A New Soft Recovery Pulse Width Modulation Quasi-Resonant Converter with Multiple Order Valley-Fill Network.

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Abstract -- A new Soft Recovery (SR) Quasi-Resonant Converter (QRC) having multiple order valley fill network is introduced. It is combined with normal quasi-resonant converter with valley fill network of which the surrounding components are composed of diodes and capacitors. The reverse recovery loss of main rectifier diode is eliminated by this method utilizing multiple resonance. The proposed converter has PWM capability with high efficiency and is suitable for high voltage and high power applications. By extension of this concept to other switching converters, a new family of SR PWM QRC can be shown.

I. Introduction

DC to DC switching converter is widely used for various applications. The inductor in DC to DC converter plays major role to store and transfer the energy. But, induced voltage in the inductor also produces another trouble such as noise, EMI and switching loss. Moreover, peak reverse recovery surge current that feed from main rectifies diode force to destroy the switch device or restrict the capability of supplying output power. Therefore, It is hardly possible to supply large output power without reducing above surge current. Many soft switching techniques are introduced to improve these problems. Zero voltage transition (ZVT) PWM converter[1] which is one of the quasi resonant (QR) converters[2] and passive snubber PWM Converter[3][4] are known to reduce hard switching problems. The ZVT PWM converters, however, should adopt additional auxiliary active switch and its complex driving circuit for soft switching operation. On the other hand, the passive snubber PWM converter generates undesirable parasitic oscillation across the switching rectifier when the main rectifier diode is in off state. This parasitic oscillation becomes one of the unstable and noise factors. This paper proposes a new soft recovery PWM quasi-resonant converter (SR PWM QR Converter) that contains Multiple-order Valley Fill Network (MVFN) for snubber of main diode utilizing multiple resonance. As a result of MVFN, the capability of supplying output power and the efficiency of output power is remarkably improved and other parasitic oscillation is reduced significantly. As multiple-order valley fill network (MVFN) is composed of passive elements only, the system is also simple in control and design with increased reliability.

II. The Soft Recovery Pulse Width Modulation Quasi-Resonant Boost Converter.

(SR PWM QR Boost Converter.)

A. Basic principle

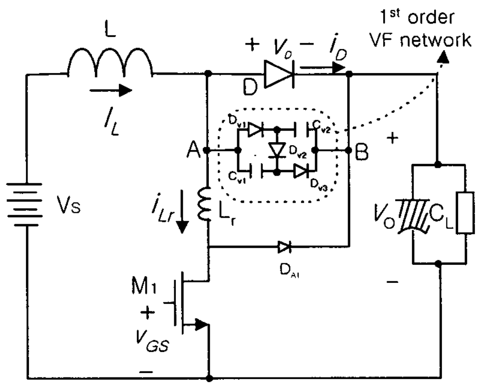
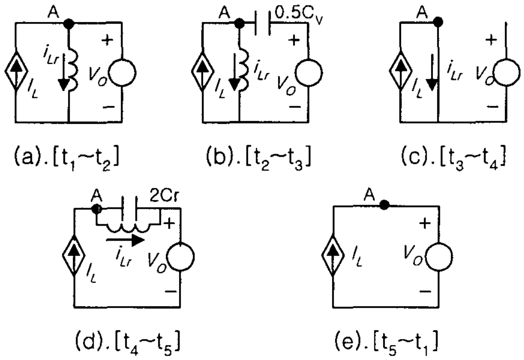


Fig.1 Proposed SR PWM boost QR converter.

Fig.1 shows proposed boost type soft recovery pulse width modulation quasi resonance converter (SR PWM QRC) including 1st order valley fill (VF) network combining an auxiliary diode D_{A1} and resonant inductor L_r. The 1st order valley fill (VF) network composed of D_{V1}, D_{V2}, D_{V3}, C_{v1} and C_{v2} is similar to well known valley fill network which is used for line filter if the value of capacitor becomes large[5]. But, the value of capacitor in valley fill network is very small and its main function is to provide soft recovery condition to the main rectifier D in turn-off duration. As the valley fill capacitors (C_{v1}, C_{v2}) across the rectifier are overcharged twice the voltage of V_O at turn-on interval of switch M_1, A simple capacitor replaces to valley fill network. The valley fill network divides the overcharged voltage by half and eliminates re-discharging problem. As a result of valley fill network, the main rectifier D is turned off softly when the switch M_1 is turned on at zero current condition. The switch M_1 does not turn off softly, however, turn-off loss is not large because the switching speed of MOSFET is much faster than that of diode. The value of L_r is chosen small enough to shorten discharging time and work as a part of lossless snubber. Though the 1st order valley fill network is useful for soft recovery of main diode D, The reverse recovery problem of another diode when out power becomes large exists still in the D_{V2}, the center diode of valley fill network. The reverse recovery of the D_{V2} occurs in turn-off duration when it tries to divide the overcharged voltage of the capacitors (C_{V1} and C_{V2}) to half. Therefore, in order to provide soft switching condition to the center diode of the 1st order valley fill network, another valley fill network is necessary across the center diode of the 1st order valley fill network, which forms the 2nd order valley fill network. The 3rd order valley fill network is similarly necessary for soft switching the center diode of the 2nd order valley fill network and so on. As the number of order of valley fill network becomes higher,the magnitude of resonance waveform of higher order valley fill network in turn-on duration decays repidly and the reverse recovery loss of center diode of valley fill network becomes negligible at the end. Snubbing resonance happens multiple number of half cycle resonance with different characteristic impedance corresponding to the number of order of the valley fill network that is used for the snubber.

B. Description of operation



(a).[t_1~t_2] (b).[t_2~t_3] (c).[t_3~t_4]

(d).[t_4~t_5] (e).[t_5~t_1]

Fig.2 equivalent circuit in each mode of Fig. (1) circuit

To simplify the analysis, we assumed as follows in one period of switching operation. The current of the input inductor is considered to be constant in one cycle operation and diode is assumed to be ideal. The stray capacitance and switching time of device is assumed zero. Then, one period of switching operation is divided into five operation modes described as follow. The mode diagrams corresponding to each time duration and the theoretical waveforms of the current i_{Lr} of resonant inductor L_r, the voltage across the main diode D v_D and current i_D of main diode D are shown in Fig. 2 and Fig. 3, respectively.

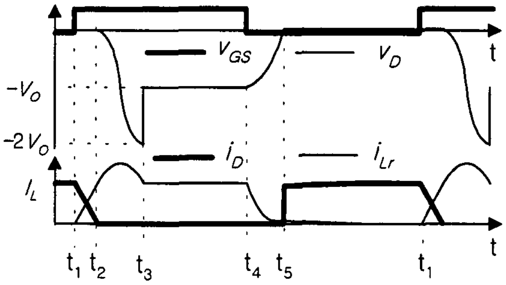


Fig.3. Theoretical waveforms of Fig.1

1) Turn -On Modes

(a). Mode 1 in the interval $t_1$to t_2 : linear ramp stage of the current L_r.

When the switch M_1 is closed at t_1, the inductor current i_{Lr} ramps up linearly to I_L. The state equation in this time duration is

$$i_{L_r}(t) = \frac{V_O}{L_r}(t - t_1) \qquad (1)$$

Initial condition in this stage is $i_{Lr}(t_1) = 0$, $v_{Cvl}(t_1) = v_{Cv2}(t_1) = 0$. At this interval, the current i_D of main diode D decreases linearly to zero, which means soft turn-off of main diode D.

(b). Mode 2 in the interval t_2 to t_3 : resonant overcharging stage of the voltage across the capacitors of VF network.

The main function of VF network is to provide soft recovery condition to the main diode D in turn-off duration. Simple capacitor across the diode is overcharged twice to V_O at initial turn-on duration of M_1. But, the 1st order VF network divides the overcharged voltage to half and eliminates re-discharging problem. On account of charged capacitor in valley fill network, the switch M_1 is turned on at zero current state and the main diode D is turned off softly. The 1st order VF network is useful for soft recovery of the main diode D. But. when the output current becomes large in this time duration, another reverse recovery current occureing at the center diode D_{V2} is possible to be eliminated by connecting D_{V2} paralell with another valley fill network. As ouput power increases, the number of order of valley fill network can be increased to keep soft turn-off conditon for every consecutive center diode in vallely fill network.

(b-1). Case that includes 1st order VF network.

When the current i_{Lr} of L_r reaches I_L at t_2, the i_{Lr} forms resonance current through the series paths of C_{V2}, D_{V2} and C_{V1}. As the capacitors of C_{V1} and C_{V2} are overcharged, the voltage v_D across D approaches to $-2V_O$ and the resonance current i_{Lr} approaches to I_L. When the resonance current i_{Lr} equals to I_L again at t_3. Induced voltage across the inductor L_r becomes zero and the voltage across the diode D steps up to $-V_O$ from $-2V_O$ at t_3. If $C_{V1} = C_{V2} = C_V$, then the resonance current i_{Lr} and the voltage across the main diode v_D are expressed as follows:

$$i_{L_r} = \frac{V_O}{Z_O}\cdot \sin \varpi_0(t-t_2)+I_L \qquad (2)$$

$$v_D = -V_O\cdot\{1-\cos\varpi_0(t-t_2)\} \qquad (3)$$

Where

$$Z_0 = \sqrt{2\cdot L_r\cdot C_V^{-1}} \qquad \varpi_0 = \sqrt{(0.5\cdot C_V)\cdot L_r}^{-1}.$$

(b-2). Case that includes multiple order VF networks.

The operation of the proposed circuit that includes multiple order VF network is same to that includes 1st order VF network in the interval of t_2 to t_3. But, additional resonance occurs after t_3 in multiple order VF networks. The 1st, the 2nd and the 3rd order VF network and its corresponding voltage across the main diode v_D is shown in Fig. 5. The 2nd and the 3rd resonance occur at the 2nd order and the 3rd order VFN converter, respectively. The equivalent circuit in multiple order valley fill network for each time duration (from ΔT_1 to ΔT_5) for the 2nd and the 3rd order VFN converter is shown in Fig.4, where bold line and arrow sign expresses the conduction loop and current direction in each time duration, respectively. As shown Fig.5, next order VF network becomes a snubber of reverse recovery current of center diode of previous order VF network. The characteristic impedance Z_O in each time duration is given in equation (4), respectively.

$$Z_O = \sqrt{L_r\cdot C_{EQ}^{-1}} \qquad (4)$$

$$\begin{aligned}
C_{EQ} &= 0.5\cdot C_{1V} \quad for\,\Delta T_1\\
&= \{(0.5\cdot C_{1V})^{-1}+(0.5\cdot C_{2V})^{-1}\}^{-1} \quad for\,\Delta T_2\\
&= (2\cdot C_{1V}+2\cdot C_{2V}) \quad for\,\Delta T_3\\
&= \{(0.5\cdot C_{1V})^{-1}+(0.5\cdot C_{2V})^{-1}+(0.5\cdot C_{3V}{}^{-1})\}^{-1} for\,\Delta T_4\\
&= (2\cdot C_{1V}+2\cdot C_{2V}+2\cdot C_{3V}) \quad for\,\Delta T_5
\end{aligned}$$

Where the C_{1V}, C_{2V}, and C_{3V} are capacitor in the 1st, 2nd and 3rd order VF networks respectively.

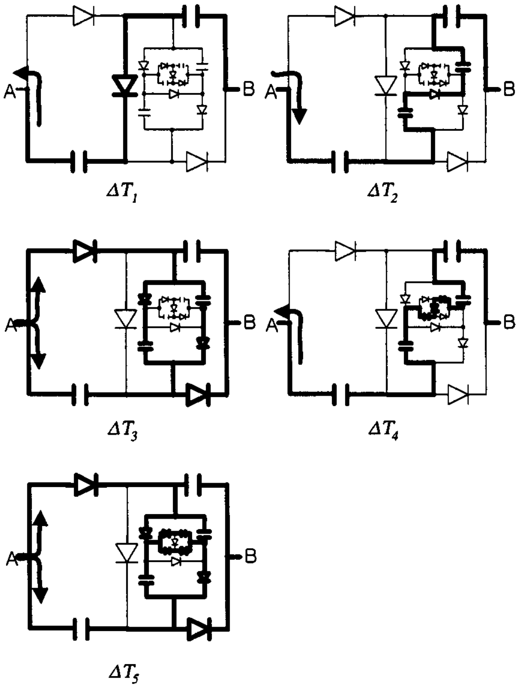


Fig.4 Equivalent circuit in the interval of t_2 to t_4 in the 3rd orders VFN converter in Fig.5 (c).

(c). Mode 3 in the interval of t_3 to t_4 : constant voltage and current stage.

When the resonance current i_{Lr} equals to I_L at t_3, the induced voltage across the L_r becomes zero and resonance stops. Therefore, the voltage of node A becomes zero and the voltage across the main diode D v_D changes abruptly from $-2V_O$ to $-V_O$. The current I_L directly flows from the drain to the ground and the energy stored in the C_L supplies the output power.

$$i_{L_r}(t-t_4) = I_L - \frac{V_O}{Z_0}\cdot\sin\varpi_0(t-t_4) \qquad (5)$$

$$v_D(t-t_4) = -V_O\cdot\cos\varpi_0(t-t_4) \qquad (6)$$

2) Turn-Off Modes

(d). Mode 4 in the interval of t_4 to t_5 : resonant discharge of VF capacitor.

When main switch M_1 is turned off at t_4, the i_{Lr} of L_r and the charge stored in the VF capacitors discharges and voltage across the VF capacitors decrease to zero. When the capacitor C_{V1} and C_{V2} discharge, the current paths form parallel branches through D_{V2} and D_{V1}, respectively and the i_{Lr} falls to zero at t_5. The equations of i_{Lr} and v_D in this stage are

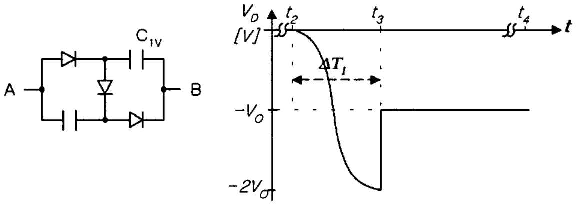
Where

$$Z_0 = \sqrt{L_r \cdot (2 \cdot C_V)^{-1}} \qquad \varpi_0 = \sqrt{2 \cdot L_r \cdot C_V}^{-1}.$$

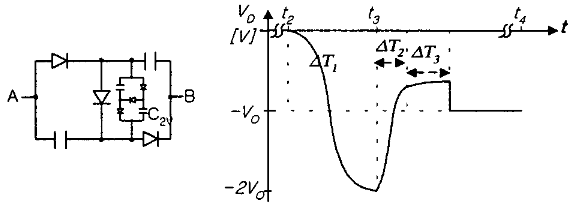
The negative current of i_{Lr} maintains zero after t_5 on account of reverse biased voltage across the D_{A1}.

(e). Mode 5 in the interval of t_5 to t_0 : I_L feeds directly to the load.

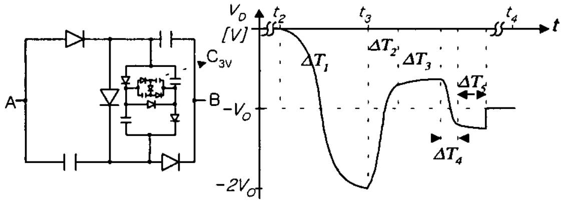
When the voltage across the VF capacitor becomes zero at t_5, the main diode D turns on and the inductor current I_L flows to load C_L through the main diode D. As small amount of negative voltage across the inductor L_r is induced in this time duration, the auxiliary diode D_{A1} is in off state. One cycle of operation has completed.



(a). 1st order FS network and corresponding V_D



(b). 2nd order FS network and corresponding V_D



(c). 3rd order FS network and corresponding V_D

Fig.5. Multiple order VF network and voltage v_D across main diode D in proposed circuit including for each multiple order VF network

C. Soft switching of rectifier diodes and multiple order VF network.

The main diode D turns off and on softly at t_2 and t_5. As the switch M_1 is also turned on softly at t_1 as shown abovse, this topology nicely solved the reverse recovery problem of the main diode appearing in conventional hard switching converter. When the proposed circuit feeds small output power, the reverse recovery current of center diode in VF network D_{V2} is negligible. As output power, however, increases to several kilowatts, the problem of reverse recovery current of center diode of valley fill network should be considered. But, this problem can be also solved by inserting the another VF network across the center diode of previous VF network as shown in Fig. 4.

III. Experimental Results

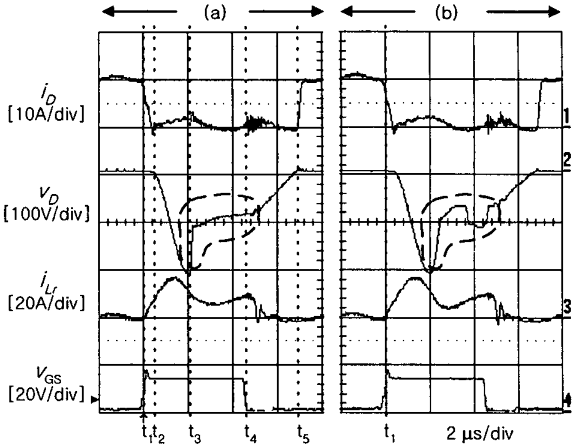


Fig.6. Experimental waveforms of Fig.1
(a) Waveforms of the 1st order VFN.
(b) Waveforms of the 3rd order VFN.

The experimental waveforms of Fig.6 are obtained from the parameters of L = 700μH, L_r = 25μH, M_1 = IRFP460, D = S30L60, $D_{V1\sim3}$ = D_{A1} = D10LC40, C_{v1} = C_{v2} = 22nF and C_L = 150μF with 100khz operating switching frequency. The Fig.6 (a) and (b) are the waveforms of the proposed circuit including the 1st and the 3rd order valley fill network, respectively. Main parameters to be designed are only the values of C_V and L_r which are determined by the minimum load current, maximum duty factor and operating switching frequency. The experimental one of the 1st order valley fill networks in the Fig.6 (a) agrees well with the theoretical waveforms in the Fig.3. We can easily observe parasitic oscillating problem in the interval of t_3 to t_4 at passive snubber PWM Converter. But, this parasitic oscillation is remarkably reduced in this proposed converter as shown in the experimental waveforms in the interval of t_3 to t_4 and t_4 to t_5, which is possible to conform in Fig. 6(a). While approximately constant voltage across the main diode D is observed in the dashed area in the proposed converter of the 1st order valley fill network in Fig.6 (a). An additional resonance wave having five different value of characteristic impedance shown in equation (4) can be observed in the dashed area of the proposed converter of the 3rd order valley fill network in Fig.6 (b). In the previous chapter, we had discussed that magnitude of resonance waveform decays rapidly in higher order valley fill network. Its theoretical waveform is also shown in Fig.5. We can conform it in experimental waveform of Fig.6 (b), which agrees well to theoretical one of Fig.5(c). The comparison of power efficiency between conventional and proposed converter with the 2nd order VF network is shown in Fig.7 where η and P_O are efficiency of output power and output power, respectively. Contrary to conventional converter, We can obtain good efficiency of output power up to 1-kilowatt output power in proposed converter as shown Fig.7. As the output power increases, the reverse recovery current in the main diode D causes to increase the power dissipation of the MOSFET switch M_1 as well as the main diode D in conventional hard switching converter. Finally, As output power increases in conventional converter, reverse recovery surge current of main diode D forces the switch M_1 destroyed. We can observe it in Fig.7. If MOSFET switch M_1 and main diode D is selected properly, the proposed converter including the 3rd order VF network is not hard to obtain a good efficiency of output power up to several kilowatts with negligible power loss of center diode of VF network.

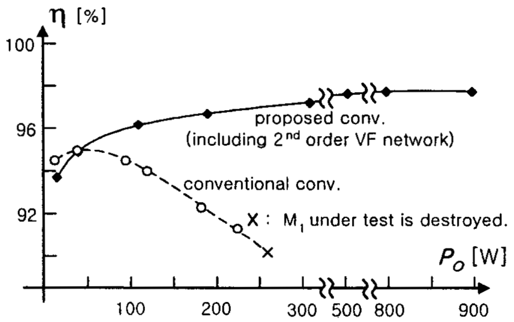
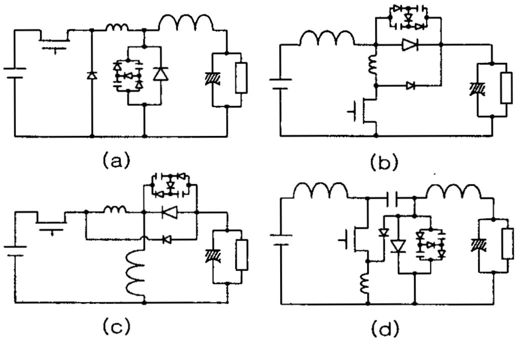


Fig.7 Comparison of efficiency between proposed converter and conventional converter

IV. Extension the concept to other topology.



(a) Buck. (b) Boost. (c) Buck/boost. (d) Cûk

Fig.8. The family of SR PWM Converter.

The Fig.8 shows a family of SR PWM QR converter is generated by applying proposed boost converter of the 1st order valley fill network to the other type of converters. The 1st order valley fill network can simply replace to multiple order valley fill networks to obtain good efficiency in large output power.

V. Conclusion

A new Soft Recovery Converter that has PWM capability satisfying soft switching condition is realized by introducing a new multiple order valley fill networks. As a result of the valley fill network, the reverse recovery loss of rectifier diodes can be minimized and the overcharged voltage across each capacitor is reduced to one half. In order to suppress reverse recovery current of valley fill network in switching transition, additional valley fill network connect to parallel with center diode of previous order valley fill network. Soft switching without loss in kilowatt grade output power could be accomplished by this multiple order valley fill network, which are realized with only passive elements. The switching operation is also stable without parasitic oscillation. The experimental results for the 1st and the 3rd order valley fill network agree well to analysis. Soft switching for large output power can be realized by the suggested multiple order valley fill networks with good efficiency. The concept to combine various types of QR converter with valley fill network generates another new family of Soft Recovery PWM Quasi Resonance Converter.

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