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Rugged Resonant Pole and Its Applications in Soft-Switching Converter

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Abstract: The soft-switching operation principle and operation performance of rugged resonant pole (RRP) is given. The applications of RRP in soft-switching DC-DC converter and soft-switching inverter are discussed in detail. RRP can constitute buck-boost soft-switching DC-DC converter and isolated soft-switching DC-DC converter with the automatic limitation performance of output power. Partial series resonant DC-DC converter with RRP can realize the zero-voltage/zero current switching of power devices. RRP can be applied to full-bridge phase-shifted converter to realize the soft-switching of power devices in lagging leg. Resonant pole inverter and resonant DC link inverter with RRP can be constituted. The operation principle and performance and soft-switching condition of each converter are discussed. The simulation and experimental results are given.

Key words: rugged resonant pole, soft-switching, DC-DC converter, inverter

Considerable switching losses in traditional PWM hard-switching converter limit the further improvement of switching frequency. Soft-switching converter is realized by adding an auxiliary circuit to hard-switching converter. It forces power devices to switch in zero-voltage-switching (ZVS) or zero-current-switching (ZCS) condition, reducing and even eliminating switching losses. Switching frequency can be improved greatly, which is not only of benefit to reduce the size and weight of converter, but also of benefit to improve the efficiency and reliability of converter. Many kinds of auxiliary circuits are proposed, studied and improved. The rugged resonant pole (RRP) topology is presented by A. Cheriti in 1990[1]. The circuit diagram is shown in Fig.1(a). Because of the clamping diode D_3 and freewheeling diode D_4, the circuit has high reliability and thus has the name of "rugged". This paper discusses the applications of the RRP in soft-switching DC-DC converter and soft-switching inverter in detail. The soft-switching operation principle of RRP is given. This topology can realize the soft-switching of its power devices and provide the ZVS condition for other power devices in circuit.

1 Operation Principle of RRP

As shown in Fig.1(a), RRP consists of power devices M_1, M_2, freewheeling diodes $D_1 - D_4$, clamping diode D_3, snubber capacitors C_1, C_2, resonant capacitors C_3, C_4 and resonant inductor L. $C_1 - C_4$ includes the parasitic capacitors of all the power devices and all the diodes. M_1 and M_2 are switched complementarily with given dead time. Supposing the load inductor is far larger than resonant inductor, the variation of load current is very slow in one operation period of RRP and load current can be replaced by an equivalent current source I_d. If the turn-on voltage-drops of power devices and diodes and the resistor of resonant inductor are not considered, the operation process can be described as follows. At time t_0, M_1 turns on under zero voltage in the freewheeling period of D_1. The negative current i_L of inductor decreases to zero and then increases linearly through M_1. When i_L reaches load current I_d, corresponding to time t_1, D_4 stops conducting. L and C_3, C_4 resonate while i_L charges C_4. The voltage of C_4, u_{C_4} is clamped to input voltage U_i by D_3 at time t_2. i_L freewheels through D_3 and M_1. After a period of time, M_1 turns off softly at time t_3 because of the snubber of C_1. L resonates with C_1 and C_2. Positive i_L charges C_1 and discharges C_2. At time t_4, the voltage of C_2 declines to zero and D_2 conducts naturally. i_L feeds back the energy to power supply through D_3 and D_2. At time t_5, i_L falls to I_d and D_3 turns off. L resonates with C_3, C_4 again. C_4 discharges and u_{C_4} decreases. M_2 turns on during the conducting period of D_2 and achieves zero voltage turn-on. At time t_6, i_L falls to zero and

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increases reversely through M_2. At time t_7, u_{C_4} decreases to zero and the conduction of D_4 keeps u_{C_4} zero. i_L freewheels through D_4 and M_2. At time t_8, M_2 turns off. The voltage of M_2 increases slowly because of the charge and discharge of C_2 and C_1. Then M_2 achieves soft turn-off. At time t_9, the voltage of C_1 falls to zero. D_1 conducts naturally and i_L feeds back the energy to power supply through D_1 and D_4. If M_1 is controlled to turn on during this period, it obtains zero voltage turn-on. At time t_{10}, i_L decreases to zero again and one operation cycle is accomplished. The operation waveforms are shown in Fig.1(b). With the alternate on and off of M_1, M_2, RRP converts DC voltage into a high frequency DC pulse voltage u_{C_4}.

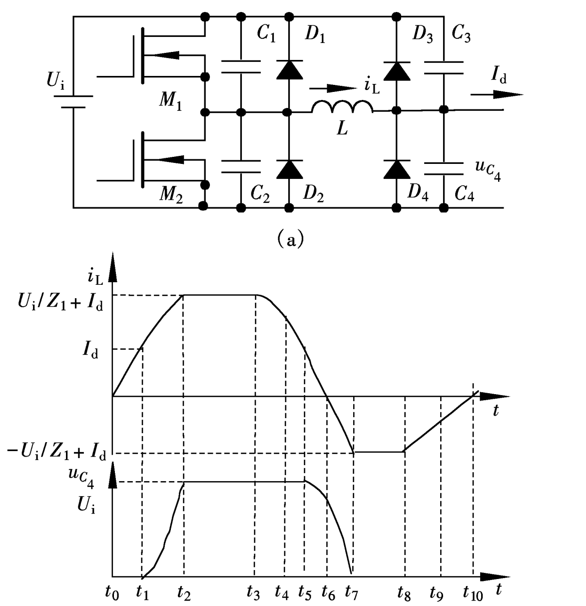

Fig.1 Rugged resonant pole. (a) Diagram of circuit; (b) Operation waveforms

M_1 and M_2 can realize zero voltage turn-off at any time because of the snubber of C_1 and C_2. If the turn-on time of M_1 and M_2 is in the freewheeling period of D_1 and D_2, M_1 and M_2 can realize zero voltage turn-on. Inductor current determines the freewheeling time of D_1 and D_2. So if the inductor current is controlled to meet inequality (1), the soft-switching of M_1 and M_2 can be achieved[2].

$$I_d - U_i/Z_1 \leqslant i_L \leqslant I_d + U_i/Z_1 \quad (1)$$

where the load current I_d must be controlled within the following constraints.

$$-(U_i/Z_1 - U_i/Z_2) \leqslant I_d \leqslant U_i/Z_1 - U_i/Z_2 \quad (2)$$

where $Z_1 = \sqrt{L/(C_3 + C_4)}$, $Z_2 = \sqrt{L/(C_1 + C_2)}$.

U_i/Z_1 is the peak value of resonant current when L, D_3 and D_4 resonant. U_i/Z_2 is the peak value of resonant current when L resonates with C_1 and C_2. The difference of these two resonant currents determines the load capacity of RRP.

Fig.2 shows the experimental waveforms of RRP. The input voltage equals to 300 V. Resonant inductor is 30 μH. C_3 and C_4 equal to 20 nF. C_1 and C_2 equal to 1 nF. Switching frequency is 100 kHz[3]. Fig.2(a) and (b) show the drain-source voltage waveform u_{ds} and drive voltage waveform u_{gs} of M_1 and M_2, respectively. It can be seen that the drive signal is exerted on device after u_{ds} falls to zero, indicating that M_1 and M_2 realize ZVS turn-on. While the turn-off of M_1 and M_2 is in soft-switching state. Fig.2(c) shows the voltage waveform u_{C_4}. It is a high-frequency DC pulse, thewid-

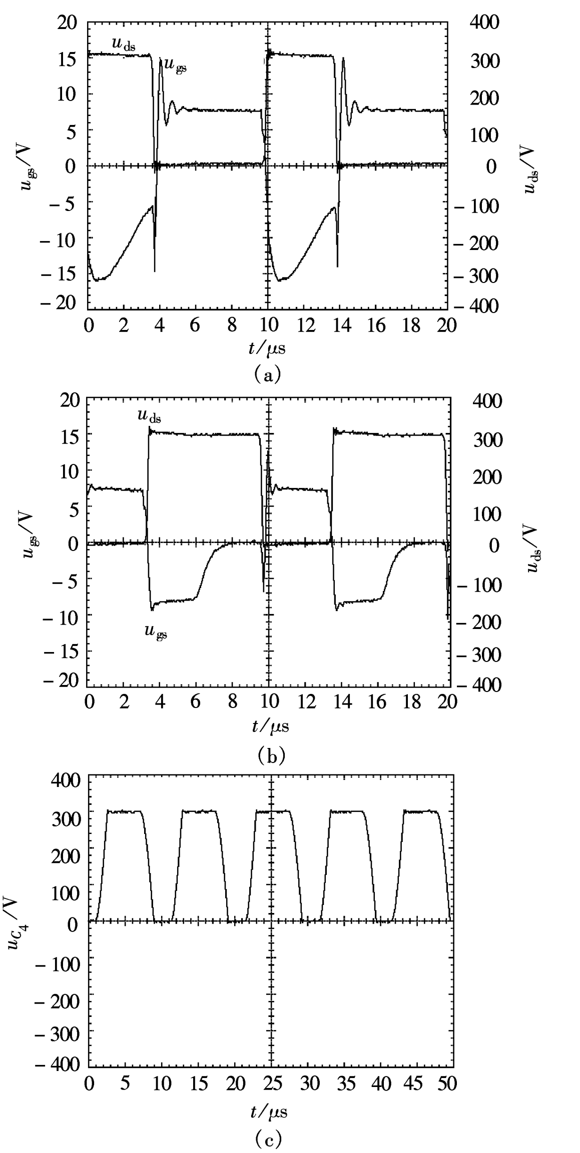

Fig.2 Experimental waveforms of rugged resonant pole. (a) $M_1: u_{gs}, u_{ds}$; (b) $M_2: u_{gs}, u_{ds}$; (c) u_{C_4}

th of which can be regulated and the maximum value of which is clamped by diode. The voltage stress is low and active clamper circuit is unnecessary.

Anti-paralleled diodes D_1 and D_2 have no problem of reverse recovery. So, there is no need of fast-speed diode. D_3 and D_4 also have good operation condition. Their du/dt is limited by resonant capacitor and di/dt is limited by resonant inductor.

2 Applications of RRP in Soft-Switching DC-DC Converter

2.1 Buck-boost soft-switching DC-DC converter[3]

It can be seen from the operation principle of RRP that this circuit is an independent chopper. It converts DC voltage into high-frequency DC pulse voltage. Connecting a filter inductor and capacitor at the output terminal of RRP can constitute the soft-switching DC-DC converter, the diagram of which is shown in Fig.3. DC pulse voltage is filtered to output DC voltage U_o, which can be expressed approximately as[3]

$$U_o = DU_i = (0.5 + \frac{t_{M_1} - t_{M_2}}{2T})U_i \qquad (3)$$

$$t_{M_1} + t_{M_2} \approx 0.9T \qquad (4)$$

where D is defined as the duty cycle of u_{C_4}; T is switching period; t_{M_1} represents the freewheeling time that the current i_L of resonant inductor flows through D_3 when M_1 is turning on, corresponding to the time that u_{C_4} is clamped to U_i; t_{M_2} is the time that i_L freewheels through D_4 when M_2 is turning on, corresponding to the time that u_{C_4} equals to zero; t_{M_1} and t_{M_2} equal approximately to the turn-on time of M_1 and M_2 respectively. So, changing the turn-on time of M_1 and M_2, D can be changed and U_o can be modulated. It means that RRP operates as a buck converter and PWM control strategy can be applied to converter.

Because the reverse flow of resonant inductor current is possible, the load power can be fed back to power supply. Converter can operate in no load and the energy of load can revive. A boost converter can be formed by exchanging the input and output terminal of circuit shown in Fig.3. This buck-boost soft-switching DC-DC converter can be applied to two-quadrant drive of DC motor and the charger of storage battery.

2.2 Isolated soft-switching DC-DC converter with the performance of output power limitation[4]

Because the current of resonant inductor flows in

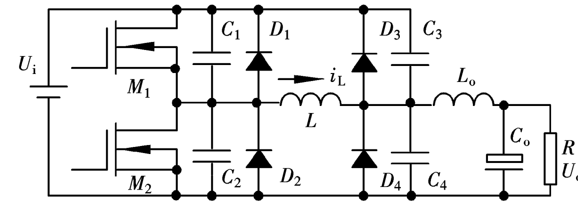

Fig.3 Diagram of buck-boost soft-switching DC-DC converter

two directions, the voltage of inductor varies in two directions. If a transformer is connected in series with the resonant inductor of RRP and the secondary-side of transformer is followed by rectifier and filter, an isolated soft-switching DC-DC converter can be composed, the diagram of which is shown in Fig.4(a). Resonant inductor can be replaced by the leakage inductor of transformer. Different from the circuit shown in Fig.3, this converter adopts pulse-frequency-modulation control. Two power devices switch complementarily and the duty cycle approaches 50%. It is capacitor C_3 and C_4 that transfer the power to load. During the process that the primary-side current of transformer changes from M_2 to M_1, the secondary-side current freewheels through D_5 and D_6. And the voltage of transformer is zero. Transformer won't transfer the power until the current of resonant inductor rises and reaches the sum of the transformer exciting current and the refracted load current. When the voltage of C_4 rises to be larger than U_i, D_3 conducts and converter stops transferring power to load. During the period of power transferring, the current of primary-side is constant to be I_a, which is the refracted current of load. The output power is limited by the charger capacitor C_4 and the capacitor voltage at the beginning of transferring power. Defining K as the winding ratio of transformer, the output power of converter can be expressed as follows.

$$P_o = KU_oI_a = 2I_af_s \times \left(\frac{I_a t_d^2}{2(C_3 + C_4)} + t_d U_i \cos\left(\arcsin\left(-\frac{ZI_a}{U_i}\right)\right)\right) \qquad (5)$$

where

$$Z = \sqrt{\frac{L_r}{C_3 + C_4}}$$

$$I_a = \frac{I_o}{K}$$

$$t_d = -\frac{(C_3 + C_4)U_i\cos(\arcsin(-ZI_a/U_i))}{I_a}$$

Fig.4(b) shows the performance curves of converter's output power under different frequencies. It can be seen that the output power can be controlled by changing the frequency. When load current is excessively large and the output power of converter will reduce automatically without any control. This performance makes the circuit shown in Fig.4(a) be suitable

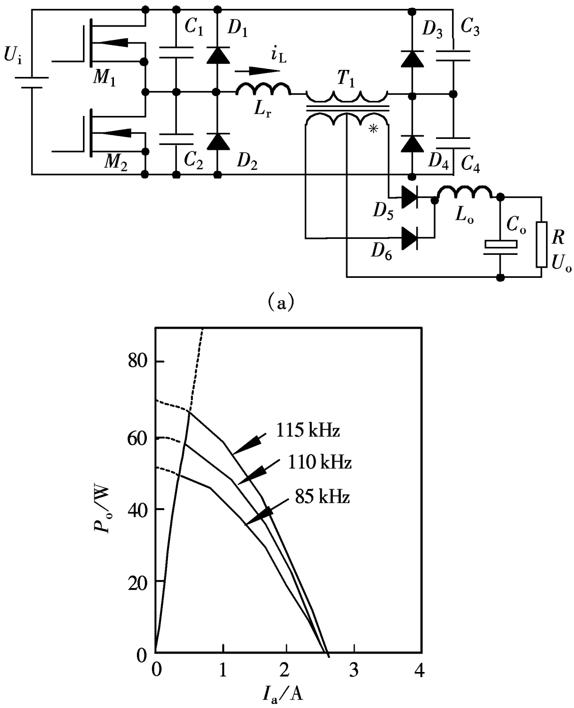

Fig.4 Isolated soft-switching DC-DC converter. (a) Diagram of circuit; (b) Performance curve of output power

for the applications whose output power needs to be controlled, i.e., the charger of battery. When the input voltage is 310 V, output voltage is 22 V and output power equals to 70 W, the largest efficiency of converter reaches 87%[4].

2.3 ZV/ZCS partial series resonant DC-DC converter[5]

The isolated DC-DC converter mentioned above is a partial series resonant DC-DC converter (PSRC). Operating below resonance frequency, the PSRC with ZCS can be achieved and the diodes of the output rectifier are commutated under zero-current. But, the main power device shall suffer the short current caused by parasitic capacitors during turn-on transient state and turn off under an imperfect ZCS condition because of small magnetizing current. To resolve these problems, the PSRC with ZV/ZCS is proposed. As shown in Fig.5, an auxiliary circuit (RRP) is added to main power devices M_1 and M_2. It is composed of two diodes (D_7, D_8), two capacitors (C_7, C_8), two auxiliary switches (M_{1a}, M_{2a}), auxiliary inductor L_a and saturation inductor L_s. When M_2 turns on, leakage inductor current i_{L_r} flows through C_1-L_r-M_2, and then D_2-L_r-M_2. The input power is delivered to the output. When i_{L_r} reduces to magnetizing current, no current flows to the secondary side of transformer and the rectifier diode commutates at zero current. L_s is in unsaturation state. It acts as open state and bears the input voltage. M_2 turns off and auxiliary switch M_{2a} turns on under zero voltage condition simultaneously. Then auxiliary circuit operates. L_s is in saturation state. The energy stored in L_a is large enough to discharge the parasitic capacitors of M_1 and M_{1a}, providing ZVS turn-on condition for M_1 and M_{1a}. Thus an operating half cycle is ended.

It has the advantages of the conventional PSRC, i.e., two times output voltage, operation below resonant frequency. Main power devices can achieve soft-switching for the entire load ranges. The saturation inductor can ensure the ZVS turn-on of the auxiliary switch. This circuit is suitable for high power and high switching frequency applications.

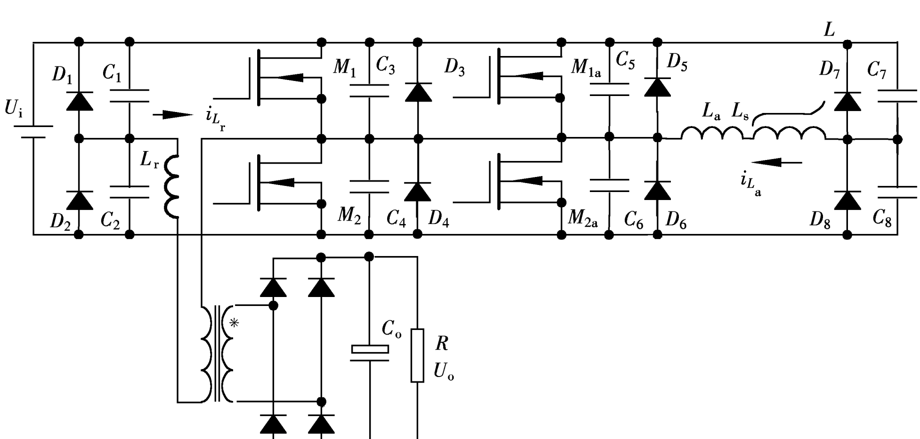

Fig.5 Diagram of ZV/ZCS partial series resonant DC-DC converter

2.4 Applications in phase-shifted full-bridge DC-DC converter

Full-bridge converter is used much more in middle and large power applications. Phase-shifted control is one method to realize the soft-switching of power devices in full-bridge converter. As shown in Fig.6, it realizes the ZVS of power devices by the resonance of inductor L_r (including the leakage inductor of transformer) and the output capacitors of power devices. Devices in each bridge conduct complementarily. The turn-on angle of M_1&M_2 leg is led to that of M_3&M_4 leg by phase α. So, M_1&M_2 leg is defined as leading leg and M_3&M_4 leg is defined as lagging leg.

In order to realize zero voltage turn-on of power

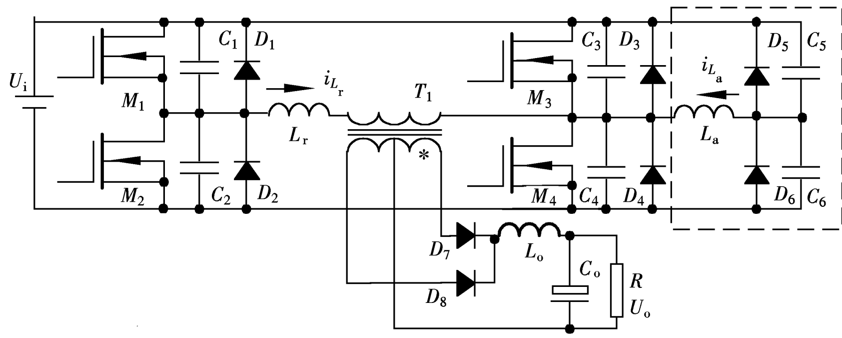

Fig.6 Diagram of full-bridge phase-shifted DC-DC converter

devices, there must be enough energy to discharge the power device that will turn on and charge the power device that will turn off in the same leg. During the switching process of leading leg, the current of resonant inductor is the sum of refracted load current and exciting current of transformer. Resonant inductor is in series with output filter inductor and energy is large enough to realize the zero voltage turn-on of power devices in leading leg easily. But during the switching process of lagging leg, load current freewheels through rectifier, there is only resonant inductor energy and it is difficult to realize zero voltage turn-on of power devices in lagging leg. For this reason, Ref.[6] proposed to add an auxiliary resonant circuit in the lagging leg as shown by dotted line in Fig.6. This auxiliary resonant circuit and the lagging leg constitutes an RRP. After M_4 turns off, the primary-side current i_{L_r} of transformer and resonant inductor current i_{L_a} of auxiliary net charges C_4 and discharges C_3, which makes M_3&M_4 zero voltage turn-on easy. In order to provide ZVS condition for M_3, it must be sure that at time t_1 when M_3 turns on, the voltage of C_4 is charged to U_i and i_{L_a} is still larger than zero and saturation inductor L_r is still in linear state. That is

$$\left.\begin{aligned} u_{C_4}(t_1) &= Z(I_c + I_a)\sin(\omega_1 t_1) = U_i \\ i_{L_a}(t_1) &= \frac{L_e}{L_a}(I_c + I_a)(\cos(\omega_1 t_1) - 1) + I_a \geqslant 0 \\ i_{L_r}(t_1) &= \frac{L_e}{L_r}(I_c + I_a)(\cos(\omega_1 t_1) - 1) + I_c \geqslant - I_c \end{aligned}\right\} \tag{6}$$

where I_c is the critical saturation current of L_r; K is defined as the winding ratio of transformer; I_o is load current. The following equations can be got from Eq.(6).

$$\begin{aligned} L_e &= \frac{L_r L_a}{L_r + L_a}, \quad Z = \sqrt{\frac{L_e}{C_3 + C_4}}, \\ \omega_1 &= \frac{1}{\sqrt{L_e(C_3 + C_4)}}, \quad I_a = \frac{U_i}{\sqrt{L_a/(C_5 + C_6)}} \end{aligned} \tag{7}$$

Compared to Fig.1, I_d equals to zero for auxiliary net. So i_{L_a} varies in the region of $\pm I_a$, which means that the largest current of resonant inductor I_a has nothing to do with load of converter. While it depends on input voltage and the characteristic impedance of auxiliary circuit. The relationship of I_a and I_o meets inequality (8).

$$\frac{I_o}{K} > I_c > \frac{U_i}{Z} - I_a \tag{8}$$

This circuit can realize ZVS of power devices under arbitrary load and input voltage, while the loss of duty cycle can be reduced greatly.

3 Applications of RRP in Soft-Switching Inverter

There are two types of inverter using soft-switching technology. One is resonant pole inverter (RPI)[7], the other is resonant DC link inverter (RDCLI)[8].

3.1 Rugged resonant pole inverter

Resonant pole inverter is composed by adding an auxiliary resonant pole to each leg of inverter. Auxiliary circuit provides ZVS or ZCS condition for each leg. As shown in Fig.7(a), rugged resonant pole single-phase inverter is made of two RRPs. Three

RRPs can constitute a three-phase inverter[2,9]. Each leg of inverter can be controlled independently and the inverter has good output performances.

The maximum output current i_{L_f} of resonant pole can be expressed by the following equation.

$$I_{L_{fmax}} = \sqrt{2(I_o^2 + (U_o \omega C_f)^2)} \quad (9)$$

where I_o and U_o are the RMS value of output current and output voltage, respectively; ω is angle-frequency of output sinusoidal waveform. If $I_{L_{fmax}}$ is controlled to meet inequality (2), the zero voltage turn-on can be realized.

This paper does some simulation study of this topology with Pspice software. Simulation parameters are the same as the experimental ones of circuits in Fig.2. Inverter adopts double-polarity PWM control. That is to say M_1&M_4 and M_3&M_2 switch simultaneously. Simulation waveforms are shown in Fig.7(b) and (c). Output voltage of inverter bridge $u(3,14)$ are the difference of output voltages $u(3,7)$ and $u(14,7)$ of the two RRPs. i_{L_f}, i_{L_1} and i_{L_2} are the current of filter inductor, resonant inductor L_1 and L_2, respectively. So inverter can use arbitrary control strategies such as SPWM and DPM etc.

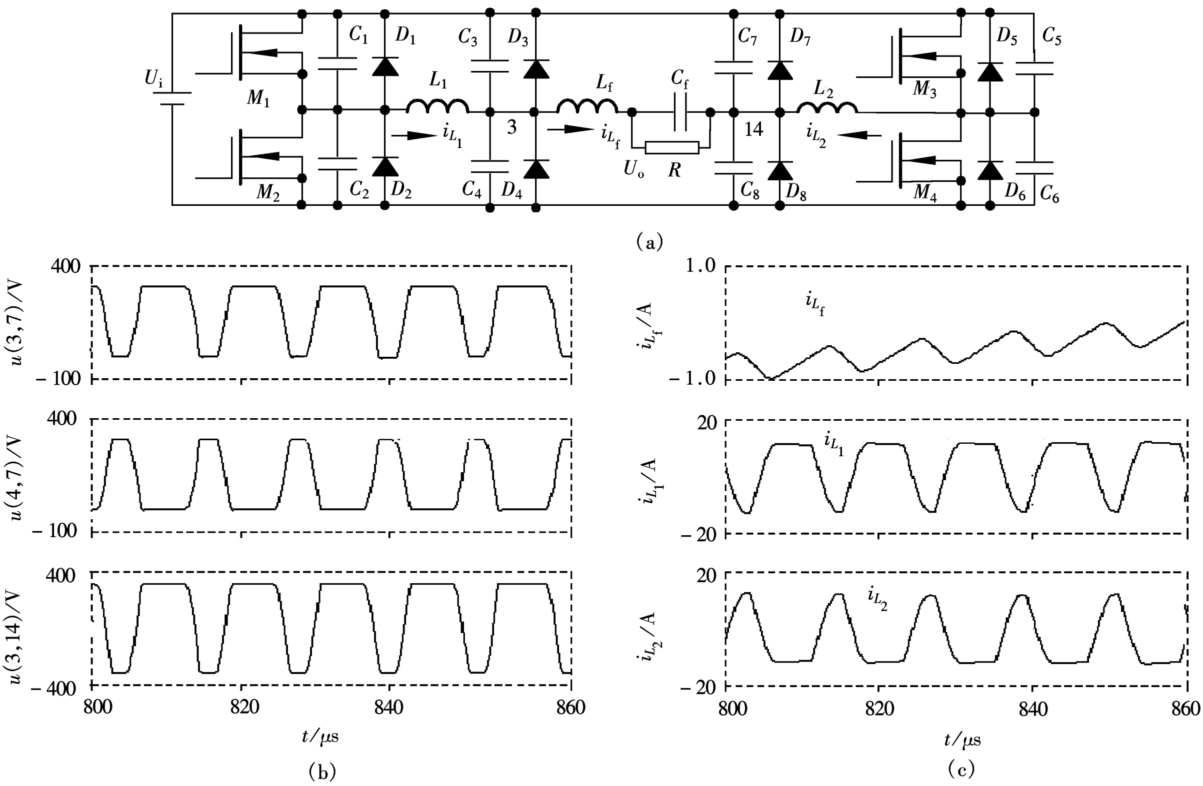

Fig.7 Rugged resonant pole single-phase inverter. (a) Diagram of circuit; (b) and (c) Simulation waveforms

3.2 Rugged resonant DC link inverter[2,11]

As shown in Fig.8(a), the construction of rugged resonant DC link inverter (RRDCLI) is simpler than that of RRPI. Rugged resonant pole is located between full-bridge inverter and DC power supply. With the resonance of inductor and capacitor, the input voltage of inverter u_{C_4} is a high-frequency DC pulse voltage that zeroes periodically, providing ZVS condition for all power devices in inverter bridge. If the power devices $M_3 - M_6$ in inverter bridge are commutated when u_{C_4} is zero, they can operate in ZVS condition. To ensure that the power devices in inverter bridge realize ZVS, the zero-voltage time of u_{C_4} must be longer than the switching time of the power devices in inverter bridge. Because the discrete switching instants coincide with the zero voltage in DC link, the output characteristic of RDCLI is poorer than that of RPI under the same frequency[10].

With discrete pulse control strategy, high-frequency pulse wave u_{C_4} is converted into modulation wave u_{ab}, the pulse quantities of which are distributed according to output frequency. u_{ab} is converted into output sinusoidal wave u_o through filter. The maximum output current of RRDCL equals to the maximum value of the current of filter inductor. That is

$$I_{dmax} = \pm I_{L_{fmax}} = \pm 1.2\sqrt{2(I_o^2 + (U_o \omega C_f)^2)} \quad (10)$$

where I_{dmax} is restricted by inequality (2); coefficient

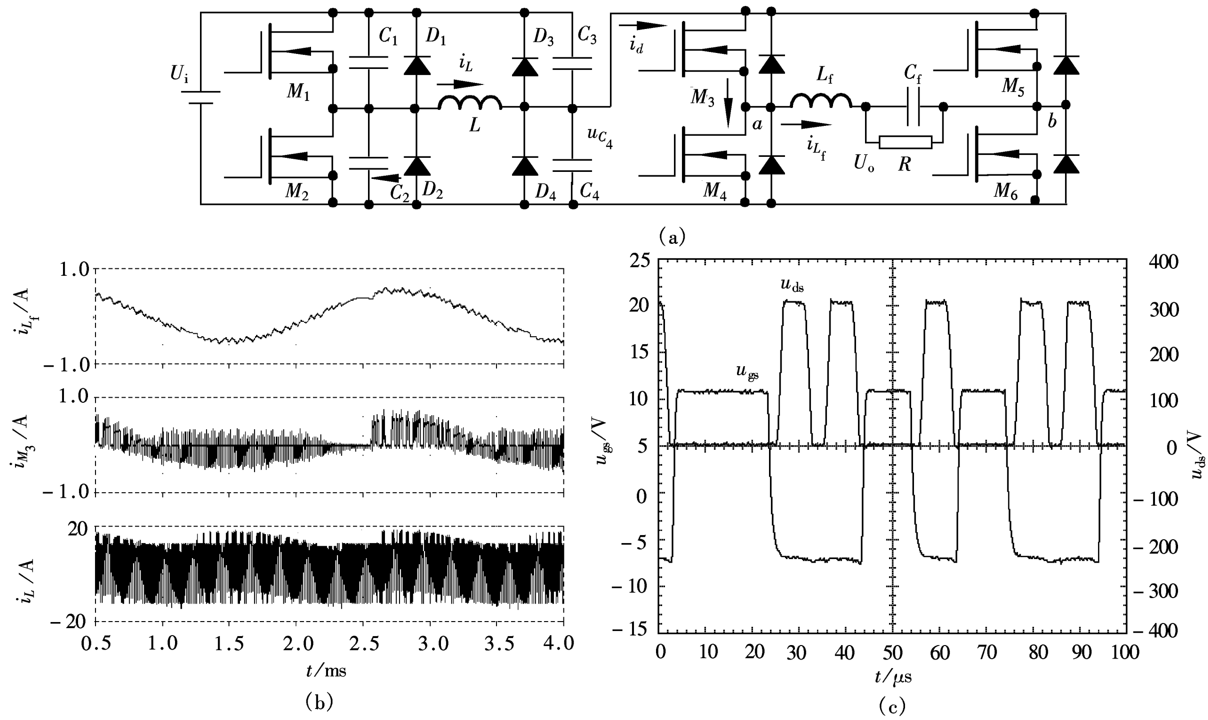

Fig.8 Rugged resonant DC link inverter. (a) Diagram of circuit; (b) Simulation waveforms; (c) Experimental waveforms

1.2 is the pulsation of filter inductor current under hysteresis control. When the output voltage of inverter is 115 V/400 Hz, output power is 250 V · A and filter capacitor is 10 μF, I_{dmax} equals to 5.61 A, meeting the requirement of inequality (2). The simulation waveforms of inverter are given in Fig.7(b). i_{L_f} is the current of filter inductor. i_{M_3} is the current that flows through M_3. i_L is the current of resonant inductor in resonant pole. The peak value of i_{M_3} is the one of i_{L_f}. Fig.8(c) shows the experimental waveforms of drive voltage u_{gs} and drain-source voltage u_{ds} of M_4. It can be seen that M_4 is ZVS on and off. The distortion of u_o is low and less than 1%. A radar power supply was manufactured with this RRDCLI topology. It converts single phase 220 V, 50 Hz AC voltage into 270 V DC voltage U_i by the rectifying of diodes and the filtering of capacitor. RRDCL converts U_i into 90 kHz DC pulse voltage u_{C_4}, the average value of which is 180 V. Full bridge inverter converts pulse voltage into 115 V, 400 Hz AC voltage. Output power is 250 V · A. The switching frequency of DC link is much larger than that of output voltage, which leads to excellent dynamic response characteristic, low distortion of output sinusoidal waveform and high reliability. It has been operating without breakdown for 7 years[11].

4 Conclusions

This paper discusses in detail the various applications of RRP in soft-switching DC-DC converter and soft-switching inverter. The following conclusions can be drawn.

1) All active and passive devices of RRP operate in soft-switching condition, resulting in small power losses, low switching stress and high reliability.

2) RRP functions as a chopper. It can constitute buck-boost soft-switching DC-DC converter which is controlled with PWM strategy. This DC-DC converter is suitable for the two-quadrant drive of DC motor and the charger of storage battery.

3) RRP can constitute isolated soft-switching DC-DC converter. It has the automatic limitation performance of output power with frequency control.

4) Partial series resonant DC-DC converter with RRP can realize the ZV/ZCS of main power devices.

5) RRP can be applied to full-bridge phaseshifted circuit. It is benefit for power devices in lagging leg to realize soft-switching.

6) RRP can constitute single-phase and three-phase rugged resonant pole inverter. Each leg of inverter can be controlled independently. So SPWM control strategy can be applied to inverter.

7) RRP can constitute rugged resonant DC link inverter, providing ZVS conditions for power devices in inverter bridge.

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结实型谐振支路及其在软开关变换器中的应用

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摘　要　本文给出了结实型谐振支路实现软开关的工作原理和运行特性,详细讨论了结实型谐振支路拓扑在软开关直直变换器和软开关逆变器中的各种应用. 结实型谐振支路可构成升降压软开关直直变换器、具有输出功率自动限制特性的隔离型软开关直直变换器,可实现部分串联谐振直直变换器功率管的零电压、零电流开关,可用于移相控制全桥直直变换器实现滞后桥臂功率管的软开关,可构成结实型谐振极逆变器和结实型谐振直流环节逆变器.本文对各变换器的工作原理、特性、实现软开关的条件进行了讨论,给出了实验和仿真波形.

关键词　结实型谐振支路, 软开关, 直直变换器, 逆变器

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