Application of New Resonant Switches in Energy Storage Devices

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Abstract- **In this paper a ZVT-PWM and a ZCT- PWM resonant switches are introduced .These switches can be applied to PWM converters instead of main switch to perform soft switching condition. Applying these switches to buck and boost converters provides a bidirectional converter for ultracapacitors interface. The simulation results justify the converter operation analysis**.

I. Introduction

Ultracapacitors are new family of energy storage devices that have many applications in power electronics. Ultracapacitors (UCs) have 10 times more energy storage capacity than electrolytic capacitors. In comparison to batteries UCs can provide much higher power pulses. However, they can store less energy than batteries. Thus, combining UCs with batteries creates a complete energy storage device which is suitable for high power applications [1]. One significant application of UCs is in hybrid vehicles. UCs existence beside batteries can store high percentage of vehicle breaking energy [2]. Other uses of UCs are in elevators, weak electric distribution systems and drives in transportation [2-5].

Because of UCs voltage variations during charge and discharge modes and voltage difference between batteries and UCs, a bidirectional power electronic interface is necessary to transfer energy [6]. Since the energy storage is usually limited, an efficient converter is required as interface. A simple solution is a switching Buck-Boost converter (a) block diagram and (b) interface converter circuit for UCs are shown in Fig.1. In order to reduce switching losses, soft switching technique are developed [7]. In this paper two new resonant switches are introduced which can replace the buck-boost switches and provide soft switching condition for both the active and passive switches. Applying these switches to converters would provide resonant condition only during switching transition times. If the switch voltage is reduced to zero during switching transition time, the switch is called zero voltage transition (ZVT) switch. Zero current transition (ZCT) provides zero current during switching transition time.

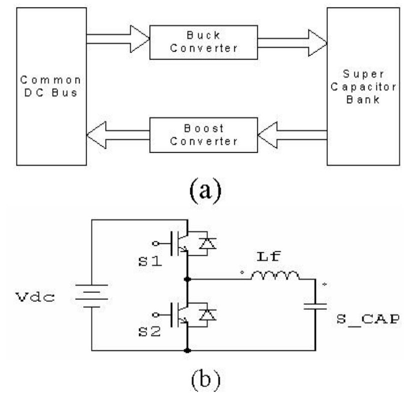


Fig.1. A general (a) block diagram and (b) interface converter circuit for ultracapacitors.

II. RESONANT SWITCHES

The proposed zero voltage and zero current transition switches topologies are shown in Fig. 2. These switches can be applied to any PWM converter to replace the main switch. For UCs applications, these switches must be applied to a buck-boost converter of Fig.1. In order to clarify the converter operation, the switches are applied to a buck and a boost converter separately.

III. BUCK ZVT-PWM CONVERTER

Fig. 3 shows the circuit diagram and key waveforms of the buck ZVT-PWM converter. The ZVT switch consists of main switch (S_1), resonant capacitor (C_r), resonant inductor (L_r) and auxiliary switch (S_2). To simplify the Analysis, output filter inductor assumed large enough to be considered as an ideal DC current sink (I_o). As shown in Fig. 4, six operation stages exist within one switching cycle.

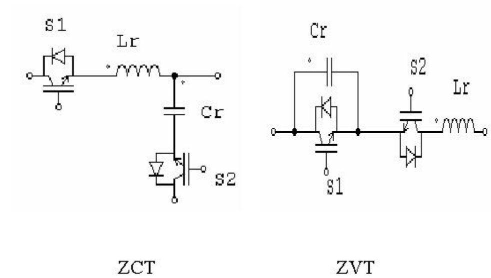


Fig.2. Proposed ZVT & ZCT switch

Mode 1- ($t_0 < t < t_1$): Prior to t_0 the main switch (S_1) is on and its current is equal to output current. At t_0 switch S_1 is at zero voltage, since C_r is linearly charge by I_o to V_s voltage at t_1 where D_f is turned on with ZV Condition.

Mode 2- ($t_1 < t < t_2$): At t_1 L_r current continues to decrease due to the resonance between L_r and C_r. At t_2 L_r current is reduced to zero and resonance stops. C_r voltage and L_r current relations are represented by:

$$V_{Cr}(t) = V_s + Z_0 I_o \sin(\omega_0 (t - t_1)) \tag{1}$$

$$i_{Lr}(t) = I_o \cos(\omega_0 (t - t_1)) \tag{2}$$

Where

$$Z_0 = \sqrt{\frac{L_r}{C_r}} \quad \text{and} \quad \omega_0 = \frac{1}{\sqrt{L_r C_r}} \tag{3}$$

Mode 3- ($t_2 < t < t_3$): This interval is identical to the freewheeling stage of the buck PWM converter and output current freewheels in D_f.

Mode 4- ($t_3 < t < t_4$): At t_3 S_2 is turned on. Resonance between C_r and L_r continues C_r discharges until its voltage is reduced to zero at t_4, where the anti-parallel diode of S_1 starts to conduct. The relation of C_r voltage and L_r current are represented by:

$$V_{Cr}(t) = Z_0 I_o (1 + \cos(\omega_0 (t - t_3))) \tag{4}$$

$$i_{Lr}(t) = -I_o \sin(\omega_0 (t - t_3)) \tag{5}$$

Mode 5- ($t_4 < t < t_5$): At this stage V_s is applied to L_r and its current passed through zero and goes to Io. To achieve ZVS, the turn-on signal of S_1 should be applied while its body diode is conducting.

Mode 6- ($t_5 < t < t_6$): At t_5 L_r current reaches to I_o and D_f turned off with ZC condition. During this stage energy transfers to output.

The ZVT switch can be applied to boost converter as well. However, in order to explain both switches, ZVT is applied to buck converter and ZCT to boost converter.

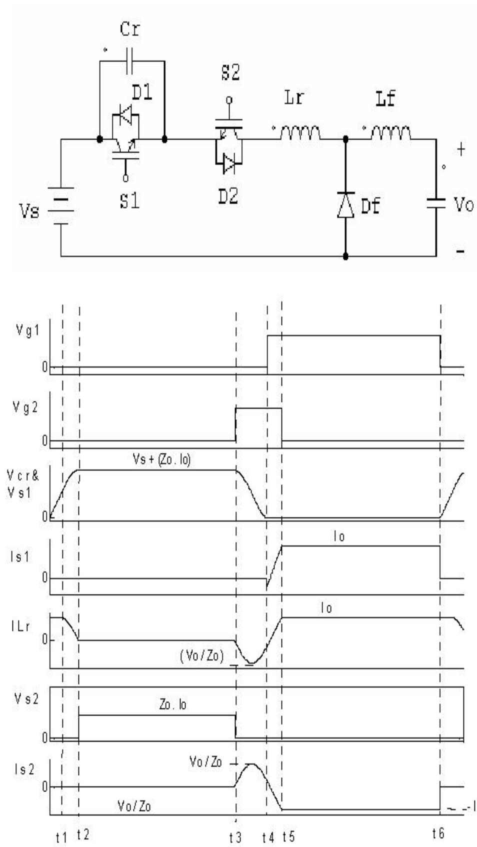


Fig.3. circuit diagram and key waveforms of buck ZVT

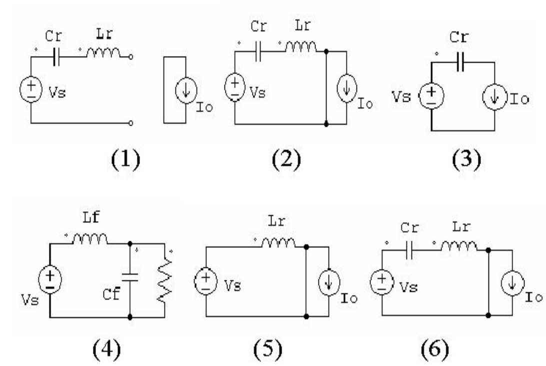


Fig.4. Equivalent circuits for different operation stages of the buck ZVT converter.

IV. BOOST ZCT-PWM CONVERTER

Fig.5 shows the circuit diagram and key waveforms of the boost ZCT-PWM converter. To simplify the analysis input current and output voltage are considered constant. This converter has six operation stages in one switching cycle as shown in Fig .6

Mode 1- ($t_0 < t < t_1$): At t_0 switch S_1 is turn on. Prior to t_0 the input current follows via D_f to output. L_r current increases linearly. S_1 Turn on is approximately ZCS.

Mode 2- ($t_1 < t < t_2$): At t_1 L_r current reaches to I_i and D_f turned off with ZC condition. L_r and C_r start to resonate via S_1 & D_2. The relations of C_r voltage and L_r current are represented by:

$$V_{C_r}(t) = V_o \cos(\omega_0 (t - t_1)) \quad (6)$$

$$i_{L_r}(t) = I_i + \frac{V_o}{Z_0}\sin(\omega_0 (t - t_1)) \quad (7)$$

Mode 3- ($t_2 < t < t_3$): At t_2 C_r current reaches to zero and because S_2 is off, resonance stops. At this stage input inductor charges via input voltage source.

Mode 4- ($t_3 < t < t_4$): This stage starts with turning on of S_2. L_r and C_r continue to resonance until L_r current goes to zero at t_4. Then anti-parallel diode of S_1 starts to conduct. To achieve ZVS, the turn-on signal of S_1 should be applied while its body diode is conducting. L_r current reaches to zero if:

$$\frac{V_o}{Z_0} > I_{i_{max}} \quad (8)$$

Mode 5- ($t_4 < t < t_5$): At t_4 resonance is stops. C_r Charge linearly by constant current I_i until brings to V_o at t_5. C_r voltage represented by:

$$V_{C_r}(t) = V_{C_r}(t_4) + \frac{I_i}{C_r}(t - t_4) \quad (9)$$

Mode 6- ($t_5 < t < t_6$): when C_r voltage reaches to Vo D_f turn on with ZVS condition. During this interval energy is transferred to output. At t_6 S_1 is turn on again, starting another switching cycle

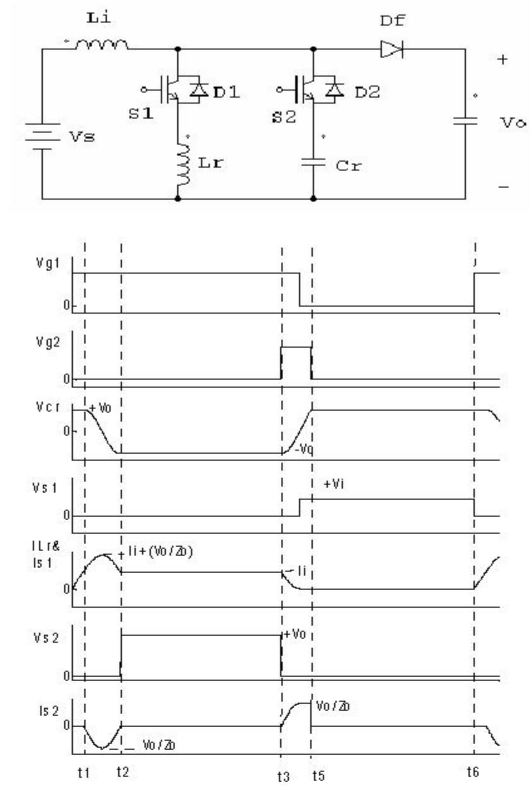


Fig.5. circuit diagram and key waveforms of boost ZCT

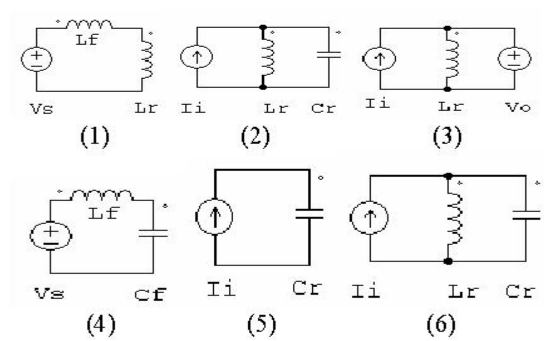
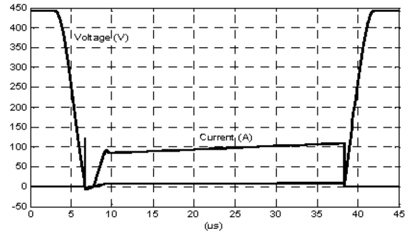


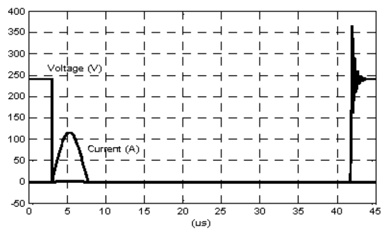
Fig. 6. Equivalent circuit for different operation stages of the boost ZCT converter.

V. SIMULATION RESULTS

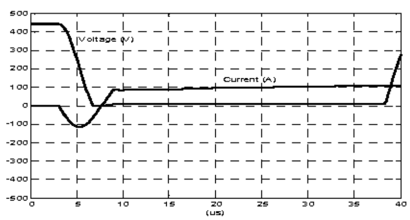
Using Matlab simulink software, the proposed converters are simulated. Buck ZVT converter simulation results at 200 V input voltage and 100A output current are shown in Fig. 7 and boost ZCT converter simulation results at 200V output voltage and 50 A input current are shown in Fig, 8. It can be seen that both transistors and flywheel diode (D_f) commutate under soft switching condition in both converters.



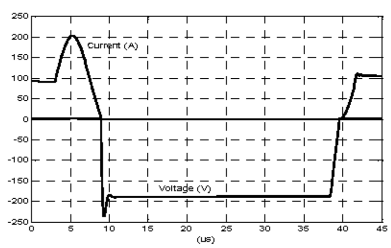
a) Voltage & current of main switch S_1



b) Voltage & current of auxiliary switch S_2

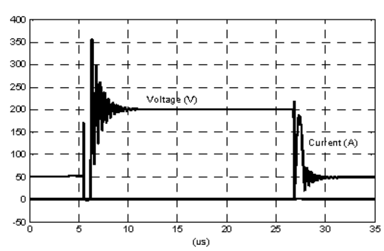


c) C_r voltage & L_r current

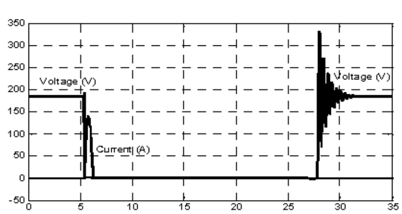


d) Voltage & current of flywheel diode D_f

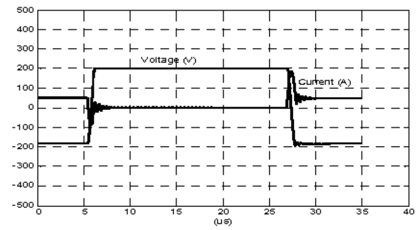
Fig.7. simulation results of buck ZVS converter.



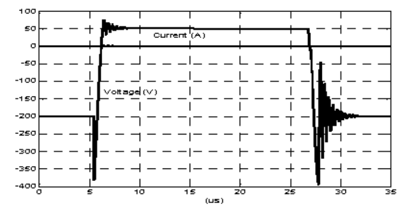
a) Voltage & current of main switch S_1



b) Voltage & current of auxiliary switch S_2



c) C_r voltage & L_r current



d) Voltage & current of flywheel diode D_f

Fig.8. Simulation results of boost ZCS converter

VI. CONCLUSIONS

In this paper a resonance ZVT-PWM switch and ZCT-PWM switch are proposed and are applied to buck and boost converters. The combination of these converters produces an efficient interface converter between ultracapacitors and batteries. In the proposed converter, all switches and diodes are soft switched with simple PWM control. According to simulation results, voltage and current overlaps during switching instants are very small and thus switching losses are minimized.

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