Novel Zero-Current-Transition PWM Converters

Guichao Hua, Eric X. Yang, Yimin Jiang, and Fred C. Lee, *Fellow, IEEE*

***Abstract*—A new family of zero-current-transition (ZCT) pulse-width-modulated (PWM) converters is proposed. The new family of converters implements zero-current turn-off for power transistor(s) without increasing voltage/current stresses and operates at a fixed frequency. The proposed converters are deemed most suitable for high-power applications where the minority-carrier semiconductor devices (such as IGBT's, BJT's, and MCT's) are predominantly used as the power switches. Theoretical analysis is verified on a 100 kHz, 1 kW ZCT-PWM boost converter using an IGBT.**

I. Introduction

RECENTLY, a number of soft-switching PWM techniques were proposed aimed at combining desirable features of both the conventional PWM and resonant techniques [1]–[5]. Among them, the zero-voltage-transition (ZVT) PWM technique is deemed desirable since it implements zero-voltage switching (ZVS) for all semiconductor devices without increasing voltage/current stresses [4], [5]. This technique minimizes both the switching losses and conduction losses and is particularly attractive for high-frequency operation where power MOSFET's are used as power switches.

Due to continuous improvement of switching characteristics, lower conduction losses, and lower cost, IGBT's are gaining wide acceptance in switched-mode power converters/inverters. Since IGBT is a minority-carrier devices, it exhibits a current tail at turn-off which causes considerably high turn-off switching losses. To operate IGBT's at relatively high switching frequencies, either the ZVS or the zero-current switching (ZCS) technique can be employed to reduce switching losses. Basically, ZVS eliminates the capacitive turn-on loss, and reduces the turn-off switching loss by slowing down the voltage rise and reducing the overlap between the switch voltage and switch current. This technique can be effective when applied to a fast IGBT with a relatively small current tail. However, employing ZCS technique eliminates the voltage and current overlap by forcing the switch current to zero before the switch voltage rises. ZCS is deemed more effective than ZVS in reducing IGBT switching losses, particularly for slow devices [6], [7].

Several ZCS techniques were reported [7]–[13]. It is well-known that the conventional resonant converters, such as the parallel-resonant converter, series-resonant converter, and LCC-type converters, can achieve ZCS for power transistors when operated below the resonant frequency. Constant-frequency operation is also achievable if phase-shift control is employed in full-bridge topologies [10]. However, these types of circuits usually are operated with large amount of circulating energy and thus require the power devices and other circuit components to be rated for significantly higher VA ratings, as compared to their PWM counterparts.

As a compromise between the ZCS resonant and PWM techniques, the ZCS quasi-resonant (QRC) technique was proposed [11]–[13]. While the underlying power conversion principle of ZCS-QRC's is similar to that of the PWM converters, a resonant network is employed to shape the switch current waveform so that the power transistor is operated with ZCS and the rectifier diode with ZVS. Compared with the conventional resonant converters, the ZCS-QRC's operate with less circulating energy. However, these converters operate with sinusoidal current through the power switch(es) which results in high peak and rms currents for the power transistors and high voltage stresses on the rectifier diodes. Furthermore, when the line voltage or load current varies over a wide range, ZCS-QRC's are modulated with a wide switching frequency range, making the circuit design difficult to optimize.

This paper presents a new family of zero-current-transition (ZCT) PWM converters. The proposed ZCT-PWM converters implement zero-current turn-off for the transistors without substantially increasing voltage/current stresses of the switches. They are particularly suited for high-power/high-voltage applications where the minority-carrier semiconductor devices (such as IGBT's, BJT's, and MCT's) are used as the power switches. In the following section, the ZCT-PWM boost converter is used as an example to illustrate the principle of operation.

II. Principles of Operation

The circuit diagram and key waveforms of the ZCT-PWM boost converter are shown in Fig. 1. The converter differs from a conventional PWM boost converter by the introduction of a resonant branch, which consists of a resonant inductor, L_r, a resonant capacitor, C_r, an auxiliary switch, $S1$, and an auxiliary diode, $D1$. This resonant branch is active only during a short switching-transition time to create the ZCS condition for the main switch. In the analysis, the boost inductor, L_f, is assumed to be large enough to be considered as a current source, I_i. In steady-state, five operating stages exist within one switching cycle (refer to Fig. 2):

a) T_0-T_1: Prior to T_0, the main switch, S, is conducting, and C_r is charged with certain negative voltage, $-V_{Cr}^{\text{peak}}$. At T_0, the auxiliary switch, $S1$, is turned on, starting a resonance between C_r and L_r. This resonance forces the transistor current to decrease in a sinusoidal fashion.

Manuscript received October 25, 1993; revised June 10, 1994.

The authors are with the Virginia Power Electronics Center, The Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA.

Eric X. Yang is currently with Harris Power Research and Development, Latham, NY 12110 USA.

IEEE Log Number 9405302.

After a quarter of the resonant period, t_{d1}, the C_r voltage reduces to zero, and the L_r current reaches its maximum value, $I_{Lr}^{\max}$:

$$t_{dl} = \frac{1}{4}T_r, \tag{1}$$

and

$$I_{Lr}^{\max} = \frac{V_{Cr}^{\text{peak}}}{Z_r}, \tag{2}$$

where $T_r = 2\pi\sqrt{L_r C_r}$ and $Z_r = \sqrt{L_r/C_r}$ are the resonant period and impedance of the resonant tank, respectively. It can be seen that to achieve zero-current turn-off for the transistor, I_{Lr}^{peak} has to be greater than I_i. After the transistor current drops to zero and its anti-parallel diode starts to conduct, the gate-drive signal of S is disabled at $t = t_0 + t_{d1}$.

b) T_1-T_2: $S1$ is turned off shortly after S is turned off. In steady-state operation (as explained later), the resonant inductor current at T_1 is always equal to I_i. Thus the time delay between these two gate-drive turn-off signals, t_{d2}, determines the peak voltage of C_r:

$$V_{Cr}^{\text{peak}} = \frac{Z_r I_i}{\cos(2\pi T_{d2}/T_r)} \tag{3}$$

if

$$V_{C_r}^{\text{peak}} \leq V_0. \tag{4}$$

In steady-state operation, V_{Cr}^{peak} cannot exceed V_0, since $D1$ would otherwise conduct during operating stage T_4-T_0. Defining $\alpha = 2\pi(T_{d2}/T_r)$, (3) becomes

$$V_{Cr}^{\text{peak}} = \frac{Z_r I_i}{\cos\alpha}. \tag{5}$$

Combining (2)–(5) yields

$$I_{Lr}^{\max} = \frac{I_i}{\cos\alpha} \geq I_i, \tag{6}$$

which means that as long as inequality (4) is satisfied, ZCS operation will be guaranteed regardless of the input voltage and load current. In a practical design, T_{d2} can be selected at around 0.07 T_r, so that I_{Lr}^{peak} is about 10% higher than I_i, and ZCS is ensured. When $S1$ is turned off at $T1$, both D and $D1$ will start to conduct, and L_r and C_r continue to resonate until the I_{Lr} current decays to zero at T_2.

c) T_2-T_3: At T_2, L_r and C_r complete the half-cycle resonance, and $D1$ is reverse-biased. This operating stage is identical to the transistor-off stage of the PWM boost converter.

d) T_3-T_4: At T_3, S is turned on, and the boost inductor is charged by the input voltage. Meanwhile, C_r and L_r form a half-cycle resonance through S and the anti-parallel diode of $S1$, which reverses the polarity of the C_r voltage.

e) T_4-T_0: Operation of the circuit is identical to that of the transistor-on period of the PWM boost converter. At T_0, $S1$ is turned on again, and the switching cycle is repeated.

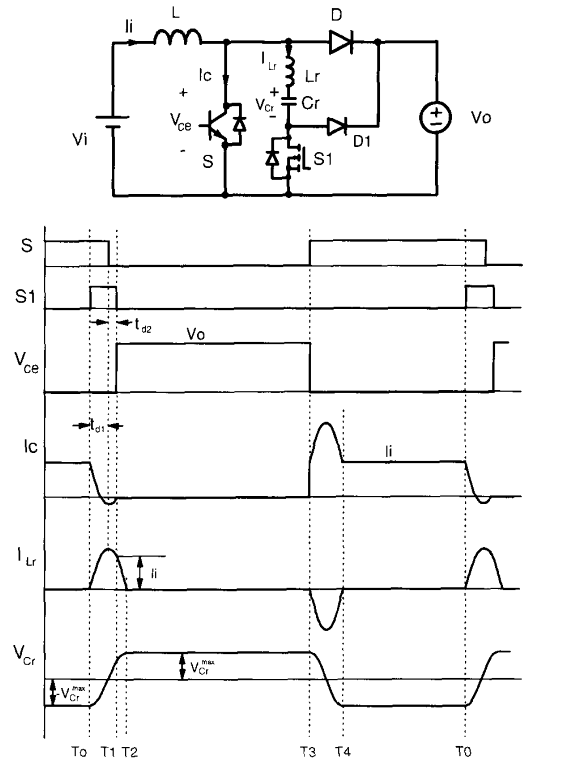


Fig. 1. Circuit diagram and key waveforms of the ZCT-PWM boost converter.

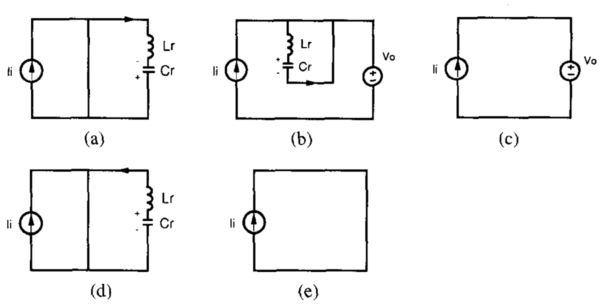


Fig. 2. Equivalent circuits for five topological stages. (a) T_0-T_1. (b) T_1-T_2. (c) T_2-T_3. (d) T_3-T_4. (d) T_4-T_0.

It is interesting to note that in steady-state operation, the energy stored in the resonant tank remains constant over the entire switching cycle. This can be clearly seen from the above description. During each topological stage (shown in Fig. 2), either the voltage across the resonant tank (L_r plus C_r) is zero or the current through it is zero, so there is no energy transfer between the resonant elements and other parts of the circuit. Fig. 3 shows the state-plane trajectory of the resonant tank. The energy stored in the resonant tank, which is self-adjusted in accordance with line and load conditions, can be given by

$$E_{\text{res}} = \frac{1}{2}L_r\left(\frac{I_i}{\cos\alpha}\right)^2. \tag{7}$$

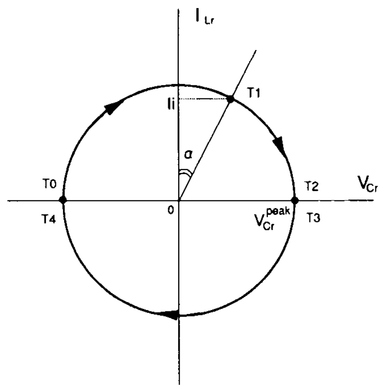


Fig. 3. State-plane trajectory of the resonant tank.

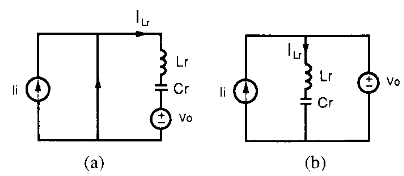


Fig. 4. An additional topological stage occurs when the circuit offsets the balance operating point: (a) $I_{Lr} > Ii$ and (b) $I_{Lr} < Ii$ at T_1.

This circulating energy increases as input current increases (when line voltage decreases or load current increases). In a practical circuit, since the resonant transition time is very short with respect to the switching cycle, the resonant inductance is very small compared to boost inductance. Therefore, the circulating energy of the ZCT-PWM converter is quite small compared to a conventional ZCS resonant converter, as illustrated in the design example given in Section IV.

It was mentioned that in steady-state operation, the resonant inductor current at T_1 is always equal to I_i, regardless of line or load condition change. Assuming that for some reason I_{Lr} at T_1 is larger than I_i. In this case, there will be an additional topological stage inserted between mode (b) and mode (c) in Fig. 2, as shown in Fig. 4(a). During this operating stage, the resonant branch transports energy to the load. Therefore the energy stored in the resonant branch decreases. In contrast, if I_{Lr} at T_1 is lower than I_i, there will be another topological stage inserted between mode (b) and mode (c) in Fig. 2, as shown in Fig. 4(b). It can be seen that the boost inductor will pump some energy into the resonant branch during this operating stage. Therefore, the energy stored in the resonant branch will increase until it reaches the balance point given by (7).

From steady-state operation, it can be seen the ZCT-PWM technique implements zero-current turn-off for the power transistor without penalizing the voltage stresses of both the power transistor and the rectifier diode. Although the main switch current waveform exhibits a resonant peaking, it does not increase the conduction loss, since the average current through the power switch (IGBT) is essentially the same compared with its PWM counterpart. Another unique advantage of the proposed technique is that it has minimum circulating energy. Equation (7) reveals that regardless of the line and load changes, the energy stored in the resonant tank will always be adaptively adjusted so that it is only slightly higher than what is needed for creating the ZCS condition.

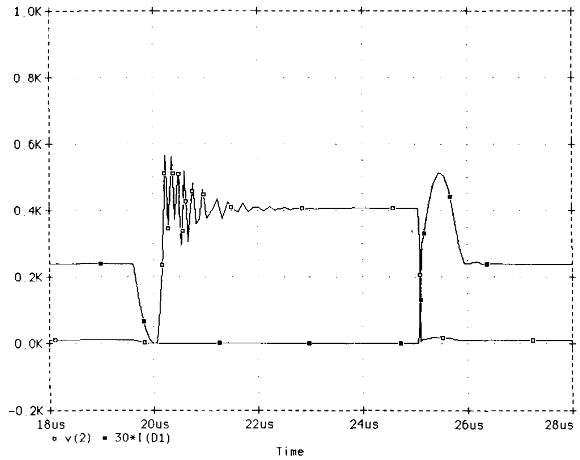
For high-voltage applications (such as power-factor correction (PFC)) where the boost diode suffers from a severe reverse-recovery problem, an additional inductor (or a saturable inductor) in series with the rectifier diode or the main switch is usually used to suppress the reverse-recovery problem. At transistor turn-off, this inductor invokes a high-voltage spike on the transistor due to high di/dt across the inductor. To suppress this voltage spike, a large dissipative snubber is frequently used. For a ZCT boost converter with the same additional inductor, however, this voltage spike is much reduced due to controlled di/dt across the inductor at transistor turn-off. As a result, a much smaller snubber can be used to absorb this ringing. Fig. 5 shows the simulation results of typical transistor voltage waveforms in these two cases. Similarly, for isolated topologies, the ZCT technique can significantly reduce the transistor turn-off voltage spike caused by leakage inductance of the transformer.

III. Extension of the ZCT Concept to Other Topologies

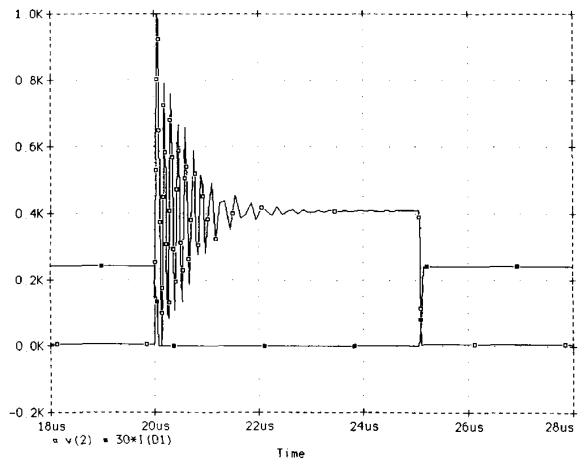
From the circuit topological point of view, every resonant-type converter (including the conventional resonant, quasi-resonant, and multi-resonant converters) can be viewed as a variation of its PWM counterpart. By incorporating certain type of resonant network, it creates a resonance to achieve ZVS or ZCS. For different resonant converters, of course, the type of resonant network employed is different.

One common characteristic of resonant-type topologies is that they all employ a resonant inductor (sometimes a resonant inductor plus a resonant capacitor) in series with the power switch or the rectifier diode to shape switch voltage/current waveforms. Soft-switching is achieved by utilizing the resonance between this resonant inductor and certain resonant capacitors, which are usually in parallel with the semiconductor devices. Due to the fact that these resonant elements are placed in the main power path, the resultant resonant converters are always subjected to inherent problems. First, since the resonant inductor is subjected to bidirectional voltage, it inevitably generates additional voltage stress on the semiconductor devices. Second, since all the power flows through the resonant inductor, substantial circulating energy is always created, which significantly increases conduction losses. In addition, the energy stored in the resonant inductor strongly depends on the line voltage and load current. Therefore, soft-switching condition is sensitive to line voltage and load current changes. This is why most resonant converters are unable to maintain soft-switching for a wide line and load range.

To alleviate the above-mentioned limitations, it is necessary to remove the resonant element(s) from the main power path. Instead of using a series resonant element, an alternative way is to use a shunt resonant network across the power switch. During the switching transition, the shunt resonant network is activated to create a partial resonance to achieve ZVS or



(a)



(b)

Fig. 5. Typical transistor V/I waveforms of boost convert using an additional inductor for damping reverse-recovery of the diode: (a) with the ZCT-PWM technique, and (b) with the PWM technique.

ZCS. When switching transition is over, the circuit simply reverts back to the familiar PWM operating mode. In this way, the converter can achieve soft-switching while preserving the advantages of the PWM converter. In fact, the above-suggested concept of using a shunt resonant network has been adopted in the ZVT-PWM converters [4]. Apparently it can also be applied to implement ZCT, as illustrated above.

It should be mentioned that ZVT or ZCT can be implemented in perhaps a number of different ways. One should keep it in mind that it is desirable to minimize the circulating energy and circuit complexity. Furthermore, it also is desirable to implement some form of soft-switching for the auxiliary switch as well.

The ZCT concept can be extended to any switched-mode power converters or inverters. Fig. 6 shows six basic ZCT-PWM topologies. Fig. 7 shows a single-switch three-phase ZCT-PWM boost converter. By running this circuit in discontinuous conduction mode, it can provide fairly good power

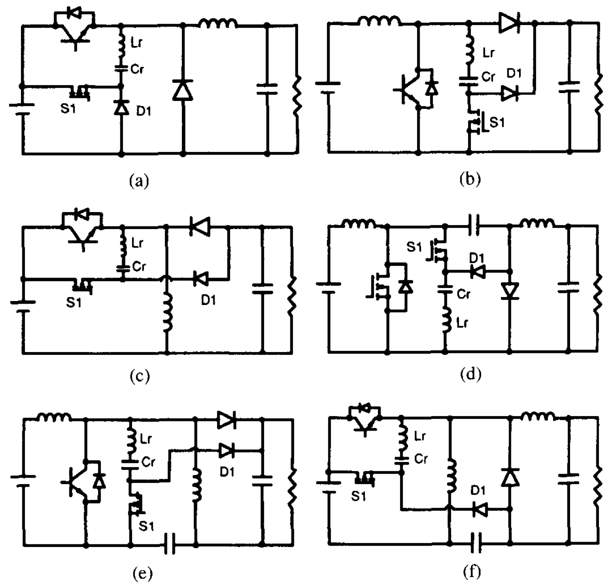


Fig. 6. Six basic ZCT-PWM topologies. (a) Buck. (b) Boost. (c) Buck-boost. (d) Cuk. (e) Sepic. (f) Zeta.

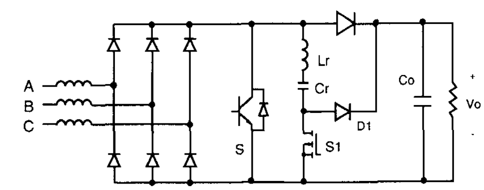


Fig. 7. A simple three-phase ZCT-PWM boost converter.

factor with simple fixed-frequency and fixed-duty-cycle control. The use of the shunt resonant network enables the circuit to operate at much higher switching frequencies. The features of the ZCT-PWM converters are summarized in the following:

- zero-current turn-off for the power switch,
- low voltage/current stresses of the power switch and rectifier diode,
- minimal circulating energy,
- wide line and load ranges for ZCS,
- constant-frequency operation.

IV. Experimental Verification

A 100 kHz, 1 kW ZCT-PWM boost converter was implemented to illustrate the operation of the new converters. The circuit is regulated at 400 V output with a 200–300 V input range. The circuit diagram of the experimental converter is shown in Fig. 8. In the breadboarded converter, the main power switch is implemented by an IR fast-series IGBT, IRGPF40 (V_{CE} = 600 V, I_C = 40A, t_r = 37 ns, and T_f = 420ns, rated for up to 8 kHz switching frequency operation). Since the auxiliary switch only handles a little resonant transition energy, a small MOSFET, IRF830, is employed. The small diode in series with $S1$ is used to block its slow body-diode from conduction. L_r and C_r are selected at 10 μH and 8.2 nF, respectively. With

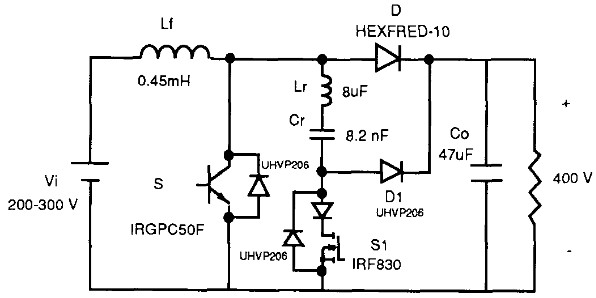


Fig. 8. Power stage circuit diagram of the 100 kHz, 1 kW ZCT boost converter.

this design, the maximum circulating energy of the circuit, which occurs at full load and low line, is approximately 18 W, which is less than 2% of the output power.

It is shown that ZCS is always maintained when the line voltage or load current changes over a wide range. Fig. 9(a) shows the oscillograms of the ZCT-PWM boost operating at 250 V input and 700 W output. Compared with waveforms of the PWM circuit operating under the same conditions, it can be seen that the IGBT turn-off current tail is essentially alleviated. Fig. 10 shows the efficiency measurements of ZCT and PWM boost converters. It can be seen that the ZCT technique significantly improves the efficiency. Due to the high turn-off switching loss of the IGBT device, the hard-switched PWM circuit is not able to operate above 800 W output power. Table I shows the loss breakdown estimation for two boost converters operating at 250 V input and 700 W output. For the PWM converter, it can be seen that the major power dissipation comes from the turn-off switching loss of the IGBT, which is about 37 W. The estimation of IGBT switching losses is based on the actual switch voltage/current waveforms, roughly in agreement with the data given in the IGBT designer's manual [14]. For the ZCT circuit, power losses involved in the operation of the auxiliary resonant shunt are only about 1.8 W, which is less than 0.3% of the output power.

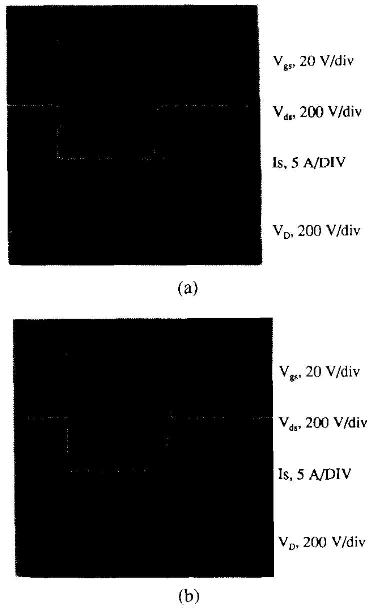


Fig. 9. Oscillograms of two IGBT boostconverters operating at $V_i = 250$ V, $P_o = 700$ W, and $f_s = 100$ kHz. (a) Using ZCT-PWM technique. (b) Using PWM technique.

TABLE I
LOSS BREAKDOWN OF PWM AND ZCT-PWM BOOST CONVERTERS AT P_0=700 W AND V_i=250 V

Component losses	PWM boost	ZCT-PWM boost
IGBT conduction	3.3 W	3.0 W
IGBT turn-on switching	3.0 W	3.0 W
IGBT turn-off switching	37.0 W	5.2 W
auxiliary switch	N/A	1.0 W
auxiliary diodes	N/A	0.6 W
resonant tank (L_r and C_r)	N/A	0.2 W
diode conduction	1.7 W	1.7 W
diode switching	2.9 W	2.9 W
boost inductor	2.0 W	1.9 W
others	1.5 W	1.5 W
total	51.4 W	21.0 W
efficiency	93.1 %	97.1 %

V. CONCLUSION

Because of continuous improvement of switching characteristics, lower conduction losses, and lower costs, IGBT's are gaining wide acceptance in today's power processing circuits, particularly in high-power applications. In practice, due to high switching losses (mainly turn-off current tail), the switching frequency of the hard-switched IGBT circuits has been limited to low tens of kHz range. Performance (efficiency, size, weight, and EMI noise, etc.) of these converters can be improved significantly by implementing ZCS and thereby boosting the operating frequency. Although a number of ZCS resonant techniques have been presented to date, they all have severe limitations, such as high circulating energy, limited load range, variable frequency control, and complicated design.

Based on the concept of shunt resonant network, this paper presents a novel ZCT technique and a new family of ZCT-PWM converters. The proposed converters feature zero-current turn-off for the power transistor, while retaining the advantages of conventional PWM converters, such as low voltage/current stresses of the semiconductor devices and constant-frequency operation. The shunt resonant network operates only during switching-transition, thus during most portions of the switching cycle, the converter operates like a PWM circuit. Consequently, the design of the power stage components and control is similar to that of the conventional PWM converters. Furthermore, ZCT operation is independent of line and load conditions, and the circulating energy of the converter is always maintained minimum. These features make the ZCT-PWM technique attractive for high-power

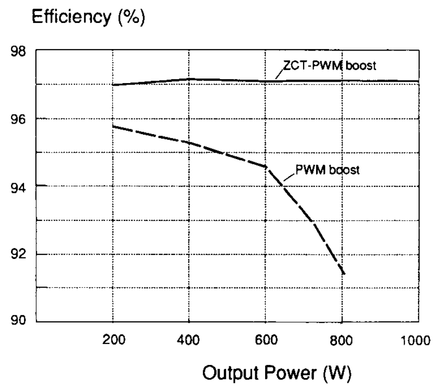


Fig. 10. Efficiency comparison of ZCT-PWM and PWM boost converters using IGBT.

applications where the minority-carrier devices such as IGBT's and MCT's are employed.

References

[1] C. P. Henze, H. C. Martin, and D. W. Parsley, "Zero-voltage-switching in high frequency power converters using pulse width modulation," in *IEEE Appl. Power Electron. Conf. Proc.*, 1988, pp. 33–40.

[2] O. D. Patterson and D. M. Divan, "Pseudo-resonant full-bridge dc-dc converter," in *IEEE Power Electron. Specialists Conf. Rec.*, 1987, pp. 424–430.

[3] J. A. Sabate, V. Vlatkovic, R. Ridely, and F. C. Lee, "High-voltage, high-power, ZVS, full-bridge PWM converter employing an active switch," in *IEEE Appl. Power Electron. Conf. Proc.*, 1991, pp. 158–163.

[4] G. Hua, C. Leu, and F. C. Lee, "Novel zero-voltage-transition PWM converters," in *IEEE Power Electronics Specialists Conf. Rec.*, 1992, pp. 55–61.

[5] G. Hua and F. C. Lee, "An overview of soft-switching techniques for PWM converters," *EPE J.*, no. 1, 1993.

[6] J. Kolar, H. Ertl, L. Erhartt, and F. Zach, "Analysis of turn-off behavior and switching losses of a 1200V/50A zero-voltage or zero-current switched IGBT," in *Proc. IEEE Appl. Power Electron. Conf.*, 1991, pp. 1508–1514.

[7] G. Hua and F. C. Lee, "Novel full-bridge zero-current-switched PWM converter," in *Proc. 4th Europ. Conf. Power Electron. and Appl.*, vol. 2, 1991, pp. 29–34.

[8] E. Buchanan and E. J. Miller, "Resonant switching power conversion technique," in *IEEE Power Electron. Specialists' Conf. Rec.*, 1975, pp. 188–193.

[9] S. Freeland and R. D. Middlebrook, "A unified analysis of converters with resonant switches," in *IEEE Power Electron. Specialists' Conf. Rec.*, 1987, pp. 20–30.

[10] F. S. Tsai, P. Materu, and F. C. Lee, "Constant-frequency, clamped-mode resonant converters," *IEEE Trans. Power Electron.*, vol. 3, no. 4, pp. 460–473, 1988.

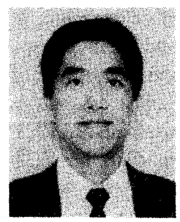
[11] K. H. Liu and F. C. Lee, "Resonant switch—A unified approach to improve performance of switching converters," in *IEEE Int. Telecommun. Energy Conf. Proc.*, 1984, pp. 334–341.

[12] K. H. Liu, R. Oruganti, and F. C. Lee, "Quasi-resonant converters—Topologies and characteristics," *IEEE Trans. Power Electron.*, vol. 2, pp. 62–74, 1987.

[13] M. M. Jovanovic, F. C. Lee, and D. Y. Chen, "A zero-current-switched off-line quasi-resonant converter with reduced frequency range: Analysis, design, and experimental results," *IEEE Trans. Power Electron.*, vol. 4, no. 2, pp. 215–224, 1989.

[14] International Rectifier Corp., *IGBT Designer's Manual*, IRC, 1991.

Guichao Hua, for a photograph and biography please see page 219 of the March 1994 issue of this Transactions.



Eric X. Yang received the B.S. and M.S. degrees in electrical engineering from Tsinghua University, China, in 1982 and 1984, and the Ph.D. degree from Virginia Polytechnic Institute and State University in 1994.

From 1984 to 1988, he was employed as a lecturer in the Department of Electrical Engineering at Tsinghua University, where he taught undergraduate courses and also engaged in the research of developing medical ultrasonic instruments based on microprocessors. In 1989, he joined the Virginia Power Electronics Center. He was actively involved in power electronics research in the areas of modeling, control, dc–dc and ac–dc converter design, high-frequency converters, and computer-aided design for switching power circuits. Since 1994, he has been a member of the technical staff at Harris Power Research and Development in Latham, NY, working on device characterization and soft-switching technique.

Yimin Jiang, for a photograph and biography please see page 219 of the March 1994 issue of this Transactions.

Fred C. Lee (S'72–M'77–SM'87–F'90), for a photograph and biography please see page 219 of the March 1994 issue of this Transactions.