts. It is seen that there is not any voltage and current stress on the main switch.

It is shown the current and the voltage waveforms of auxiliary switch obtained from experimental results is given in Fig. 6. It is seen that there is not any voltage stress on the auxiliary switch. The current stress on the auxiliary switch is an acceptable value. This switch is softly turned on and turned off with ZCS.

It is shown the current and the voltage waveforms of main diode obtained from experimental results is given in Fig. 7. The reverse recoveries of the main diode D_F are minimum value because it is turned off with ZCS and turned on with ZVS. It is seen that there is not any voltage and current stress on the main diode.

It is seen in Fig. 8 that the voltage value of snubber capacitor is an appropriate value. It is shown the experimental results of currents of L_a and L_b in Fig. 9 respectively.

Theoretical analysis and experimental results show that ZVT-ZCT PWM DC-DC boost converter excellently assures to soft switching for all of the semiconductors without never the voltage and the current stress.

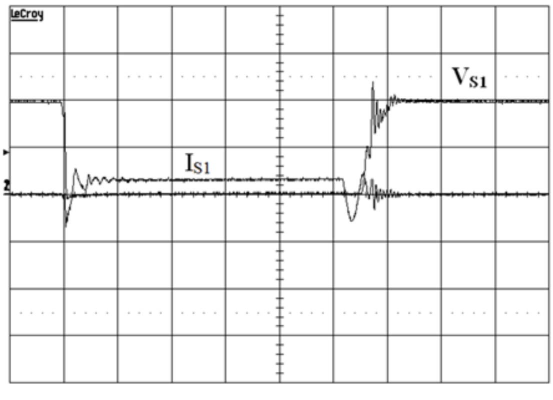

Fig. 5 The current and the voltage of main switch in experimental results (200 V/div, 10A/div and 1 µs/div)

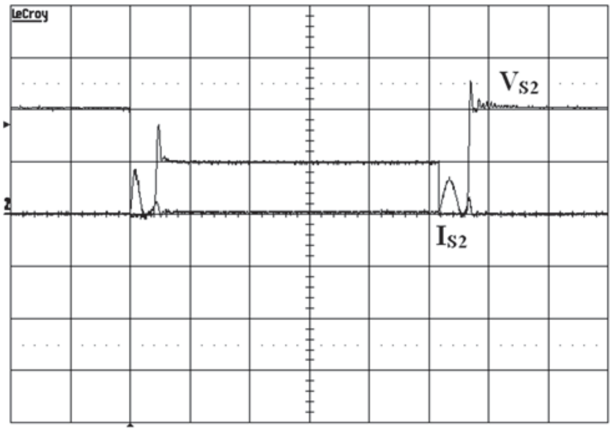

Fig. 6 The current and the voltage of auxiliary switch in experimental results (200 V/div, 10A/div and 1 μs/div)

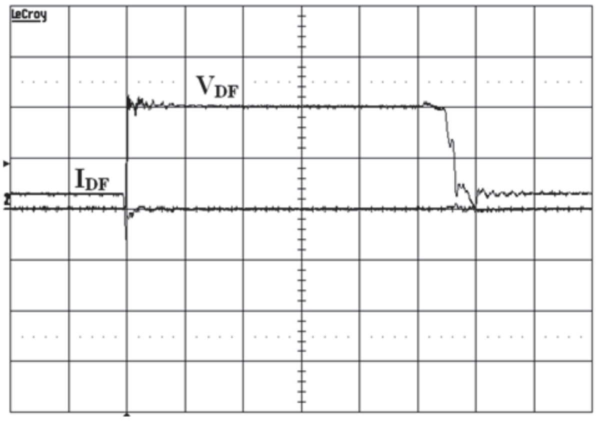

Fig. 7 The current and the voltage of main diode in experimental results (200 V/div, 10A/div and 1 μs/div)

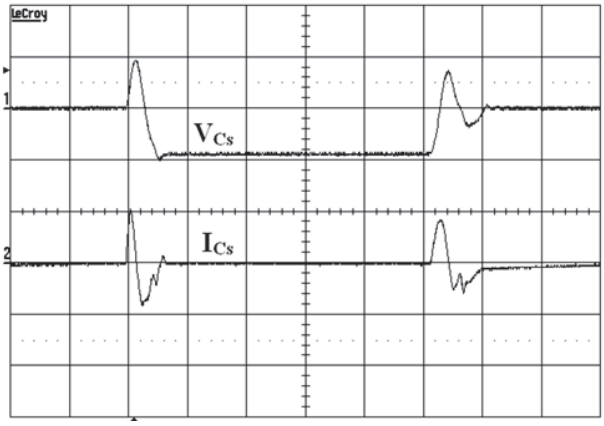

Fig. 8 The current and the voltage of snubber capacitor in experimental results (200 V/div, 10A/div and 1 μs/div)

Total efficiency of the proposed converter is equal to 98.4% at nominal power. In [6], total efficiency of converter is determined by 97.6% at the same operational conditions. So, it seems that the total efficiency of proposed converter is improved by using both of ZVT and ZCT techniques.

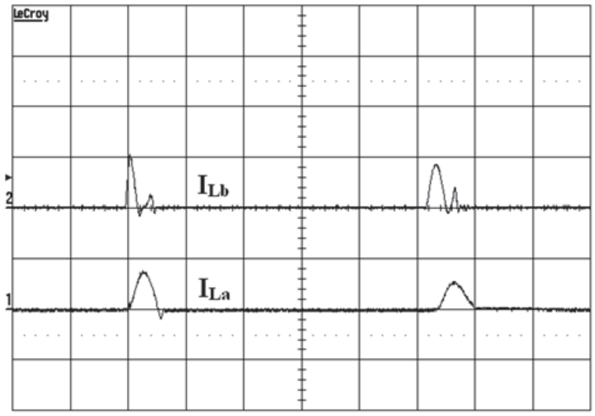

Fig. 9 The currents of snubber inductances La and Lb in experimental results (200 V/div, 10A/div and 1 μs/div)

IV. Conclusions

In this paper, an improved ZVT-ZCT-PWM DC-DC boost converter with active snubber cell is proposed. The improved converter has advantages of the previous ZVT and ZCT studies and also it eliminates disadvantages of them. The snubber cell of the proposed converter operates in a little part of the period and provides ZVT turn on and ZCT turn off for the main switch in a lossless manner. Moreover, it provides ZVS turn on and ZCS turn off for the main diode. Thus, it minimizes the reverse recovery losses of the main diode. This improved converter does not compose any extra voltage or current stress on the main devices.

The extra voltage stress does not occur on the auxiliary switch and it turns on and turns off with ZCS. Additionally, the current stress on the auxiliary switch is acceptable level. The extra current or voltage stress does not occur on the other auxiliary elements and all of them operate under soft switching.

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