A NEW ZERO-VOLTAGE ZERO-CURRENT MIXED MODE SWITCHING DC/DC CONVERTER WITH LOW DEVICE STRESSES

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ABSTRACT

This paper proposes a new soft switching DC/DC converter with combined zero-voltage and zero-current switching. The power transfer mechanism of the proposed converter is different from that of the resonant type converter such as resonant converter and quasi-resonant converter. The VAR rating of the resonant capacitor of the proposed converter is very small compared with that of the resonant type converter. The applied voltages to all the devices are limited to the supply voltage. This converter can operate in both constant and variable frequency with simple control. The basic operation and analysis of the proposed converter is described. The simulation is performed under the condition of 100 kHz and several kW output power and experimental results are presented.

I. INTRODUCTION

Resonant type converters are being widely used for the demand of light weight and small size converter system in a variety of industrial and aerospace applications because of its ability of high switching frequency operation with low switching losses. Such resonant type converters can be classified into series- and parallel-resonant converters [1-4] and quasi-resonant converter [5-7]. There are two types of quasi-resonant converters which are zero-voltage switching quasi-resonant converter (ZVS-QRC) and zero-current switching quasi-resonant converter (ZCS-QRC). The switching behaviour of all of these converters is to turn on/off under the zero voltage or zero current condition. The power transfer of the resonant converter occurs through the L-C resonant link. Therefore, the VAR ratings of the reactive components of the resonant converter are high, and the control method is usually complicated. The (ZVS-QRC) has low current stress but the active switch voltage stress is proportional to the load. The

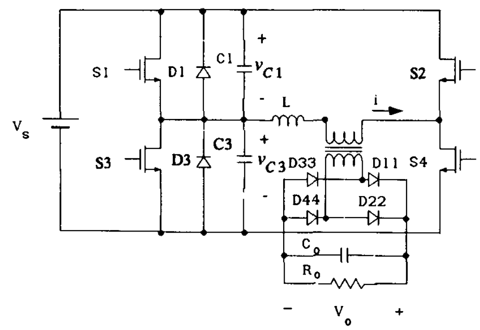


Fig. 1. Circuit diagram of the proposed converter.

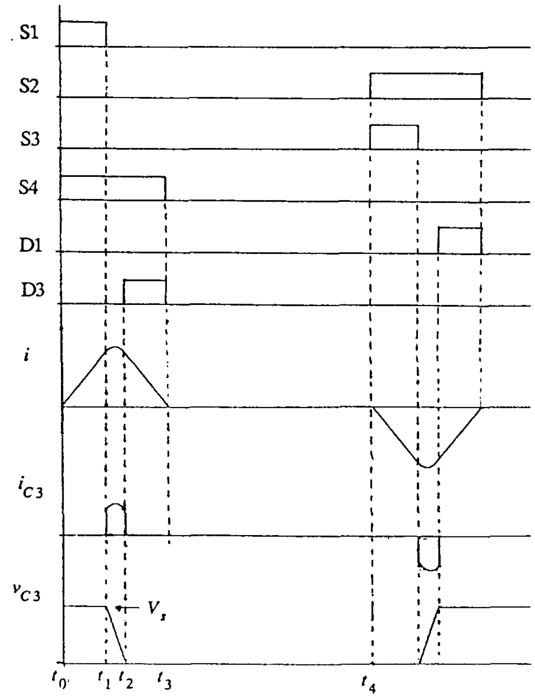


Fig. 2. Typical waveforms of the proposed converter.

applied voltage to the free-wheeling diode of the ZCS-QRC is about two times the supply voltage.

It would be better to achieve such a soft switching condition to avoid the aforementioned problems. Especially, for high power applications the converter would become smaller size, lighter weight and more economic if those problems are overcome. This paper proposes a new converter combined with zero voltage and zero current switching legs. The device voltage stresses of the proposed converter are limited to the supply voltage and the VAR ratings of the resonant capacitors are significantly reduced compared with those of the resonant converter and QRC.

The proposed converter is thought to be one way to achieve a high power converter having high power density. The basic operations and analyses for both constant and variable frequency modes are described under the conditions of 100 kHz and several kW output power and experimental results are presented.

II. PROPOSED CIRCUIT AND BASIC OPERATIONS

The basic configuration of the proposed converter is full bridge type as shown in Fig. 1. One pole is composed of series connected two switchs to which capacitors and diodes are connected in parallel. The other pole is composed of series connected two switches only. The associated typical waveforms of the proposed converter are illustrated in Fig. 2. The waveshape of the inductor current is determined according to four operation modes : powering, resonance, free-wheeling and discontinuous mode as shown in Fig. 3. The respective mode operations are as follows.

A. Mode I : powering mode

The inductor current increases linearly from zero through switch S1, isolation transformer T and switch S4 as shown in Fig. 3(I). During this mode, power is being transfered from source to load. If the capacitor voltage v_{C1} and inductor current i are assumed zero at time t_0, then the switches S1 and S4 are turned on under zero voltage and zero current condition, respectively as shown in Fig. 2. At proper time t_1, the switch S1 is turned off with zero voltage condition.

B. Mode II : resonance mode

By turning off the switch S1 at time t_1, the inductor current path is altered from switch S1 to capacitors C1 and C3 as shown in Fig. 3(II). In this case the inductor current is partially resonant. At the same time, the capacitor voltage v_{C3} begins to decrease from supply voltage V_s to zero with resonant waveform as shown in Fig. 2. This mode ends as the capacitor voltage v_{C3} is decreased to zero. It is found that there is no need of sensing the voltage for the zero voltage switching. The capacitor current i_{C3} is very small compared with the power transfer related current i as shown in Fig. 2. This results in low VAR ratings of the capacitors.

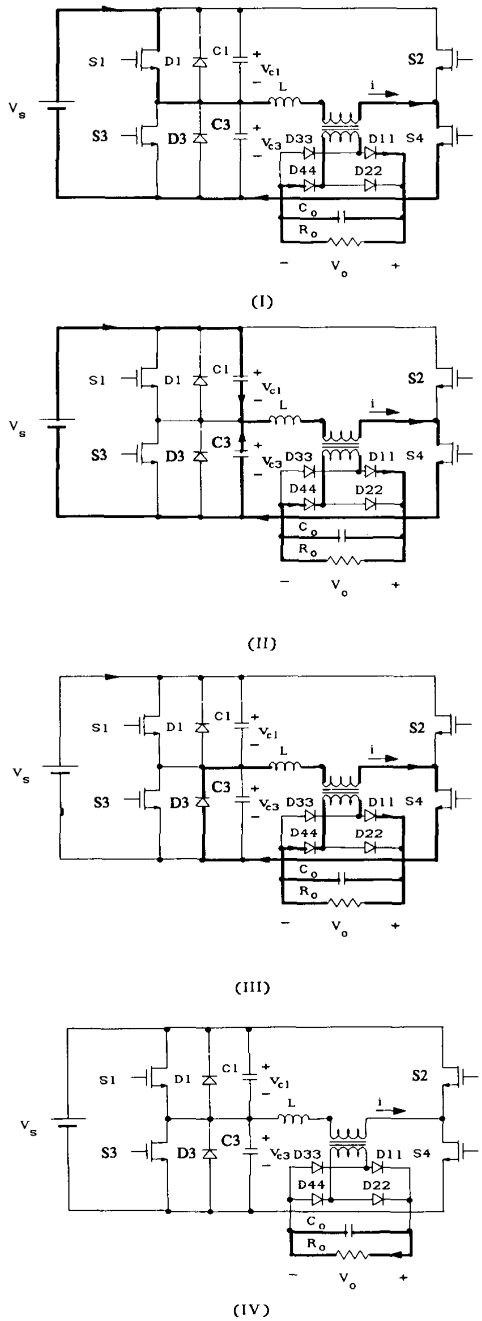


Fig. 3. Mode diagrams of the proposed converter.

C. Mode III : free-wheeling mode

As soon as the capacitor voltage v_{C3} reaches zero at time t_2, the diode D3 begins to conduct and the inductor current freewheels through diode D3, inductor L, isolation transformer T and switch S4 as shown in Fig. 3(III). During this period, the inductor current decreases linearly and reaches zero as shown in Fig. 2. The switch S4 is turned off with zero current switching condition when the inductor current is reduced to zero.

D. Mode IV : discontinuous mode

While the inductor current remains at zero, the load current still flows through the resistor R_o from the output capacitor C_o.

During the total switching cycle the applied voltages to all the switches S1-S4 and diodes D1 and D3 are limited to the supply voltage V_s as shown in Fig. 2. Besides the switches S1 and S3 are turned on and off with zero voltage switching condition and the switches S2 and S4 have zero current switching conditions. This mixed mode operation of zero voltage and zero current switching provides low switching losses and low device stresses. The conduction losses of the proposed converter would also become lower than those of the ZVS-QRC and ZCS-QRC at the same power level because the devices with lower voltage ratings have lower conduction losses. The VAR ratings of the capacitors of the proposed converter are very small compared with those of the resonant type converter, which results in reduced size and weight of the capacitors. The automatically provided zero voltage switching condition without voltage sensing improves the reliability of the converter.

III. ANALYSIS OF THE PROPOSED CONVERTER

The associated equations of the inductor current i and capacitor voltage v_{C3} in each mode are as follows :

$$i = \frac{V_s - V_o}{L} t \qquad \text{(1-a)}$$

$$v_{C3} = V_s, \qquad (t_0 \leqq t \leqq t_1) \qquad \text{(1-b)}$$

$$i = i(t_1) \cos \omega t + \frac{V_s - V_o}{Z_r} \sin \omega t \qquad \text{(2-a)}$$

$$v_{C3} = V_s - [Z_r i(t_1) \sin \omega t + (V_s - V_o)(1 - \cos \omega t)] \qquad \text{(2-b)}$$

$$\omega = \frac{1}{\sqrt{LC}} \qquad \text{(2-c)}$$

$$Z_r = \sqrt{\frac{L}{C}} \qquad (t_1 \leqq t \leqq t_2) \qquad \text{(2-d)}$$

$$C = C1 + C3, \qquad \text{(2-e)}$$

$$i = i(t_2) - \frac{V_o}{L} t \qquad \text{(3-a)}$$

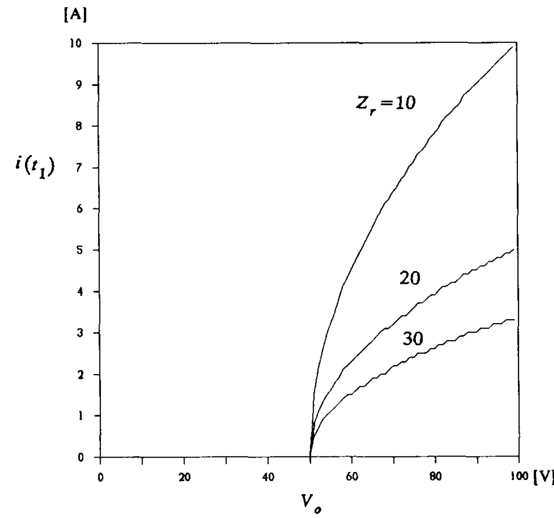


Fig. 4. Required minimum inductor current for zero voltage switching condition. V_s = 100 [V].

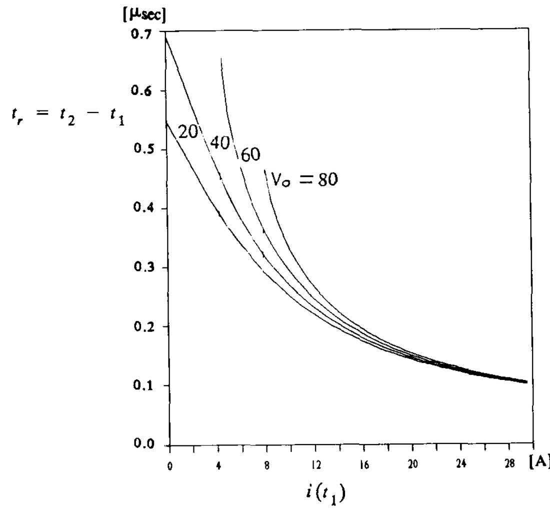


Fig. 5. The partial resonant time interval vs. the variation of the inductor current $i(t_1)$.

$$v_{C3} = 0, \qquad (t_2 \leqq t \leqq t_3) \qquad \text{(3-b)}$$

$$i = 0 \qquad \text{(4-a)}$$

$$v_{C3} = 0. \qquad (t_3 \leqq t \leqq t_4) \qquad \text{(4-b)}$$

To satisfy the zero voltage switching condition of the switch S3, the capacitor voltage v_{C3} should be decreased to zero during the second time interval, $t_1 \leqq t \leqq t_2$. As far as the output voltage V_o is less than the half of the supply voltage V_s, the capacitor voltage v_{C3} is reduced to zero regardless of the load current. If the output voltage V_o is greater

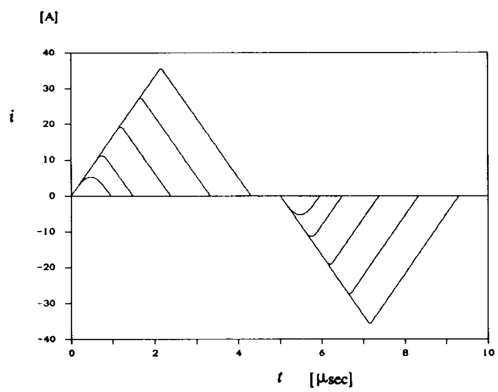


Fig. 6. Inductor current for several values of t_{on} at V_s = 100 [V] and V_o = 50 [V].

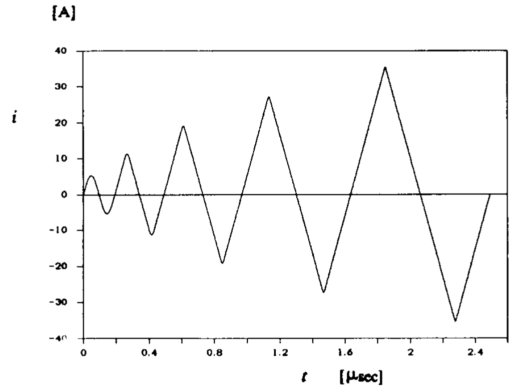


Fig. 8. Waveform of the inductor current with the variation of f_s at V_s = 100 [V] and V_o = 50 [V].

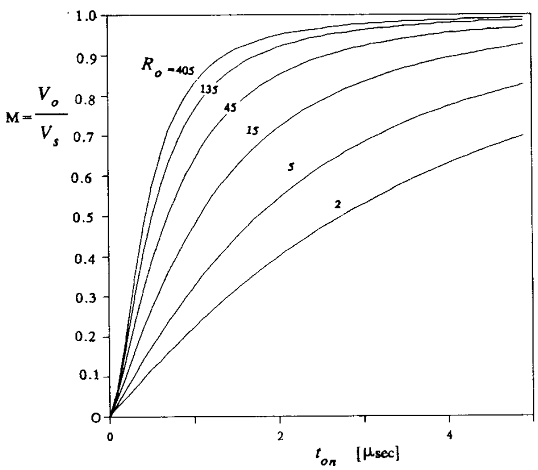


Fig. 7. Voltage conversion-ratio vs. powering time t_{on} for several values of output resistances.

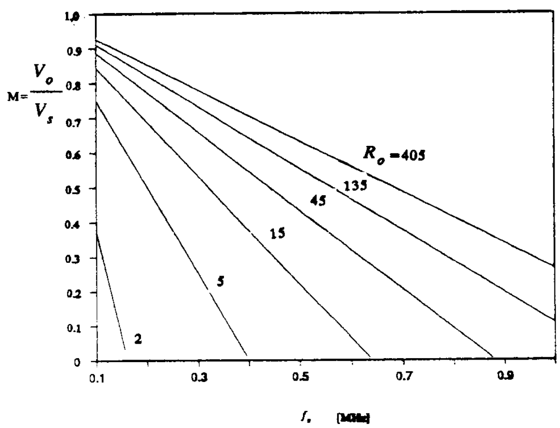


Fig. 9. Voltage conversion-ratio vs. f_s for several values of output resistances.

than the half of the supply voltage V_s, there should be a minimum inductor current to provide the zero voltage switching condition of the switch S3. The relations between the required minimum inductor current at time t_1 to satisfy the soft switching condition and output voltage with the three different values of the characteristic impedances are shown in Fig. 4. The partial resonant time interval depends on the inductor current at time t_1 and the output voltage V_o as shown in Fig. 5. The proposed converter can also be operated on both constant and variable switching frequency modes. A detail analysis in each case is described below.

A. Constant Switching Frequency Operation

There are four modes for constant switching frequency operation of the proposed converter as shown in Fig. 3. The output power can be controlled by the adjustment of the powering time t_{on} which corresponds to the time between t_0 and t_1 in Fig. 2. Fig. 6 shows the inductor currents at the output voltage V_o = 50 [V]. Small powering time t_{on} results in small inductor current and longer resonant period. As the powering time increases the inductor current gradually becomes similar to the triangular waveform. The output voltage V_o versus powering time t_{on} with several values of the load resistances is presented in Fig. 7.

B. Variable Switching Frequency Operation

For variable switching frequency operation, one cycle of the proposed converter is divided into three modes : powering, resonance and free-wheeling mode. The inductor current with the variations of the switching frequency is presented in Fig. 8. As the switching frequency decreases, the inductor current waveform becomes triangular. The output voltage V_o versus switching frequency f_s for several values of the output resistance is presented in Fig. 9.

IV. EXPERIMENTAL RESULTS

In the experiment, the proposed converter shown in Fig. 1 is used. The converter is designed to have the maximum output power p_{max} = 500 [W] at 100 [kHz] of switching frequency. The parameter values of the converter are given as follows:

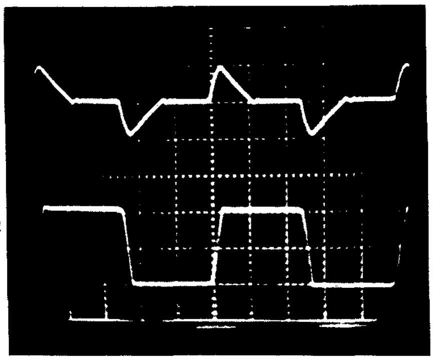
L = 6.25 [μH],
C1, C3 = 0.01 [μF],
V_s = 100 [V].

The voltage applied to the switch S1 and current waveform flowing on the inductor L in constant and variable frequency operating modes are shown in Figs. 10 and 11, respectively. As the conducting period of switch S1, t_{on}, increases, the inductor current increases and the output voltage increases with decreased resonant period. As switching frequency increases, the output voltage decreases at constant resistance R_o. These oscillograms show that the switches S1 and S4 are turned on and off under zero voltage and zero current switching condition, respectively. It is shown that the applied voltages to all the switches are limited to the supply voltage V_s.

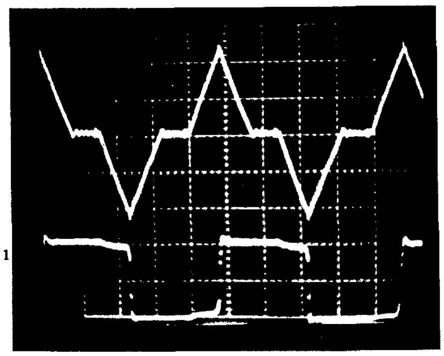
Fig. 12 shows the current and voltage waveform of the capacitor C1 at R_o = 10 [OHM] and t_{on} = 1.5 [μsec]. The capacitor current magnitude is half of the inductor current in resonant mode because the inductor current is the sum of the currents flowing in two capacitors C1 and C3. It shows that the VAR ratings of the capacitors are low compared with those of the resonant type converter.

V. CONCLUSION

The proposed converter is combined with zero voltage switching and zero current switching legs. This results in low device voltage and current stresses and low VAR ratings of the reactive components compared with the resonant type converters. Power control method of the proposed converter is similar to that of the conventional PWM converter. The features of the proposed converter can be summarized as fol-

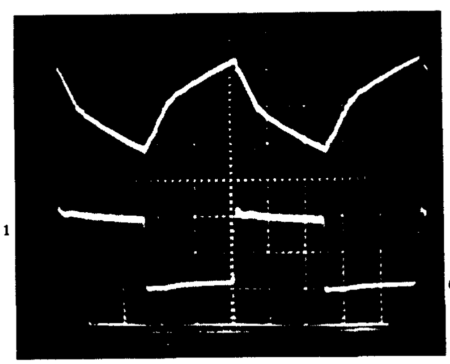


(a) t_{on} = 0.15 μsec, V_o = 13.8 [V].

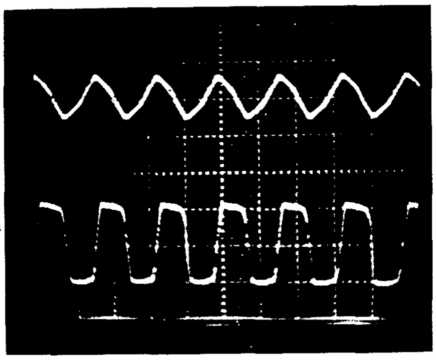


(b) t_{on} = 1.5 μsec, V_o = 50 [V].

Fig. 10. Waveforms of inductor current i and capacitor voltage v_{C1} at constant switching frequency of 100 [kHz]. V_s = 100 [V], R_o = 10 [OHM], i : 5 A/div, v_{C1} : 50 V/div, and time : 2 μsec/div.



(a) f_s = 100 [kHz], V_o = 79 [V].



(b) f_s = 330 [kHz], V_o = 42 [V].

Fig. 11. Waveforms of inductor current i and capacitor voltage v_{C1} at variable switching frequency mode: V_s = 100 [V], R_o = 10 [OHM], i : 10 A/div, v_{C1} : 50 V/div, and time : 2 μsec/div.

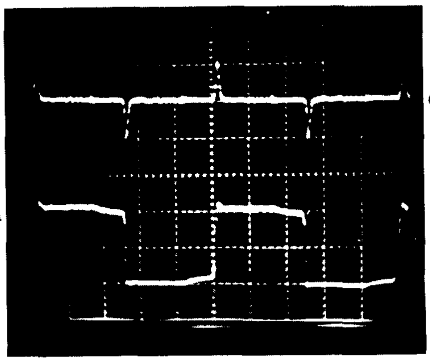


Fig. 12. Current and voltage waveform of the capacitor C1: V_s = 100 [V], t_{on} = 1.5 μsec, R_o =10 [OHM], i_{C1} : 5 A/div, v_{C1} : 50 V/div, and time : 2 μsec/div.

lows :

1) low switching losses due to combined zero voltage and zero current switchings,
2) low device voltage stresses,
3) low VAR ratings of the reactive components,
4) simple control,
5) high frequency operation,
6) automatically provided zero voltage switching condition without sensing.

These good features show a possibility for more effective approach to the high power application with high power density.

References

[1] F. C. Schwarz, " An improved method of resonant current pulse modulation for power converters," IEEE Trans. Ind. Elec. Cont. Inst., vol. IECI-23, No. 2, May 1976, pp. 133-141.

[2] R. L. Steigerwald, " High-frequency resonant transister DC-DC converters," IEEE Trans. Ind. Elec., vol. IE-31, No. 2, May 1984, pp. 181-191.

[3] R. King and T. A. Stuart, " A normalized model for the half-bridge series resonant converter," IEEE Trans. Aer. Elec. Sys., vol. AES-17, No. 2, Mar. 1981, pp. 190-198.

[4] G. B. Joung, C. T. Rim and G. H. Cho, " An integral cycle mode control of series resonant converter," IEEE-PESC Rec., 1988, pp. 575-582.

[5] K. H. Liu, R. Oruganti and F. C. Lee, " Resonant switches - topologies and characteristics," IEEE-PESC Conf. rec., 1985, pp. 106-116.

[6] W. A. Tabisz, P. Graclzki and F. C. Lee, " Zero voltage switched quasi-resonant buck and flyback converter - exrerimental results at 10 MHz," IEEE-PESC Conf. Rec., 1987, pp. 404-413.

[7] F. C. Lee, " High-frequency quasi-resonant converter technologies," Proceedings of the IEEE, vol. D6, No. 4, Apr. 1988.