Cyclic Quasi-Resonant Converters: A New Group of Resonant Converters Suitable for High Performance DC/DC and AC/AC Conversion Applications

Jung G. Cho and *Gyu H. Cho*

Dept. of Electrical Engineering, Korea Advanced Institute of Science and Technology
P.O.Box 150 Chongryang, Seoul 130-650, Korea (FAX : 82-02-960-2103)

ABSTRACT

The conventional resonant switch and quasi-resonant converters[QRC] are generalized from the viewpoint of switch cell. A new resonant switch and a new family of resonant converters which are named as *Cyclic Resonant Switch[CRS]* and *Cyclic Quasi-Resonant Converters[CQRC]*, are proposed as a part of the generalized topologies of QRC's. The proposed CQRC's show very simple operation and easy control and analysis and they overcome the limited control range characteristics of the conventional QRCs. Further, they can be applied for AC chopper as well as DC/DC converter. Steady state operations and characteristics of the buck type CQRC are analyzed and verified by the experiment in a condition of 200 KHz, 1 KW power level.

I. INTRODUCTION

In switching power converters, the resonant conversion techniques have been renewed fast to replace the conventional PWM converters since it is firstly introduced in the last sixties. So far, a number of resonant converter topologies and control methods are introduced, however most of them show complex topologies and or difficulties in control, analysis and design.[1-4] Further, the zero cross switchings are often not assured or the characteristics are mostly different from those of the conventional PWM converters.

The quasi-resonant converters[QRC] with the concept of resonant switch was proposed by Liu and Lee[5] and have been hot issues in recent years. They have well known merits such as simple circuit topology, simple control and analysis and similar characteristics to the conventional PWM converters for full wave mode operation. The topology of resonant switch has also been extended and generalized and several groups of QRC's have been suggested and experimented over a range of several mega-hertz switching frequency.[6-8]

Even though, the QRC's can be thought to be promising converters to replace the conventional hard switched PWM converters, they have several shortcomings unsolved yet. In the case of halfwave mode operation, the QRC's show high nonlinear and load dependent characteristics and thus, it is not easy to use where the load variation is wide. On the other hand, for fullwave mode operation, the QRC's show the degrading efficiency characteristics when the load is decreased from its maximum value. Further, in either case, the control range is limited depending on the load resistance and characteristic impedance of LC resonant elements.

In this paper, the conventional zero current resonant switch and QRC's are generalized by using the concept of switch cell and generalizing the type of switches. As a part of the generalized ones, a new resonant switch, named as *Cyclic Resonant Switch[CRS]* and a new family of resonant converters, named as *Cyclic Quasi-Resonant Converters[CQRC]*, are proposed to improve the performance of the conventional QRC's and to extend their applications to AC chopper.

Previously the conventional 4-basic PWM DC/DC converters were unified and modeled by the concept of switch cell, just name of *PWM switch*.[9,10] In this paper, it is extended to 6-basic PWM DC/DC converters and a unique topology of 3-terminal PWM switch cell is extracted from them by slightly changing the circuit topologies. A general topology of resonant switch cell is generated by incorporating LC resonant elements to the PWM switch cell and generalizing the switch types. Simply by replacing the switch cell of the conventional 6-basic PWM DC/DC converters with general resonant switch cell, general topologies of 6-basic QRC's are obtained and two groups of resonant converters are generated according to the switch types: one is the conventional QRC group and the other is the newly proposed CQRC group.

The proposed CQRC's which include two active switches, show similar DC characteristic to those of fullwave mode operated QRC's. The operation and analysis, however, are simplified and the limited control range characteristic is overcome. Besides, the degrading efficiency characteristic according to decreasing load current from its maximum value can be improved. So, the DC characteristics of CQRC's are closer to those of the PWM converters than those of the conventional QRC'c. For these reasons, the conventional control and modeling techniques for PWM converters can also be applied to CQRC's. Furthermore, by replacing the switches with bidirectional ones, the CQRC's can also be used for AC chopper which can be operated on four quadrants.

Circuit operating principle and steady state operation of buck type CQRC are described and the DC transfer characteristics and the switch stresses are also analyzed and compared with those of the conventional QRC's. Modeling of the CQRC's is also performed using DC and AC model of CRS cell. Experimental results at 200 *KHz*, 1 *KW* level are shown to verify the operational principle and characteristics.

II. GENERALIZATION OF THE RESONANT SWITCH AND QUASI-RESONANT CONVERTERS

A. Unification of 6-Basic PWM Converters Using the Concept of Switch Cell

The conventional 6-basic PWM DC/DC converters are shown

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in the left part of Fig. 1. It is shown that all of them contain two switches composed of one active and one passive switches. A large number of approaches were suggested to model and unify them. It was shown that the 4-basic PWM converters can be unified and modeled by using the concept of 3-terminal PWM switch cell.[9,10] In this paper, it is extended to 6-basic PWM converters and a unique topology of 3-terminal PWM switch cell is extracted by slightly changing the circuit topologies but without modifying the overall functions as shown in right part of Fig. 1. The extracted 3-terminal PWM switch cell consists of one active and one passive switches as shown in Fig. 2(a) and can be generalized by using general switches as shown in Fig. 2(b). From the right part of Fig. 1, it can be seen that the voltage source (or capacitor) must be connected between terminal 1 and 2 and the current source(s) (or inductor(s)) must be connected to terminal 3.

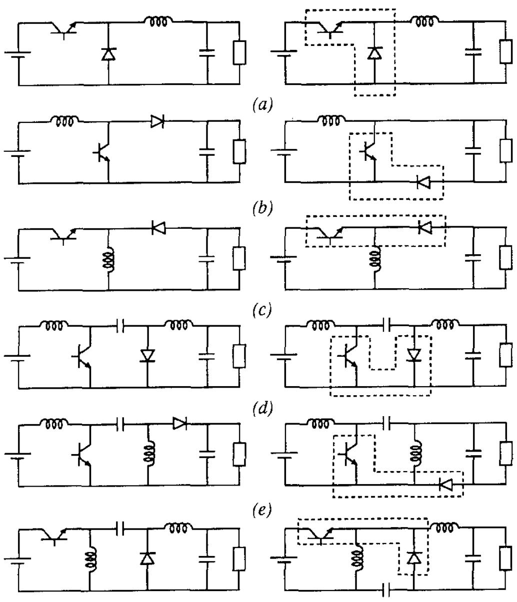


Fig. 1 Extracting switch cell from the conventional 6-basic PWM DC/DC converters: (a) buck, (b) boost, (c) buck-boost, (d) Cuk, (e) sepic, (f) zeta.

B. General Topology of Resonant Switch

The concept of resonant switch was firstly introduced by Liu and Lee[5] and it has been extended and generalized.[6,7] In this paper, a generalization of resonant switch is performed by using the concept of 3-terminal switch cell and generalizing the type of switches. Consequently, a general topology of 3-terminal resonant switch cell is obtained by incorporating the LC resonant elements to the 3-terminal PWM switch cell, an inductor is inserted in series with S_1 for zero current switching and a capacitor is shunted to S_2 for zero voltage switching, as shown in Fig. 3. According to the switch configurations of the general resonant switch cell, two groups of resonant switch cell can be obtained, one is conventional resonant switch, the other is the newly proposed CRS as shown in Table 1. The CRS includes two active switches instead of one active and one passive switch configuration of the conventional resonant switch.

Switching waveforms of the proposed CRS are shown in Fig. 4 with those of the PWM switch and conventional resonant switches, for comparison. The switching waveforms of the PWM switch and the conventional resonant switches are well known and simple as shown in Fig. 4(a) to (b). Switching operation of the CRS is very similar to that of the PWM switch, two switches are turned on and off alternately without any overlap period. The switching waveforms of CRS are shaped sinusoidally for complete single resonant cycle as shown in Fig. 4(c) and the averaged level of switching waveforms are identical to those of the PWM switch. The peak value of resonant voltage and current are varied adaptively according to I_3 instead of fixed values of the conventional QRC's since the LC resonant circuit is exited by two step inputs, V_{12} and I_3.

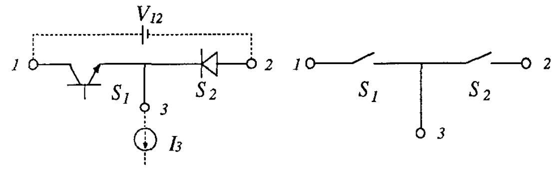


Fig. 2 Extracted 3-terminal PWM switch cell: (a) DC switch, (b) general switch.

C. Generation of the General topologies and Two Groups of QRC's

It is shown that the conventional 6-basic PWM converters can be organized by 3-terminal PWM switch cell. General topologies of 6-basic QRC's are obtained from the 6-basic PWM converters simply by replacing each switch cell with general resonant switch cell as shown in Fig. 5. According to the types of switches, two groups of QRC's can be obtained as shown in Table 2: one is a 6-basic conventional QRC's and the other is the newly proposed 6-basic CQRC's. we can see that the proposed CQRC's can be applied to the AC chopper by using bidirectional switches.

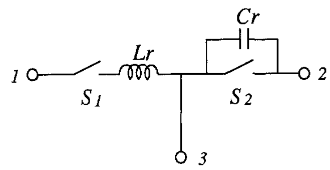
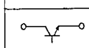
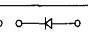
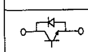
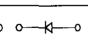
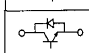
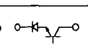
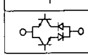
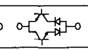


Fig. 3 3-terminal general resonant switch cell.

Table 1 Generation of the several resonant switch cells.

S_1	S_2	resonant switches
		*halfwave mode resonant switch*
		*fullwave mode resonant switch*
		*Cyclic resonant DC switch*
		*Cyclic resonant AC switch*

III. ANALYSIS OF BUCK TYPE CQRC

A. Principle of Operation

The circuit topologies of buck type of CQRC's are shown in Fig. 6(a) and (b), as DC/DC converter and AC chopper, respectively. To analyze their steady state behavior, the following assumptions are made:

- o L_f is much larger than L_r, so the output filter $L_f C_f$ and the load are treated as a constant current source.
- o All devices and reactive elements are ideal.

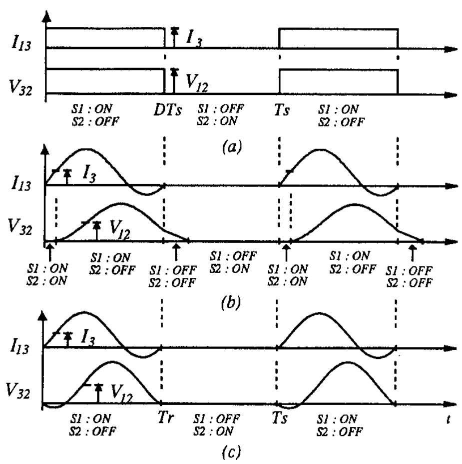


Fig. 4 Comparison of the switching waveforms of the each switch cell: (a) PWM switch, (b) conventional resonant switch(fullwave mode), (c) proposed cyclic resonant switch.

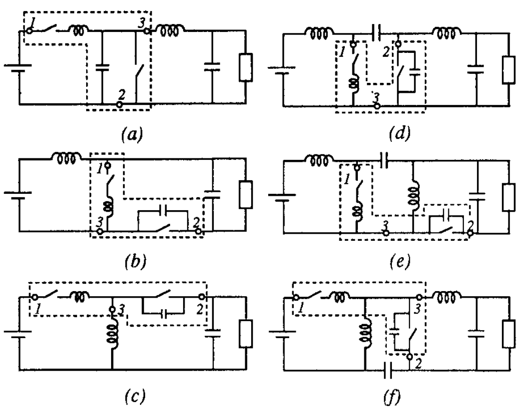
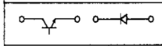
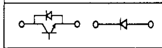
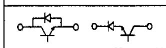
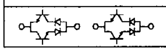


Fig. 5 A family of general circuit topologies of QRC's: (a) buck, (b) boost, (c) buck-boost, (d) Cuk, (e) sepic, (f) zeta.

Table 2 Generation of the several families of QRC's according to the types of switches

S_1 S_2	family of resonant converters
	*conventional QRC's (halfwave mode)*
	*conventional QRC's (fullwave mode)*
	*proposed CQRC's (DC/DC converters)*
	*proposed CQRC's (AC choppers)*

The following variables are defined:

- o Characteristic impedance, $Z_r = \sqrt{L_r/C_r}$
- o Resonant angular frequency, $\omega_r = 1/\sqrt{L_r C_r}$
- o Resonant period, $T_r = 1/f_r = 2\pi/\omega_r$

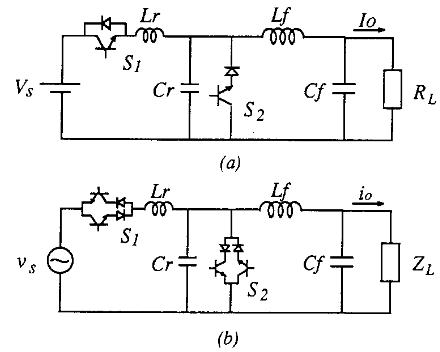


Fig. 6 Circuit topologies of the buck type CQRC's: (a) DC/DC converter, (b) AC chopper.

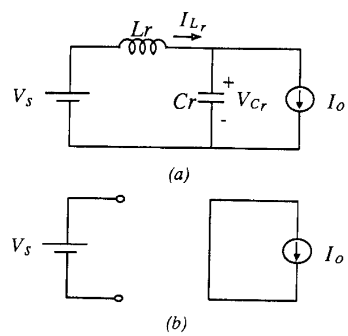


Fig. 7 Equivalent circuits for each switching stage: (a) resonant stage, (b) freewheeling stage.

A switching cycle can be divided into two stages instead of four stages of the conventional QRC's and the associated equivalent circuits for these stages are shown in Fig. 7(a) and (b). Suppose that the inductor current I_{Lr} and the capacitor voltage V_{Cr} are all initially zero and S_2 carries the steady state output current I_o. At time T_o, switching cycle starts by turning on S_1 with zero current and turning off S_2 with zero voltage.

(i). Resonant Stage (T_o,T_r);

As shown in Fig. 7(a), voltage source V_s and the current source I_o are simultaneously applied to LC resonant circuit at time T_o in serial and parallel, respectively. Consequently, the resonant circuit is excited by two step inputs. The state equations are given by

$$L_r \frac{dI_{L_r}(t)}{dt} = V_s - V_{C_r}(t) \qquad (1)$$

$$C_r \frac{dV_{C_r}(t)}{dt} = I_{L_r}(t) - I_o \qquad (2)$$

with initial conditions, $I_{L_r}(0) = 0$, $V_{C_r}(0) = 0$. Thus, I_{L_r} and V_{C_r} become

$$I_{Lr}(t) = \sqrt{(V_s/Z_r)^2 + I_o^2}\,\sin(\omega t - \tan^{-1}(Z_r I_o/V_s)) + I_o \quad (3)$$

$$V_{Cr}(t) = \sqrt{(Z_r I_o)^2 + V_s^2}\,\sin(\omega t - \tan^{-1}(V_s/Z_r I_o)) + V_s. \quad (4)$$

The resonant inductor current and capacitor voltage show all sinusoidal waveforms with dc offset I_o and V_s, respectively as shown in Fig. 8 and the amplitudes of resonant current and voltage are varied according to load current I_o, instead of fixed values of the conventional QRC's. At time Tr, after one resonant period, they come to the initial states of resonant stage as, $I_{Lr}(T_r) = 0$, $V_{Cr}(T_r) = 0$.

(ii). Freewheeling Stage ($T_r T_s$);

At time T_r, S_1 is turned off with zero current and S_2 is turned on with zero voltage simultaneously and then, the output current freewheels through the S_2 until T_s, the end of switching cycle as shown in Fig. 7(b). Overall switching waveforms are shown in Fig. 8.

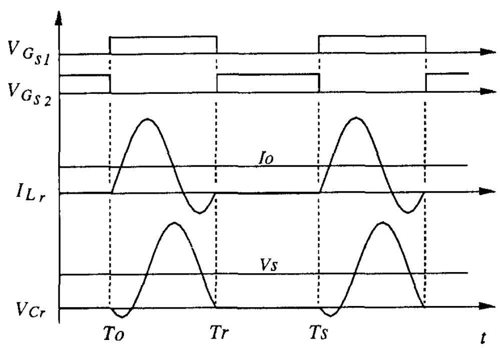


Fig. 8 Switching waveforms of the buck type CQRC.

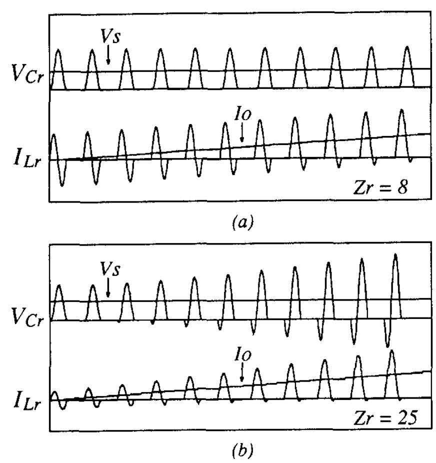


Fig. 9 Comparisons of the switching waveforms with load current variation: (a) conventional QRC with fullwave mode operation, (b) CQRC.

B. Macroscopic waveforms

To obtain illustrative switching waveforms, the combination of output filter $L_f C_f$ and load is still treated as a constant current source. The macroscopic waveforms of buck type CQRC and QRC with fullwave mode operation, are shown in Fig. 9(a) and (b), respectively to compare the switching operations according to the load current. As can be seen in Fig. 9, the peak-to-peak value of resonant current and voltage of the proposed CQRC are increased adaptively according to the load current increment while those of the conventional QRC are always fixed. This fact contributes to overcome the limited control range characteristics and to improve efficiency degrading characteristics of the conventional QRC's according to load current decrement.

Fig. 10 shows macroscopic waveforms of the buck type CQRC as AC chopper. In the real situation, the switching frequency should be much higher than the source frequency however it is shown for seven times that of source frequency to reveal the switching operations clearly. The voltage and current waveforms for given source voltage and load current are shown in Fig. 10(a) and (b), in the case of resistive load and inductive load, respectively. The amplitude of output voltage can be controlled by the ratio of the switching frequency and resonant frequency f_s/f_r for any kind of load. It is shown that the buck type CQRC as AC chopper has four quadrant operation capability.

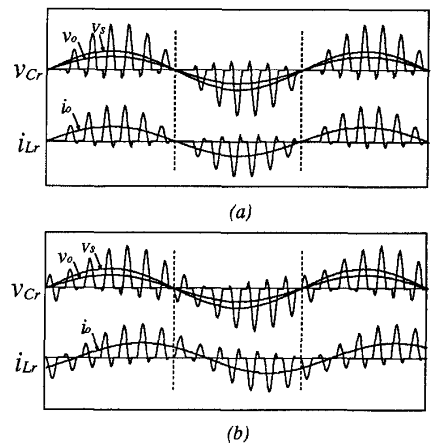


Fig. 10 Illustrative switching waveforms of the CQRC for AC chopper application: (a) resistive load case, (b) inductive load case.

IV. CHARACTERISTICS

A. DC Voltage Conversion Ratio of Buck Type CQRC

The output voltage V_o of the buck type CQRC can be solved by equating the input energy per cycle E_i to the output energy per cycle E_o where

$$E_i = V_s \int_{T_o}^{T_s} I_{Lr}(t)dt \quad (5)$$

$$E_o = V_o I_o T_s. \quad (6)$$

From eq.(5) and eq.(6), we obtain

$$V_o = \frac{T_r}{T_s} V_s = \frac{f_s}{f_r} V_s. \quad (7)$$

This relationship shows that the DC voltage conversion ratio of the buck type CQRC depends linearly on the normalized switching frequency f_s/f_r and it is plotted in Fig. 11 with that of the fullwave mode QRC for comparison. The voltage conversion ratios of the buck type QRC are well known, for halfwave mode operation, it shows nonlinear and load dependent characteristics while, for fullwave mode operation, it shows linear and almost load independent characteristics. However, in either case, the control range are limited depending on normalized load resistance R/Z_r as shown in Fig. 11(a). The voltage conversion ratio of the proposed buck type CQRC, however, shows linear and completely load independent characteristics and thus, it overcome the limited control range characteristics of the QRC's as shown in Fig. 11(b). As can be seen from these figure, the voltage conversion ratio of the CQRC is the same as that of the PWM buck converter with the normalized frequency control rather than duty ratio control.

B. DC Voltage Conversion Ratios of Other Types of CQRC

DC voltage conversion ratios of other types of CQRC can easily be derived and their characteristics are also the same as those of the corresponding PWM converters. The voltage conversion ratio characteristics for each type are plotted in Fig. 12.

C. Switch Stresses of Buck Type CQRC

The peak current and voltage stresses of the two switches can be evaluated from eq.(3) and eq.(4). The peak current stress of S_1 and S_2 are obtained as follows

$$I_{S_1} = \sqrt{(V_s/Z_r)^2 + I_o^2} + I_o. \qquad (8)$$

$$I_{S_2} = I_o. \qquad (9)$$

Similarly, the peak voltage stress of S_1 and S_2 are obtained as follows

$$V_{S_1} = V_s \qquad (10)$$

$$V_{S_2} = \sqrt{(Z_r I_o)^2 + V_s^2} - V_s \quad (\textit{for DC/DC converter}) \qquad (11)$$

$$V_{S_2} = \sqrt{(Z_r I_o)^2 + V_s^2} + V_s \quad (\textit{for AC chopper}). \qquad (12)$$

As can be seen from the above equations, the peak current stress of S_2, I_{S_2} and the peak voltage stress of S_1, V_{S_1} are the same as those of the conventional QRC's.

The peak current stress of S_1 is comparable to that of the conventional buck type QRC with fullwave mode operation which is given as

$$I_{S_1} = V_s/Z_r + I_o. \qquad (13)$$

The normalized peak current stresses for the buck type CQRC and the fullwave mode QRC according to the normalized load current are plotted with the parameter Z_r in Fig. 13(a) and (b), respectively. We can see that the peak current stress is decreased by increasing the characteristic impedance Z_r in either case and so, the Z_r is required to be increased somewhat high to reduce the the conduction loss of S_1. In the case of the conventional QRC, the increment of Z_r is limit to some value as shown in Fig. 13(a) and the limited value of Z_r can be obtained from the condition of zero current switching V_s/Z_r I_{omax} as follows

$$Z_{rmax} = \frac{V_s}{I_{omax}}, \qquad (14)$$

which is basically caused by the limited control range characteristics of the conventional QRC's according to the relation between Z_r and the maximum load current. However, in the proposed CQRC, there is no limitation for Z_r as shown in Fig. 13(b). Thus, the CQRC's can be operated more efficiently than the conventional

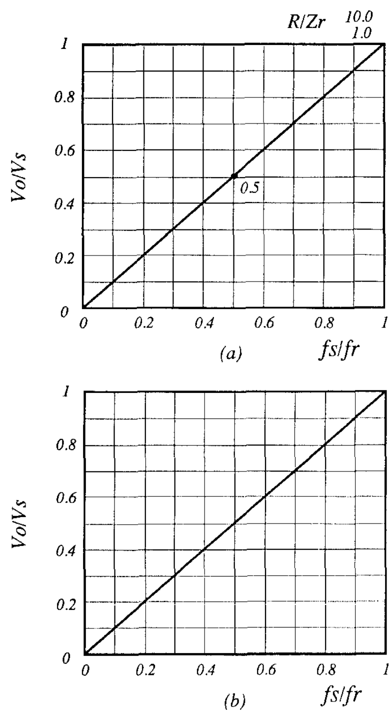


Fig. 11 DC voltage conversion ratio characteristics of the buck type QRC's: (a) conventional QRC(fullwave mode operation), (b) CQRC.

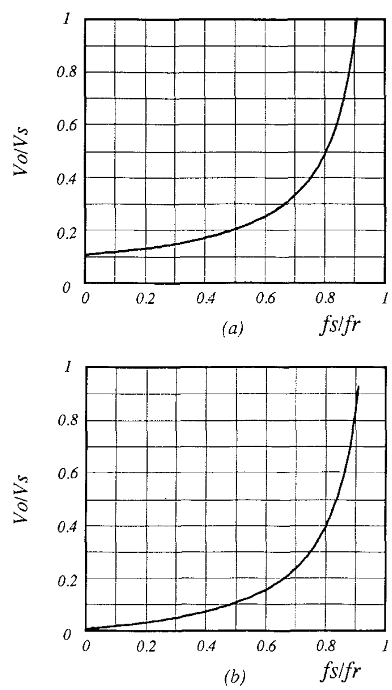


Fig. 12 DC voltage conversion ratio of the other types of CQRC's: (a) boost, (b) buck-boost, Cuk, sepic, zeta.

QRC's, if the S_2 is chosen such that the conduction losses of S_2 and D_2 are not so high. These facts are clearly revealed in Fig. 9(a) and (b), switching waveforms according to the variation of load current.

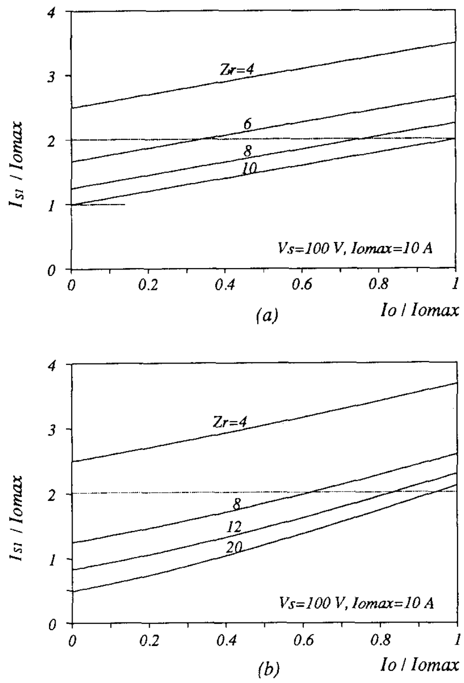


Fig. 13 Comparison of the peak current stress characteristics of S1: (a) conventional QRC(full wave mode operation), (b) CQRC.

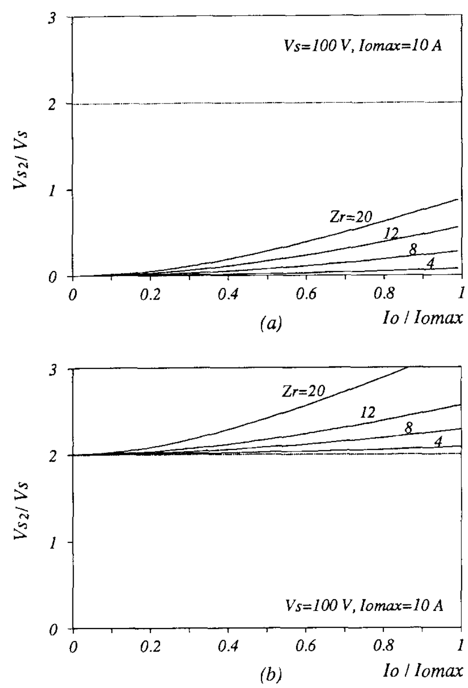


Fig. 14 Peak voltage stress characteristics of S2: (a) DC/DC converter application case, (b) AC chopper application case.

The voltage stress of S_2 differs according to its applications as shown in eq.(11) and (12). In the case of DC/DC converter, the positive part of V_{C_r} is blocked by reverse blocking diode D_2 and the only negative part of V_{C_r} acts as the voltage stress of S_2 while, in case of AC chopper, the peak voltage of V_{C_r} always acts as the voltage stress of S_2. The normalized peak voltage stress in either case according to the normalized load current are plotted with the parameter Z_r in Fig. 14(a) and (b), respectively. In designing the CQRC's, therefore, the conduction loss of S_1 and the voltage rating of S_2 should be compromised by moderate selection of Z_r.

D. Modeling of the proposed CQRC's

The DC and AC model of the PWM switch cell were obtained using the averaging concept.[9] Simply by replacing the control input with normalized switching frequency rather than duty ratio, the DC and AC model of the CRS cell can be obtained as shown in Fig. 15(a) and (b), respectively. Thus, the DC and AC model of the proposed 6-basic CQRC's can also be obtained by using the concept of switch cell, by replacing each CRS cell with its DC and AC model, respectively. Conventional design techniques for PWM converters can also be used for CQRC's because of their similar characteristics.

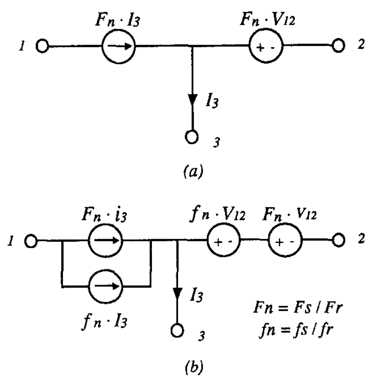


Fig. 15 DC and AC model of the CRS cell: (a) DC model, (b) AC model, capital letter: large signal, small letter: small signal.

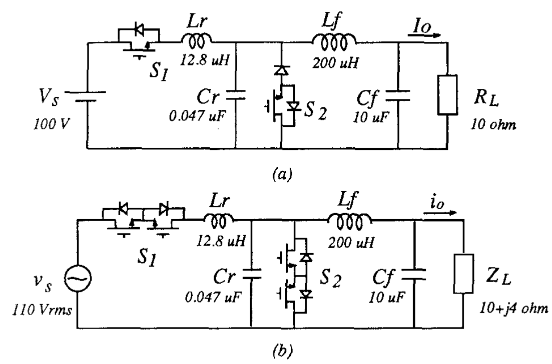


Fig. 16 Circuit diagrams of the buck type CQRC's for experiment: (a) DC/DC converter application, (b) AC chopper application.

V. EXPERIMENTAL RESULTS

1 *KW* level buck type CQRC for DC/DC converter and AC chopper are tested to verify the operational principle and characteristics. The circuit diagrams in either applications are shown in Fig. 16(a) and (b), respectively, with the component values. The resonant frequency and the characteristic impedance of LC resonant components are chosen as 200 *KHz*, 16 Ω, respectively.

The switching waveforms of DC/DC converter application are shown in Fig. 17 and it can be seen that they are well matched with the theoretical values. The measured efficiency is over 88% at full load. Fig. 18 shows the voltage conversion ratio in either applications with comparison to the theoretical value. The measured voltage conversion ratios are shown to slightly decrease with the load current increment, which is mainly caused by the conduction losses of the semiconductor devices. Fig. 19 and 20 show the waveforms of the AC chopper application of CQRC with resistive load(10 Ω) and inductive load($10 + j4$ Ω), respectively. The amplitude of the output voltage can be controlled by normalized switching frequency f_s/f_r for any kind of load and thus, it can be operated on four quadrant.

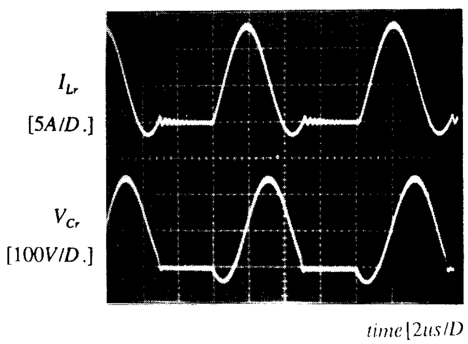


Fig. 17 Switching waveforms of the buck type CQRC for DC/DC converter: fr = 200 KHz, fs = 120 KHz

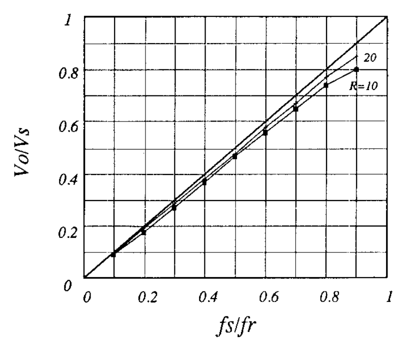


Fig. 18 Voltage conversion ratio of the buck type CQRC, marked lines; measured values.

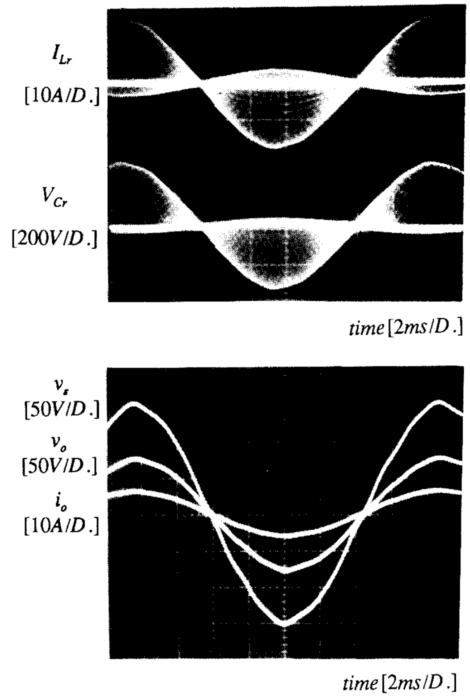


Fig. 19 Waveforms of the buck type CQRC for AC chopper (Vo=0.5*Vs): resistive load case.

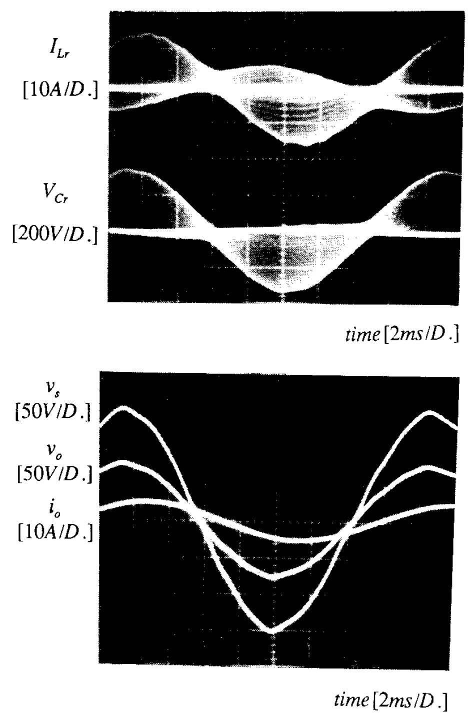


Fig. 20 Waveforms of the buck type CQRC for AC chopper (Vo=0.5*Vs): inductive load case.

VI. CONCLUSION

Generalization of the conventional resonant switch and quasi-resonant converters[QRC's] by generalizing the type of switches and by using the concept of switch cell, are presented and a new resonant switch, *Cyclic Resonant Switch[CRS]* and a new family of resonant converters, *Cyclic Quasi-Resonant Converters[CQRC's]* are proposed as a part of the generalized ones, respectively. The steady state operation and several characteristics of the proposed CQRC's are analyzed and verified by experiment in a condition of 200 KHz, 1 KW power level and the modeling method is also suggested.

It is shown that the conventional 6-basic PWM DC/DC converters can be unified by the concept of switch cell, known as *PWM switch cell* and the general topologies of 6-basic QRC's can easily be obtained from the conventional 6-basic PWM DC/DC converters by replacing the PWM switch cell with the generalized resonant switch cell. According to the types of switches, the conventional QRC's and newly proposed CQRC's can be obtained.

It is also shown that the proposed CQRC's have very similar characteristics as those of the conventional PWM converters with frequency control rather than duty ratio control. Several advantages of CQRC's over the conventional QRC's as follows:

1) simple operation (only two switching stages),
2) easy to analyze and model,
3) unlimited load range(or unlimited control range),
4) improved efficiency compared to the fullwave QRC.

Further, by using the bidirectional switches, the proposed CQRC's can be applied to high performance AC chopper as well.

REFERENCES

[1] R. L. Steigerward, "High frequency resonant transistor dc-dc converters", IEEE, Trans. on Industrial Electronics, Vol. IE-31, NO. 2, pp. 181-192, May 1984.

[2] V. Vorperian and S. Cuk, "A complete DC analysis of the series resonant converter", IEEE PESC Rec., pp. 85-100, 1982.

[3] Ira J. Pitel, "Phase-modulated resonant power conversion techniques for high frequency link inverters", IEEE Trans. on Industry Applications, Vol. IA-22, No. 6, pp. 1044-1051, Nov./ Dec. 1986.

[4] V. Vorperian, "Quasi-square-wave converters: Topologies and analysis", IEEE Trans. on Power Electronics, Vol. 3, No. 2, pp. 183-191, April 1988.

[5] K. H. Liu, R. Oruganti and F. C. Lee, "Quasi-resonant converter - topologies and characteristics", IEEE Trans. on Power Electronics, Vol. PE-2, No. 1, pp. 62-71, Jan. 1987.

[6] T. Zeng, D. Y. Chen and F. C. Lee, "Variations of quasi-resonant DC-DC converter topologies", IEEE PESC Rec., pp. 381-392, 1986.

[7] Khai D. T. Ngo, "Generalization of resonant switches and quasi-resonant dc-dc converters", IEEE PESC Rec., pp. 395-403, 1987.

[8] W. A. Tabisz and F. C. Lee, "Zero-voltage-switching multi-resonant technique -- A novel approach to improve performance of high-frequency quasi-resonant converters", IEEE PESC Rec., pp. 9-17, April 1988.

[9] R. Tymerski, V. Vorperian, F. C. Lee and W. Baumann, "Nonlinear modeling of the PWM switch", IEEE Trans. on Power Electronics, Vol. 4, No. 2, April, 1989.

[10] V. Vorperian, R. Tymerski and F. C. Lee, "Equivalent circuit models for resonant and PWM switches", IEEE Trans. on Power Electronics, Vol. 4, No. 2, April, 1989.