A Novel Soft-Switching Inverter with ZCS-ZVS Features

Jianming Yao and Thomas A. Lipo

Department of Electrical and Computer Engineering
University of Wisconsin – Madison
1415 Engineering Drive
Madison, WI 53706

***Abstract*— Device side soft-switching inverters provide a desired zero-current switching (ZCS) turn-off and zero-voltage switching (ZVS) turn-on of the switching devices with the resonance at device side. However, ZCS and ZVS cannot be realized with the same topology. A novel soft-switching inverter with both ZCS and ZVS features is proposed in this paper. The advantages of the proposed inverter topology are that all the main and auxiliary switches can be turned off with ZCS and can be turned on with ZVS. The principles of operation have been investigated with equivalent circuits at different operation modes for both ZCS and ZVS under different load current directions. The simulation with Saber gives the results that agree with the theoretical analyses.**

I. INTRODUCTION

Device side resonance soft-switching inverters [1-7] have been investigated for nearly a decade since the auxiliary resonant commutated pole (ARCP) inverter was proposed [2]. There are many topologies for zero-voltage switching (ZVS) inverters. Also some zero-current switching inverters have also been investigated. Progressing from the resonant dc link converter (RDCL) [1] to ARCP inverter, the significant change is that the resonance has been introduced at device side or load side instead of at DC link. The ARCP inverter, zero-voltage transition (ZVT) inverter [3] and auxiliary resonant snubber inverter (RSI) [4][5] all use resonant capacitor snubbers along with auxiliary inductors to achieve ZVS for the main switches and zero-current switching (ZCS) for the auxiliary switches. However, the turn-off of the main switch is not ZCS for these types of ZVS inverters. As to the zero-current transition (ZCT) inverters [6][7], such converters use the resonant capacitors and inductors in series as the resonant commutated pole to realize ZCS for the main switches. However, the turn-on of the main switches is not ZVS, although some topologies have reduced voltage across the device before turn-on of the device [7]. These topologies only eliminate either turn-on or turn-off hard-switching. To find a topology with both ZVS and ZCS features remains a challenge.

In this paper, a novel soft-switching inverter with both ZCS and ZVS features is proposed. As shown in Fig. 1, each phase leg of the ZCS-ZVS inverter uses an inductor as the series resonant snubber inductor together with a capacitor connected in between the output terminal and the positive or negative dc bus rail controlled by two auxiliary switches. If the modulation scheme, such as space vector pulse width modulation (SVPWM), can avoid two switches operate simultaneously, the resonant inductors can be combined into one and can be placed on the dc link as shown in Fig. 2 and Fig. 3.

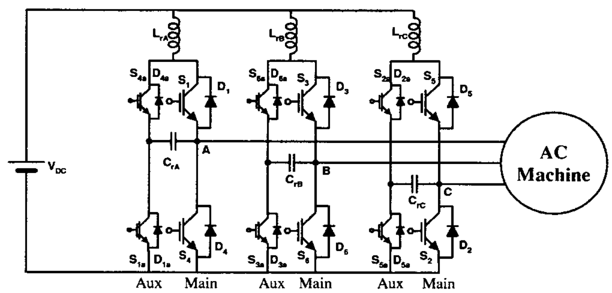


Fig. 1. Proposed ZCS-ZVS soft-switching inverter.

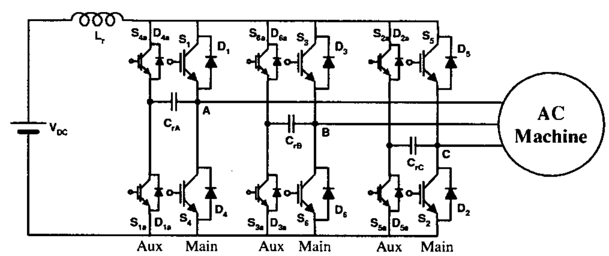


Fig. 2. Simplified ZCS-ZVS soft-switching inverter.

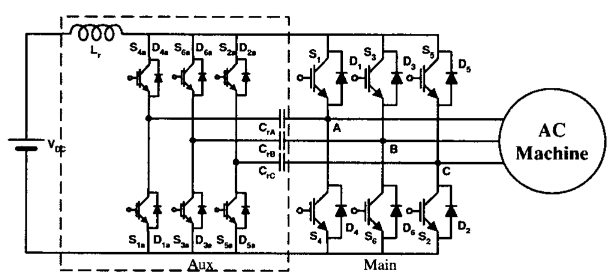


Fig. 3. Redrawn of Fig. 2 showing the auxiliary part.

II. PRINCIPLES OF OPERATION

For analysis purposes, a single phase leg circuit for the ZCS-ZVS inverter is shown in Fig. 4. If the load current is positive, i.e. the current is flowing from inverter to load, for a switching transition from upper switch S_1 conducting to

0-7803-7067-8/01/$10.00 ©2001 IEEE

lower switch S_2 conducting, ZCS turn-off condition is required for S_1 but S_2 can be turned on with ZVS naturally because of the conducting of the lower freewheeling diode D_2. On the other hand, for positive load current and the switching transition from lower switch S_2 to upper switch S_1, ZCS for the turn-off of S_2 is not required because the current is commutated from diode D_2 to switch S_1. However the ZVS turn-on condition should be provided for S_1. If the load current is negative, i.e. load current is flowing from the load to inverter, for switching transition from upper switch to lower switch, ZCS turn-off for S_1 is not required because the current is actually flowing through diode D_1 but ZVS turn-on condition is required for S_2. The last case is for negative current and switching transition from lower switch to upper switch. ZCS turn-off is required for switch S_2 and there is no requirement to provide ZVS turn-on condition for S_1 because the load current will be flowing through diode D_1 and the voltage across switch S_1 will be zero before the turn-on of S_1. In general, a soft-switching condition must be provided for upper switch S_1 when load current is positive and for S_2 when load current is negative. This can be illustrated in Fig. 5.

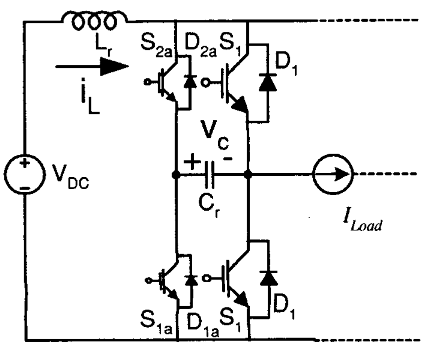


Fig. 4. One phase leg of proposed ZCS-ZVS inverter.

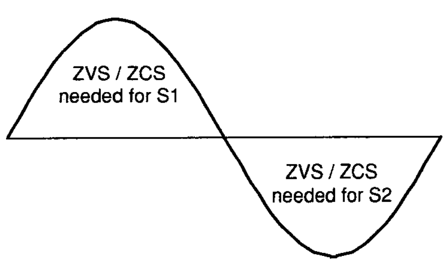
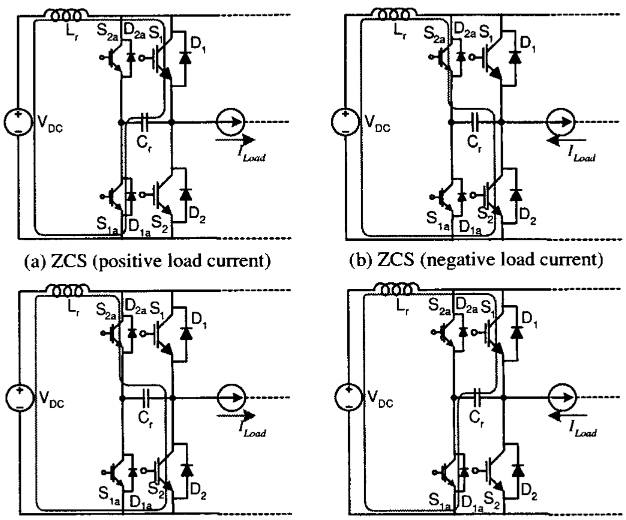


Fig. 5. Necessity of soft-switching for positive or negative load current.

To illustrate the operating principle, one phase inverter leg is used for analysis. The resonance loops for different switching states and different load current directions are shown in Fig. 6. Mode by mode analysis is discussed for one switching cycle. The circuit operation for positive load current and negative load current will be described in detail and illustrated in Fig. 7 (positive current) and Fig. 8 (negative load current).



(a) ZCS (positive load current) (b) ZCS (negative load current)

(c) ZVS (positive load current) (d) ZVS (negative load current)

Fig. 6. ZCS and ZVS loops.

A. Positive load current, one cycle operation

(a) Mode 0 [t0-t1]: Original State. Upper switch S_1 is on and load current is flowing through S_1.

(b) Mode 1 [t1-t2]: Positive Resonant Current Stage. Auxiliary switch S_{1a} is turned on and the resonance begins. The state equations are given by:

$$L_r \frac{di_L}{dt} - v_C = V_{DC} \tag{1}$$

$$C_r \frac{dv_C}{dt} + i_L = I_{Load}\,. \tag{2}$$

The initial condition are:

$v_C(t_1) = 0$

$i_L(t_1) = I_{Load}$.

The solution these equations are as follows:

$$i_L(t) = \frac{V_{DC}}{Z_0} \sin \omega_0 (t - t_1) + I_{Load} \tag{3}$$

$$v_C(t) = V_{DC} \cos \omega_0 (t - t_1) - V_{DC}\,, \tag{4}$$

where $\omega_0 = \frac{1}{\sqrt{L_r C_r}}$ and $Z_0 = \sqrt{\frac{L_r}{C_r}}$.

(c) Mode2 [t2-t3]: Negative Resonant Current Stage. Resonant current through C_r changes its direction. But the current flowing through switch S1 is the superposition of resonant current and load current. The resonant current needs to go further negative in order to offset the load current. The current path is the same as in Mode 1 so that the resonant current and voltage have the same expressions as (3) and (4).

(d) Mode 3 [t3-t4]: ZCS Stage. The current through the upper main device changes its direction and D_1 is conducting. Therefore the main switch S_1 can be turned off at ZCS. The equivalent path for the resonant current is still the same except that the diode instead of switch is conducting, so that

the resonant current and voltage change in the same manner as described by (3) and (4) until the resonant current equals to $-I_{Load}$.

(e) Mode 4 [t4-t5]: Resonant Capacitor Discharge Stage. The diode D_1 is turned off so that the load current flows through the auxiliary diode D_{1a} only. The capacitor C_r is discharged quickly. Because of the constant current is flowing through the diode, the capacitor voltage changes linearly to zero.

(f) Mode 5 [t5-t6]: Main Diode Freewheeling Stage. Main diode D_2 carries all the load current. S_2 can be turned on at ZVS.

The switching transition from upper switch to lower diode finishes with ZCS for the upper switch and ZVS for the lower switch. When the switching state needs to be changed to a condition where upper device is on and lower device is off, the following operation should be done in order to provide ZVS condition for the main switch S_1.

(g) Mode 6 [t6-t7]: ZVS Stage I. The lower auxiliary switch is turned off and the upper auxiliary switch S_{2a} is turned on to trigger the resonance. Because the lower auxiliary switch remains on until the resonance begins, the capacitor voltage initial value is zero. The resonance loop is changed so that the inductor current and capacitor voltage can be expressed as follows:

$$i_L(t) = \frac{V_{DC}}{Z_0}\sin\omega_0(t-t_1) + I_{Load} \tag{5}$$

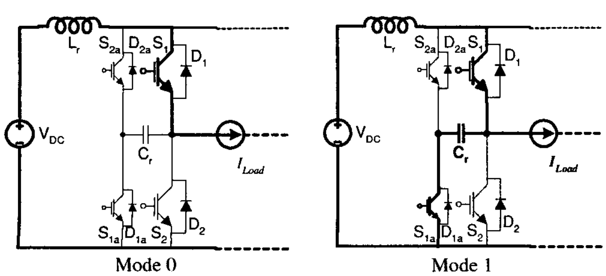
$$v_C(t) = V_{DC} - V_{DC}\cos\omega_0(t-t_1)\,. \tag{6}$$

(h) Mode 7 [t7-t8]: ZVS Stage II. When the resonant current exceeds the load current, the current through lower main inverter leg changes its direction.

(i) Mode 8 [t8-t9]: ZVS Stage III. After the resonant current reaches its peak, the current through lower main inverter leg swings back.

(j) Mode 9 [t9-t10]: ZVS Stage IV. After half of the resonant period, the resonant current becomes zero and then changes its direction.

(k) Mode 10 [t10-t11]: ZVS Stage V. After one resonant cycle, the voltage across the resonant switch returns to zero and the upper main switch S_1 can be turned on with ZVS. The voltage drop at the auxiliary inductor decreases from full dc bus voltage to zero while the current through the main switch increases. Finally, The lower main switch S_2 can be turned off at ZCS. Thus it returns to the original state, i.e. Mode 0.



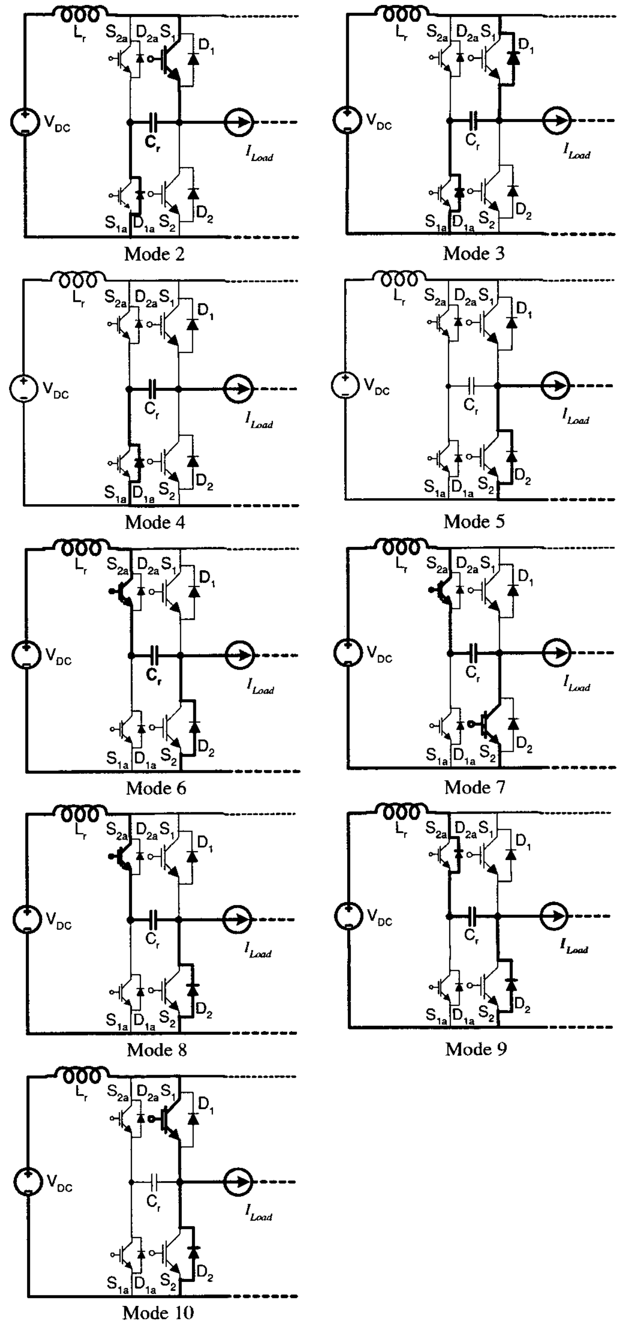
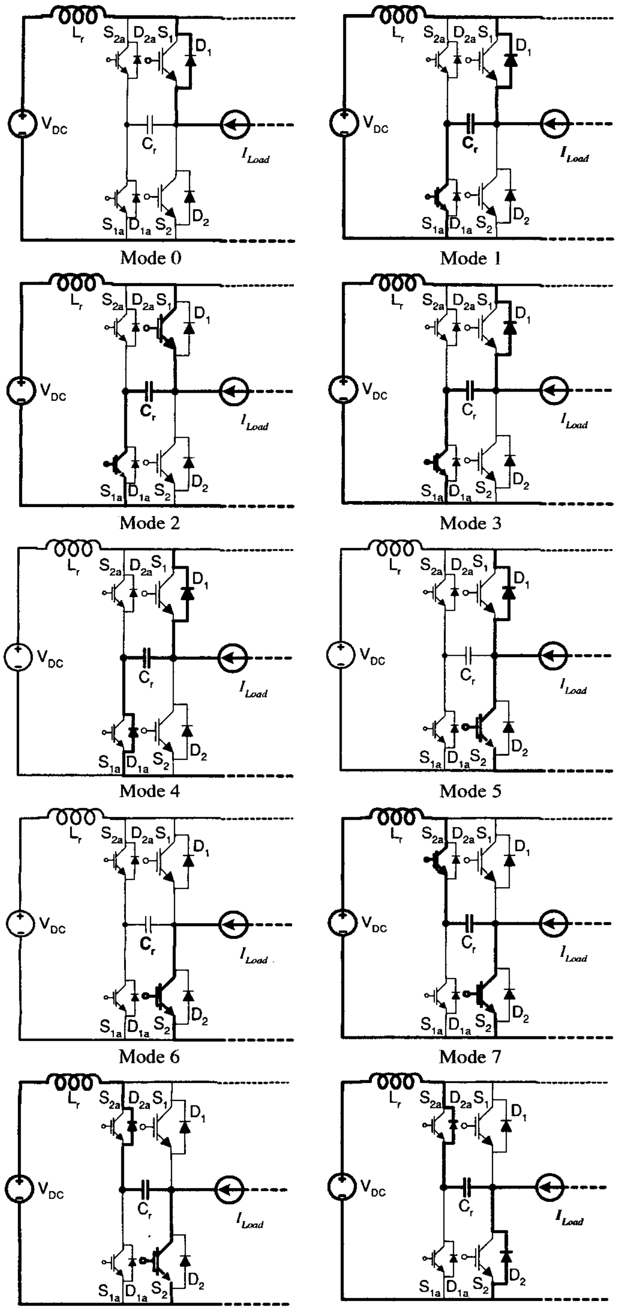


Fig. 7. Operation modes when load current is positive.

B. Negative load current, one cycle operation

For negative load current, the symmetry of the circuit provides the similar operation stages as those for positive load current.

According to the operation modes described, the theoretical waveforms for the resonance and switching states changes can be developed as shown in Fig. 9.



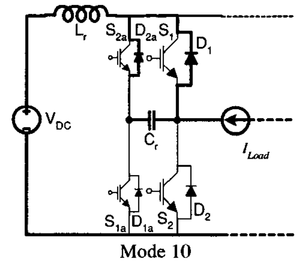
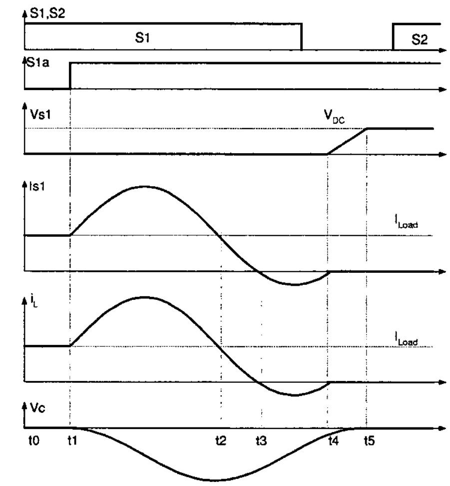
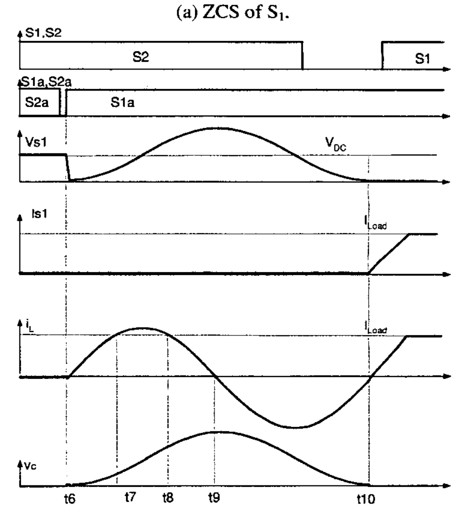


Fig. 8. Operation modes when load current is negative.



(a) ZCS of S_1.



(b) ZVS of S_1.

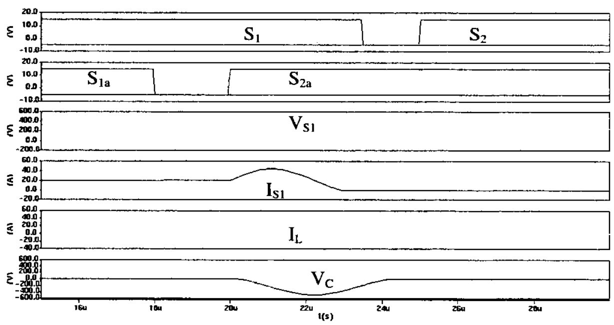
Fig. 9. Theoretical waveforms.

III. SIMULATION RESULTS

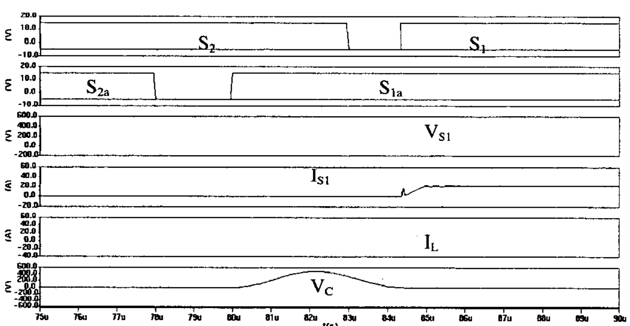
Simulation for the soft-switched ZCS-ZVS inverter has been carried out using Saber with the following parameters:

- Auxiliary capacitor: 68nF
- Auxiliary inductor: 6.8uH
- DC bus voltage: 250V
- Load current at the switching instant: 20A.

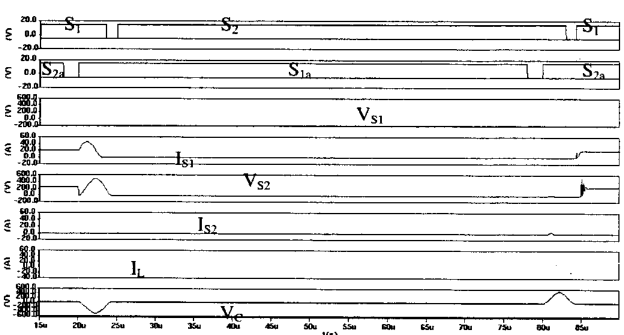
For the positive load current, the simulation waveforms for ZCS are shown in Fig. 10(a) and the waveforms for ZVS are shown in Fig. 10(b). Fig. 10(c) shows the entire switching cycle for main switch at positive load current. Fig. 11 shows the simulation results for negative load current.



(a) ZCS of S_1.

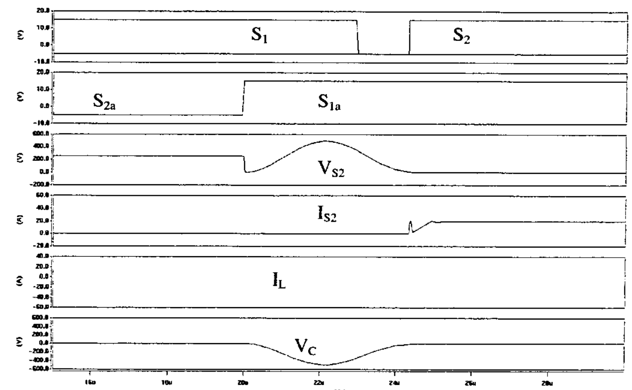


(b) ZVS for S_1.

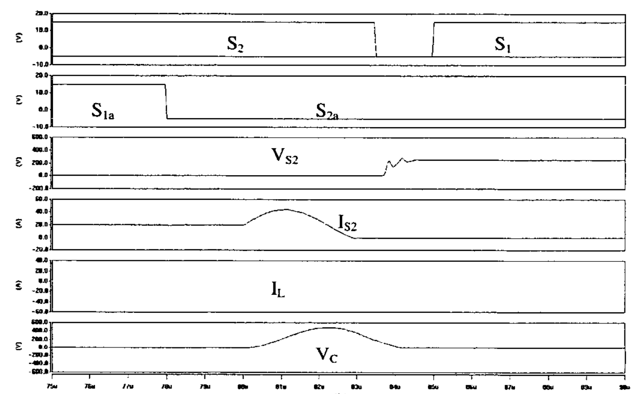


(c) Entire switching cycle

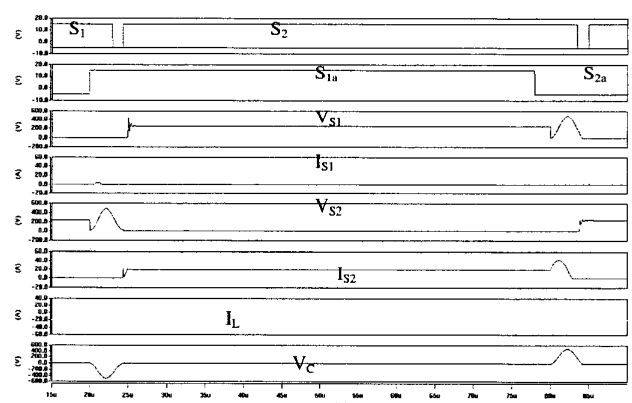
Fig. 10. Simulation waveforms showing ZCS and ZVS when load current is positive.



(a) ZVS of S_2.



(b) ZCS of S_2.



(c) Entire switching cycle

Fig. 11. Simulation waveforms showing ZCS and ZVS when load current is negative.

The simulation results agree with the theoretical analyses and the inverter realizes the symmetrical operation for positive and negative load current.

For ZCS operation, as shown in Fig. 10(a) and Fig. 11(b), the switch current goes to zero and the diode becomes conducting before turn-off occurs. For ZVS operation, as shown in Fig. 10(b) and Fig. 11(a), the switch voltage goes to zero and turn-on is initiated. The current increase to full load current occurs at the rate determined by auxiliary inductor.

IV. CONCLUSION

Differing from previous device side soft-switching inverters that can only realize either ZVS or ZCS, the proposed soft-switching inverter has the advantage of both ZCS and ZVS for the main and auxiliary switches. The number of components is the same as those ZVS or ZCS inverters and can be further simplified with just one auxiliary inductor and three resonant capacitors if simultaneous operation of two phases can be avoided by SVPWM. However, the trade-off is that the current and voltage stresses for the devices are doubled.

Theoretical analyses and simulations have verified the circuit operation under desired ZCS and ZVS conditions. Good agreement has been obtained between the two approaches. Work is in progress on the hardware implementation and experimental verification.

REFERENCES

[1] D. M. Divan, "The resonant dc link converter - a new concept in static power conversion," in *Proc. IEEE IAS Annu. Meet.*, Oct. 1986, pp.648 - 656.

[2] R. W. DeDoncker and J. P. Lyons, "The auxiliary quasi-resonant dc link inverter," in *Conf. Rec. of IEEE PESC*, June 1991, pp. 248 - 253.

[3] V. Vlatovic, D. Borojevic, F. C. Lee, C. Cuadros, and S. Gataric, "A new zero-voltage transition, three-phase PWM rectifier/inverter circuit," in *Conf. Rec. of IEEE PESC*, Seattle, WA, Jun. 1993, pp. 868 - 873.

[4] J. S. Lai, R. W. Young, G. W. Ott, J. W. McKeever, and F. Z. Peng, "A delta configured auxiliary resonant snubber inverter," *IEEE Trans. on Ind. Appl.*, Vol. 32, No. 3, May/Jun. 1996, pp. 518 -525 .

[5] J. S. Lai, R. W. Young, G. W. Ott, C. P. White, J. W. McKeever, and D. S. Chen, "A novel resonant snubber inverter," in *Conf. Rec. of IEEE APEC*, Dallas, TX, Mar. 1995, pp. 797 - 803.

[6] H. Mao, F. C. Lee, X. Zhou, and D. Borojevic, "Improved zero-current-transition converters for high power applications," in *Proc. IEEE IAS Annu. Meet.*, 1996, pp. 1145-1152.

[7] Y. Li, F.C. Lee, J. Lai and D. Borojevic, "A novel three-phase zero-current-transition and quasi-zero-voltage-transition (ZCT-QZVT) inverter/rectifier with reduced stresses on devices and components," in *Conf. Rec. of IEEE APEC*, Feb., 2000, pp.1030-1036.