Zero-Voltage-Transition Topologies for Cúk Converters

Ching-Jung Tseng Chern-Lin Chen
Power Electronics Laboratory
Department of Electrical Engineering
National Taiwan University
Taipei, Taiwan

Abstract - With continuous input and output current, wide output voltage range and small output filter, Cúk topology has gathered more and more attention in recent years. Soft switching is especially important to a Cúk converter because the power handling capability requirements of semiconductor devices are higher than those of other topologies. Several kinds of zero-voltage-transition (ZVT) topologies newly proposed can be applied to Cúk converters to achieve soft switching. These ZVT topologies combine both merits of conventional PWM converters and resonant converters. The power switches in the ZVT topologies commute under zero-voltage-switching by aid of resonant snubber cells during short ZVT time. Circuit operations are identical to common PWM topologies during rest time. Four classes of ZVT topologies for Cúk converters with power MOSFET's employed as power switches are discussed in this paper. Qualitative descriptions and experimental results are presented to illustrate each class of ZVT topology.

I. INTRODUCTION

Most DC/DC converters and power factor correctors use pulse-width-modulated (PWM) techniques as control. PWM technique prevails against other control techniques for its high power capability and ease of control. Higher power density and faster transient response of PWM converters can be achieved by increasing the switching frequency. However, as the switching frequency increases, so do the switching losses and EMI noises. High switching losses reduce the power handling capability and serious EMI noises interfere the control of PWM converters.

Cúk converters have been widely used as dc-dc converters and power factor correctors since first introduced in 1977 [1-3]. It is praised for the continuous input and output current, ripple-free input current, small output filter and wide output voltage range. However, as shown in Fig. 1, the switch utilization factor of the Cúk topology is much lower than the buck topology and the boost topology [4]. In other words, the power handling capability requirements of the semiconductor devices of a Cúk converter are much higher than those of a buck converter or a boost converter with the same output power. Reduction of switching losses and EMI noises are especially important to a Cúk converter.

To eliminate switching losses and EMI noises, a number of zero-voltage-transition (ZVT) topologies

have been proposed in recent years [5-9]. These ZVT topologies use auxiliary switches and other passive components to form shunt resonant snubber cells. Switching losses and EMI noises are reduced because the shunt resonant snubber cell helps the power switch to commute under zero-voltage-switching during short ZVT transient time. The operation principles are identical to common PWM topologies during the rest time. Control strategies and design rules of PWM topologies can be directly applied to ZVT topologies. Advantages of the conventional PWM converters and resonant converters are both maintained in ZVT converters. Several kinds of ZVT topologies can be applied to Cúk converters to reduce switching losses and EMI noises. Four classes of ZVT topologies for Cúk converters with power MOSFET's employed as power switches are discussed in this paper. Qualitative descriptions and experimental results are presented to illustrate each class of ZVT topology.

Po : Output power, Pt : (Switch V stress)*(Switch I stress)
Fig. 1. Switch utilization factors in switching circuits

II. THE ZVT TOPOLOGIES FOR CÚK CONVERTERS

To eliminate switching losses and EMI noises in Cúk converters when power MOSFET's are used as power switches, several kinds of ZVT topologies are proposed recent years. Among them, four classes of ZVT topologies are deemed desirable to Cúk converters. Circuit structures and qualitative characteristics of these four ZVT Cúk converters are presented in this section.

A. Class A ZVT Topology

The ZVT topology first introduced in [5] can be applied to a Cúk converter as shown in Fig. 2(a). It is named by class A ZVT topology hereafter in this paper. It differs from a conventional PWM Cúk converter by possessing an additional resonant snubber cell consisting of a resonant inductor (L_r), a resonant capacitor (C_r), an auxiliary switch (S_2) and an auxiliary

diode (D_2). The resonant capacitor C_r also incorporates the output capacitance of the power MOSFET. An additional diode in series with the resonant inductor or the auxiliary switch is required in practical use. This diode can prevent the resonant inductor from resonating with output capacitance of the auxiliary switch after the auxiliary diode is turned off. Key waveforms of the class A ZVT topology are shown in Fig. 2(b).

(b) Key waveforms of the class A ZVT Cuk converter
Fig. 2. Circuit diagram and key waveforms of the class A ZVT Cuk converter

The features of the class A ZVT topology are summarized as follows:

Advantages:

- Minimum voltage and current stresses of switches and diodes

The voltage and current stresses of the main switch are identical to those in an ideal lossless Cuk converter. They are even smaller than those of a hard switching Cuk converter considering voltage and current spikes during transients. The auxiliary switch has the same voltage stress as the main switch while the current stress is less than that of the main switch because it only handles small amounts of resonant transition energy [8]. Voltage and current stresses of the main diode are the same as the main switch and those of the auxiliary diode are the same as the auxiliary switch. The active and passive switches in the class A ZVT topology are subjected to minimum voltage and current stresses.

Disadvantages:

- Hard switching for the auxiliary switch and diode

The auxiliary switch and diode in the class A ZVT topology do not operate under soft switching. It can be seen from Fig. 2(b) that hard switching of these two semiconductor devices occur when the auxiliary switch turns off at t_3 . Not only the

resulted switching losses, but also the dv/dt EMI noises significantly reduce the performance of the class A ZVT Cuk converter.

- Discharge of resonant inductor limited

The main switch S_1 has to turn off after discharge of the resonant inductor L_r is accomplished. It lengthens the minimum duty cycle of the main switch. Long minimum duty cycle not only increases minimum acceptable output voltage range but also makes the class A topology not suitable to be employed under wide duty range applications.

- An additional saturable reactor required

In the class A ZVT topology, the main diode and the auxiliary diode are essentially in parallel. When the main diode is conducting, a certain percentage of current will flow through the auxiliary diode. This undesirable feature will cause considerable switching loss when the auxiliary switch turns on. An additional saturable reactor placed in series with the resonant inductor is required.

B. Class B ZVT Topology

A modification of the class A ZVT topology proposed by the authors yields the class B ZVT topology as shown in Fig. 3(a). The major difference between the class A and class B ZVT topologies is the discharge path of the resonant inductor. The anode of auxiliary diode D_2 is connected to the output instead of the anode of main diode D_1 . Several distinct advantages are acquired but no additional component is needed compared with the class A ZVT topology. The control IC's UC3855 and ML4822 designed for class A ZVT topology can be used in this topology as well. Key waveforms of the class B ZVT topology are shown in Fig. 3(b).

(b) Key waveforms of the class B ZVT Cuk converter
Fig. 3. Circuit diagram and key waveforms of the class B ZVT Cuk converter

during $t_0 - t_2$ every switching cycle. Since the snubber energy is stored in C_{r2} , power dissipative components are required to prevent unacceptable high voltage across C_{r2} . This undesirable feature reduces not only efficiency but also practicability.

- Turn-on current spike of the main switch

Penalty for applying soft switching to all semiconductor devices is the turn-on current spike of the main switch S_1 . It increases conduction losses and sometimes increases the current stress of S_1 . Although the current spike is approximately twice of the input current during turn-on. The increment of current stress of S_1 can be reduced to only 33.3% of the average current with properly selected inductor values of L_1 and L_2 . It is much less than that in discontinuous conduction mode where the current stress of S_1 is over 200% of the average current. However, the increased conduction losses indeed reduce the efficiency and the increased current stress of S_1 raises the circuit cost.

- Increased voltage stress of the auxiliary switch

The voltage stress of auxiliary switch S_2 is increased by V_{Cr2} . Since V_{Cr2} varies with wide range, voltage stress of S_2 is increased to at most two times of that of S_1 . It not only increases circuit costs but also decreases stability.

D. Class D ZVT Topology

The class D ZVT topology proposed by the authors can be applied to a Cúk converter as shown in Fig. 5(a). It also can be seen as the amelioration of the class C ZVT topology. An auxiliary diode D_2 is added to discharge resonant capacitor C_{r2} . The energy in the resonant snubber cell is reset to zero every switching cycle by adding D_2 . The increased voltage stress of the auxiliary switch is also prevented in the class D ZVT topology. Diode D_3 is added to clamp the voltage across S_2 to the output voltage when S_1 is on. It prevents high voltage spike of S_2 due to resonant ringing when body diode of S_2 is turned off at t_4 . This diode can sometimes be removed since the voltage spike of S_2 is generally small. As in the class C ZVT topology, all semiconductor devices in the class D ZVT topology, including D_2 and D_3 , also operate under soft switching. Key waveforms of the class D ZVT topology are shown in Fig. 5(b).

The features of the class D ZVT topology are summarized as follows:

Advantages:

- Soft switching for all semiconductor devices

As in the class C ZVT topology, all semiconductor devices in the class D ZVT topology also operate under soft switching. Switching losses and EMI noises are reduced to minimum.

- Energy in the resonant snubber cell reset every switching cycle

(a) Circuit diagram of the class D ZVT Cúk converter

(b) Key waveforms of the class D ZVT Cúk converter

Fig. 5. Circuit diagram and key waveforms of the class D ZVT Cúk converter

It is shown in Fig. 5(b) that the current through L_r (I_{Lr}) and the voltage across C_r (V_{Cr}) are reset to zero before S_1 turns on in every switching cycle. Although the energy temporarily stored in L_r and C_r still varies during different switching cycle, it is reset to zero every time before S_1 turns on. No energy can be accumulated in the resonant snubber cell. The problem of the class C ZVT topology is resolved by adding an auxiliary diode D_2 . The increased voltage stress of the auxiliary switch of the class C ZVT topology is also prevented. This desirable feature guarantees the class D ZVT topology eligible to be employed under long-term operation.

Disadvantages:

- Turn-on current spike of the main switch

As described in the class C ZVT topology, penalty for applying soft switching to all semiconductor devices in the class D ZVT topology is the turn-on current spike of the main switch S_1 .

- Increased voltage stress of the auxiliary diode

Although the voltage stress of the auxiliary switch S_2 is not increased as in the class C ZVT topology, the voltage stress of the auxiliary diode D_2 is increased by V_{Cr2} . Since V_{Cr2} in the class D ZVT topology is limited to a comparatively small value, voltage stress of D_2 does not increase too much. Besides, the increased voltage stress of D_2 appears for only a short period of time. A power diode with slightly larger voltage rating is sufficient.

III. EXPERIMENTAL RESULTS

Fig. 6. Key oscillograms of the class A ZVT Cúk converter.
 $V_{S1}, V_{S2}, V_{Cr} : 100\text{V/div}$; $I_{S1}, I_{S2}, I_{Lr} : 4\text{A/div}$; Time $2\mu\text{s/div}$.

Fig. 7. Key oscillograms of the class B ZVT Cúk converter.
 $V_{S1}, V_{S2}, V_{Cr} : 100\text{V/div}$; $I_{S1}, I_{S2}, I_{Lr} : 4\text{A/div}$; Time $2\mu\text{s/div}$.

Fig. 8. Key oscillograms of the class C ZVT Cúk converter.
 $V_{S1}, V_{S2} : 100\text{V/div}$; $V_{Cr2} : 50\text{V/div}$; $I_{S1}, I_{S2}, I_{Lr} : 4\text{A/div}$; Time $2\mu\text{s/div}$.

Fig. 9. Key oscillograms of the class D ZVT Cúk converter.
 $V_{S1}, V_{S2} : 100\text{V/div}$; $V_{Cr2} : 50\text{V/div}$; $I_{S1}, I_{S2}, I_{Lr} : 4\text{A/div}$; Time $2\mu\text{s/div}$.

Table I. Part lists of four ZVT Cúk converter prototypes.

	Class A	Class B	Class C	Class D
L1	800 μH	800 μH	800 μH	800 μH
L2	800 μH	800 μH	800 μH	800 μH
C1	4.7 μF	4.7 μF	4.7 μF	4.7 μF
CO	660 μF	660 μF	660 μF	660 μF
S1	2SK2198	2SK2198	2SK2198	2SK2198
D1	HFA15TB60	HFA15TB60	HFA15TB60	HFA15TB60
S2	2SK2198	2SK2198	2SK2198	2SK2198
D2	HFA15TB60	HFA15TB60	N/A	HFA15TB60
Lr	15 μH	60 μH	12 μH	12 μH
Cr(Cr1)	3.3nF	3.3nF	3.3nF	3.3nF
Cr2	N/A	N/A	22nF	22nF

In order to provide an experimental comparison of the topologies described in this paper, prototypes of four 400W, 200V DC output, 50kHz ZVT Cúk converters have been built in laboratory to verify the analysis presented. The components specifications of

Fig. 10. Commutation oscillograms of the hard switching Cúk converter.
 $V_{S1} : 100\text{V/div}$; $I_{S1} : 4\text{A/div}$; Time $2\mu\text{s/div}$.

these four circuits are listed in Table I. A hard switching Cúk converter with the same specifications is also built. The efficiency at 400W loading of the class A, B, C and D ZVT topologies and the hard switching counterpart are 95.0%, 95.2%, 94.3%, 94.7% and 88.7%, respectively.

Key oscillograms of the class A, B, C and D ZVT topologies are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9, respectively. Switch commutation oscillograms of the hard switching one are also shown in Fig. 10. It is clear seen from the oscillograms of V_{S1} and I_{S1} that the main switch in each topology operates under ZVS. The major difference of the commutation waveforms of the main switches is that I_{S1} of the class C and class D ZVT topologies have turn-on current spikes. The current spikes increase conduction losses and current stresses of the main switches. Although no current spikes appear on I_{S1} in the class A and class B ZVT topologies, the auxiliary switches operate under hard switching. It increases switching losses and EMI noises. Option should be made between the increased switching losses and EMI noises caused by hard switching of S_2 (topologies A and B) and the increased conduction losses and current stresses caused by turn-on current spikes of S_1 (topologies C and D).

Comparing the waveforms shown in Fig. 6 and Fig. 7, it can be seen that the waveforms of the class A and class B ZVT topologies are quiet similar. However, since the class B ZVT topology has robust discharge of resonant inductor and shorter ZVT time, it is recommended compared with the class A ZVT topology. Comparing the waveforms shown in Fig. 8 and Fig. 9, it can also be seen that the waveforms of the class C and class D ZVT topologies are quiet similar. Although the class C ZVT topology is easily to be implemented because the drive circuit requires no isolation, it has a serious problem that the energy is accumulated in the resonant snubber cell. This problem is solved in the class D ZVT topology by simply adding an auxiliary diode. An optional diode D_3 can also be added to prevent the voltage spike across S_2 caused by resonant ringing. The class D ZVT topology is recommended compared with the class C ZVT topology.

IV. CONCLUSION

Four classes of newly proposed ZVT topologies for Cúk converters are presented in this paper. Comparison of these four ZVT topologies is accomplished through qualitative descriptions and experimental waveforms. Characteristics of each ZVT topology are summarized as shown in Table II. The major disadvantage of the class A and class B topologies is the hard switching of the auxiliary switch and diode. It increases switching losses and EMI noises. Contrarily, soft switching is applied to all semiconductor devices, including auxiliary switches and diodes, in the class C and class D topologies. However, the penalty is the turn-on current spike of the main switch, which becomes the major disadvantage of the class C and class D topologies. It increases

conduction losses and current stress of the main switch. Option should be made between the increased switching losses and EMI noises caused by hard switching of S_2 (topologies A and B) and the increased conduction losses and current stresses caused by turn-on current spikes of S_1 (topologies C and D). Since discharge path of the resonant converter is modified in the class B ZVT topology, shorter ZVT time and robust discharge of the resonant inductor make the class B ZVT topology superior to the class A ZVT topology. Since the class D ZVT topology prevents the energy from being accumulated in the snubber cell by adding an auxiliary diode, the class D ZVT topology is deemed superior to the class C ZVT topology.

Table II. Comparison of four ZVT Cúk converters.

	Class A	Class B	Class C	Class D
Snubber components	4	4	4	5
ZVT time	mid	short	long	long
Hard switching devices	S_2, D_2	S_2, D_2	none	none
Increased stresses	none	VS_2, VD	IS_1, VS	IS_1, VD
Energy accumulated	no	no	yes	no
Isolated drive circuit	yes	yes	no	yes
Saturable reactor	yes	no	no	no
Specified control IC	yes	yes	no	no
Lr discharge limited by S_1	yes	no	yes	yes

REFERENCES

- [1] S. Cúk and R. D. Middlebrook, "A new optimum topology switching DC-to-DC converter," PESC77, pp. 160-179.
- [2] B. T. Lin and Y. S. Lee, "Power-factor correction using Cúk converters in discontinuous-capacitor-voltage mode operation," *IEEE Trans. Ind. Electron.*, vol. 44, no. 5, pp. 648-653, Oct. 1997.
- [3] M. Hernandez, C. Aguilar, J. Arau, J. Sebastian and J. Uceda, "Comparative analysis of boost and buck-boost derived topologies used as power factor correctors," IECON'95, pp.335-340.
- [4] N. Mohan, T. Undeland and W. Robbins, *Power Electronics: Converters, Applications and Design*. Wiley, 1989, pp. 98-99.
- [5] G. Hua, C. S. Leu, Y. Jiang and F. C. Lee, "Novel zero-voltage-transition PWM converters," *IEEE Trans. Power Electron.*, vol. 9, no. 2, pp. 213-219, Mar. 1994.
- [6] G. Moschopoulos, P. Jain and G. Joos, "A novel zero-voltage-switched PWM boost converter," PESC'95, pp. 694-700.
- [7] G. Moschopoulos, P. Jain, Y. F. Liu and G. Joos, "A zero-voltage-switched PWM boost converter with an energy feedforward auxiliary circuit," PESC'96, pp. 76-82.
- [8] G. Hua and F. C. Lee, "Soft-switching techniques in PWM converters," *IEEE Trans. Ind. Electron.*, vol. 42, no. 6, pp. 595-603, Dec. 1995.
- [9] K. M. Smith, Jr. and K. M. Smedley, "A comparison of voltage-mode soft-switching methods for PWM converters," *IEEE Trans. Power Electron.*, vol. 12, no. 2, pp. 376-386, Mar. 1997.