IEICE Electronics Express, Vol.6, No.12, 844–850

A new boost dc-dc converter of high efficiency by using a partial resonant circuit

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Abstract: This paper presents a new boost dc-dc converter with high efficiency by using a partial resonant circuit. The switching devices in the proposed converter are operated by a soft-switching technique (ZCS; zero current switching, or ZVS; zero voltage switching) of a new partial resonant circuit. The partial resonant circuit makes use of a step-up inductor and a loss-less snubber capacitor. The switching control technique is simplified for the switches to drive in constant switching frequency with PWM (pulse width modulation). The results are that the switching power loss is very low and the system efficiency is high.

Keywords: boost dc-dc converter, soft-switching technique, loss-less snubber, partial resonant circuit

Classification: Science and engineering for electronics

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DOI: 10.1587/elex.6.844
Received April 19, 2009
Accepted May 30, 2009
Published June 25, 2009

1 Introduction

Equipment and machinery which supply dc electricity energy require the boost dc-dc converter of high efficiency by active switching modes to make the most use of the provided energy. The switching frequency of the converter must be increased in order to achieve small size, light weight and low noise [1]. However, the switches in the converter are subjected to high switching losses and stresses. As a result, the converter brings on low efficiency. Recently, to improve the efficiency, a number of soft-switching topologies including resonant circuits have been proposed [2, 3, 4]. However, these converters increase the number of switches and complicate the sequence of switching operation.

This paper describes a new boost dc-dc converter with high efficiency. The switches in the converter are operated by a soft-switching technique of a new partial resonant circuit. The partial resonant operation makes ZCS or ZVS for the control switches without switching losses so called “soft-switching” [3, 4, 5]. The switching control technique of the proposed converter is simplified for the switches to drive in constant switching frequency [4, 6].

2 Configuration and operation principle of proposed converter

Figures 1 (a) and 1 (b) show a conventional boost converter and a proposed

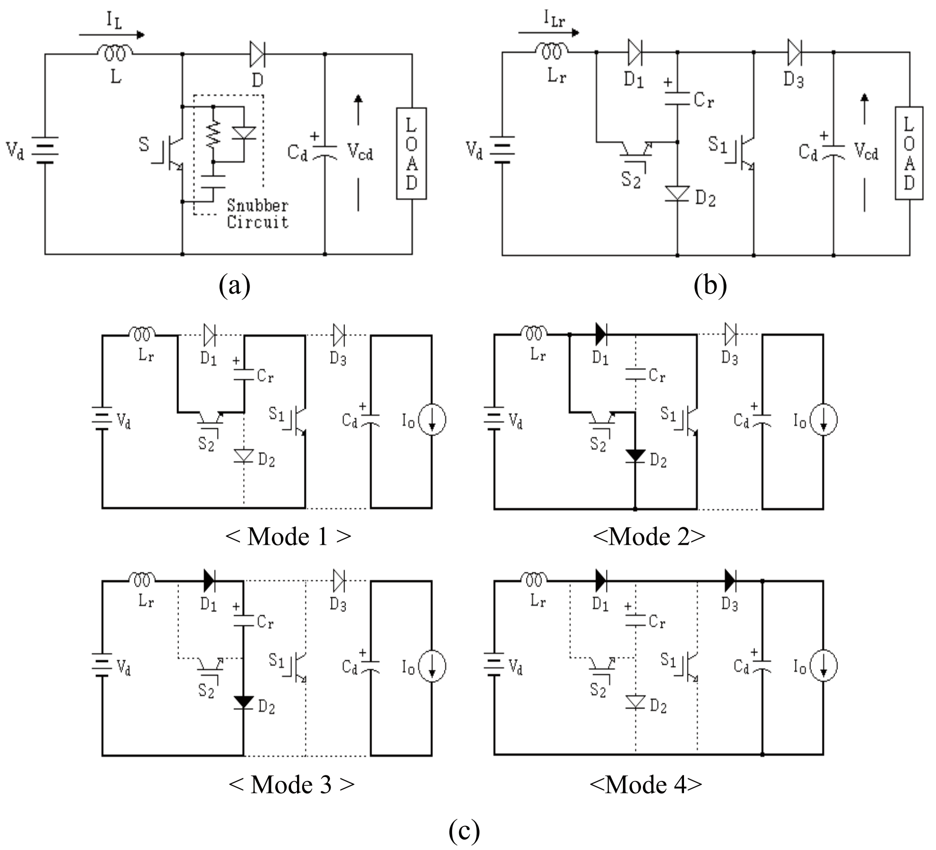

Fig. 1. Configurations of (a) conventional and (b) proposed boost dc-dc converters. (c) Equivalent circuits of operational modes in one cycle switching of the proposed converter.

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new boost converter. The proposed converter is composed of controlling devices, a step-up inductor L_r, and a snubber capacitor C_r used in similar way for the conventional converter. Furthermore, the current flowing through the inductor L_r is controlled to be discontinuous [6, 7], then the turn-on operation of the switches S_1 and S_2 becomes to be ZCS. The turn-off of the switches is also operated with ZVS by the partial resonant operation. Figure 1 (c) shows 4-equivalent circuits for operational modes in one cycle switching. The load side can be considered as a constant current source Io for one cycle switching (about 50 μs), which is caused by an output smoothing capacitor Cd of a great capacitance [7].

Mode 1 (T_1: $t_0 \leq t < t_1$)

Mode 1 begins by turning on both S_1 and S_2. This mode takes the form of a series LC resonance. The capacitor C_r discharges its electric charge through the inductor L_r. The turn-on switching occurs at zero current. The capacitor voltage is expressed as Eq. (1) and the inductor current increases according to Eq. (2).

$$v_{cr} = (V_d + V_{cd}) \cos \omega_r (t - t_0) - V_d \tag{1}$$

$$i_{Lr} = \frac{V_d + V_{cd}}{X} \sin \omega_r (t - t_0) \tag{2}$$

where $\omega_r = 1/\sqrt{L_r C_r}$, $X = \sqrt{L_r / C_r}$.

This mode ends when $v_{cr} = 0$. The time duration T_1 of this mode is evaluated as

$$T_1 = \sqrt{L_r C_r} \cos^{-1} \left(\frac{V_d}{V_d + V_{cd}} \right) \tag{3}$$

the inductor current I_1 at the end of this mode is given by

$$I_1 = \frac{1}{X} \sqrt{V_{cd}^2 + 2 V_d V_{cd}} \tag{4}$$

Mode 2 (T_2: $t_1 \leq t < t_2$)

Mode 2 begins when v_{cr} becomes zero. Then diodes D_1 and D_2 start conduction. The inductor current linearly increases according to the following equation:

$$i_{Lr} = \frac{V_d}{L_r}(t - t_1) + I_1 \tag{5}$$

This mode ends when both S_1 and S_2 are turned off. The time duration T_2 of this mode can be obtained as the following:

$$T_2 = T_{on} - T_1 \tag{6}$$

where T_{on} is the turn-on time of switches. The inductor current I_2 at the end of this mode is given by

$$I_2 = \frac{V_d}{L_r} T_2 + I_1 \tag{7}$$

Mode 3 (T_3: $t_2 \leq t < t_3$)

Mode 3 begins by turning off both S_1 and S_2. The inductor current charges C_r. This mode also forms a series LC resonance. The turn-off of

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switches occurs at zero voltage because the voltage of C_r is zero. In this mode, the capacitor voltage and the inductor current are evaluated as follows:

$$v_{cr} = V_d + \sqrt{\frac{L_r}{C_r}} I_a \sin[\omega_r(t - t_2) + \theta] \tag{8}$$

$$i_{Lr} = I_a \cos[\omega_r(t - t_2) + \theta] \tag{9}$$

where $I_a = \sqrt{\frac{C_r}{L_r} V_d^2 + I_2^2}$, $\theta = \sin^{-1}\left(-\frac{V_d}{\sqrt{V_d^2 + \frac{L_r}{C_r} I_2^2}}\right)$.

When v_{cr} becomes equal to V_{cd} and D_3 starts conduction, this mode ends. The time duration T_3 of this mode is expressed as

$$T_3 = \sqrt{L_r C_r}\left[\sin^{-1}\left(\frac{V_{cd} - V_d}{\sqrt{V_d^2 + \frac{L_r}{C_r} I_2^2}}\right) - \theta\right] \tag{10}$$

and the inductor current I_3 at the end of this mode is given by

$$I_3 = I_2 \cos\omega_r T_3 + \sqrt{\frac{C_r}{L_r}} V_d \sin\omega_r T_3 \tag{11}$$

Mode 4 (T_4: $t_3 \leq t < t_4$)

In this mode, the inductor current flows into the load. The current linearly decreases as

$$i_{Lr} = \frac{V_d - V_{cd}}{L_r}(t - t_3) + I_3 \tag{12}$$

This mode ends when $i_{Lr} = 0$. Time duration T_4 is expressed as

$$T_4 = \frac{L_r}{V_{cd} - V_d} I_3 \tag{13}$$

3 Computer simulation and experimental results

The proposed converter was analyzed by Pspice program. The output voltage was regulated at dc 300 V with dc 100 V input. L_r and C_r were selected at 70 μH and 100 nF, respectively. The capacitor C_d was 2000 μF, and the output load was replaced by a constant current source of 3 A. Switching frequency was 20 kHz and duty cycle was regulated at 30%.

Figures 2 (a) and 2 (b) show the waveforms of each part in one cycle switching. V_{g1} and V_{g2} are the gate signals of switches S_1 and S_2, v_{s1} and v_{s2} are voltages across the switches, i_{s1} and i_{s2} are currents flowing through the switches.

The switches are turned on at t_0 and C_r begins to discharge. v_{cr} becomes zero at t_1. At t_2, the switches are turned off, C_r is charged by i_{Lr}, and v_{cr} becomes V_{cd} at t_3. At t_4, i_{Lr} reaches zero and the switches are kept off till the next cycle. As the current of switches is zero at t_0, the switches are turned on at ZCS condition. As the voltage across switches is also zero at t_2, the switches are turned off at ZVS condition.

At Figures 2 (c) and 2 (d), the switch V-I locus for the conventional converter has a large area, but for the proposed soft-switching converter, it has only a small area. The area surrounded is proportional to the switching loss.

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ELectronics EXpress
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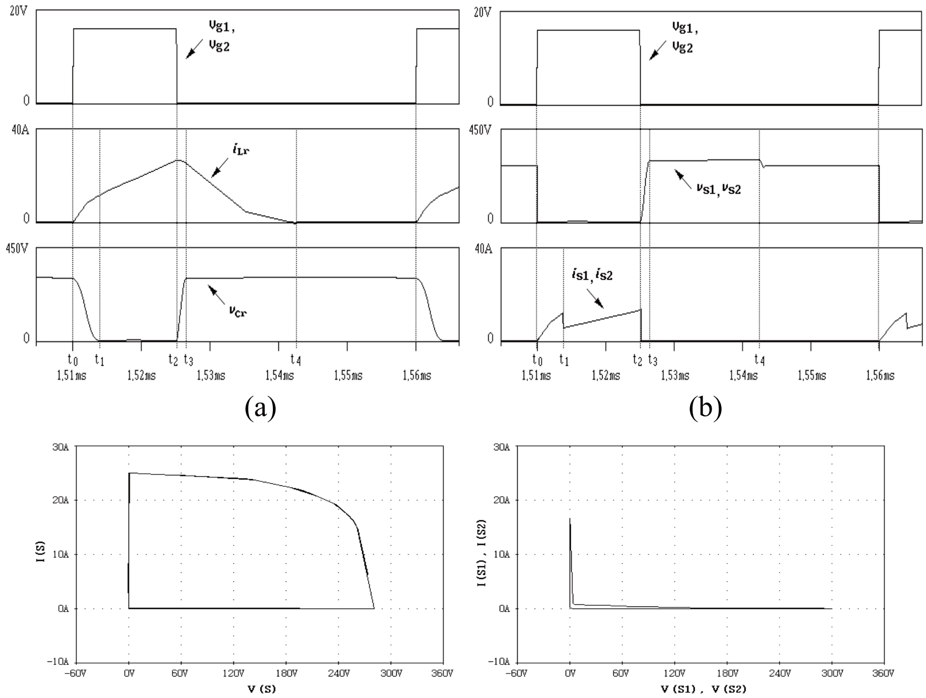

(a) (b)

(c) (d)

Fig. 2. Simulation waveforms in one cycle switching: (a) inductor current and capacitor voltage and (b) voltage and current of switches for the proposed dc-dc converter. V-I loci of the controlling switches for (c) the conventional converter and (d) the proposed converter.

In order to confirm the feasibility, the proposed converter was experimented to output a rated power of 1.0 kW. The input voltage source was supplied from the batteries of dc 100 V (25 V × 4 units), and the output voltage is fixed at dc 300 V. The output load was composed of a variable wiring resistor with the range of 10 Ω to 1000 Ω of 1.0 kW. Figures 3 (a) and 3 (b) show the waveforms of each part with a duty cycle of 30%, switching frequency of 20 kHz. The switches were operated with the soft-switching, namely turn-on at zero current and turn-off at zero voltage according to partial resonant operation. The power losses of main devices are shown in Figure 3 (c), respectively. Figure 3 (d) shows the relationship between system efficiency and output power. The output power was measured in the adjusted range of the variable resistor with PWM switching control. The snubber circuit in the conventional converter [Fig. 1 (a)] was also composed of a snubber resistor of 50 Ω and a snubber capacitor of 0.47 μF, which was generally used in hard-switching converters. Figure 3 (e) shows the relationship between output voltage and duty cycle with the load resistor 1000 Ω. As the charged voltage of capacitor C_r was added to input power source, the proposed converter generated higher output voltage than the conventional converter. To achieve discontinuous current mode (DCM), the duty cycles of the proposed converter and the conventional converter were measured and regulated below

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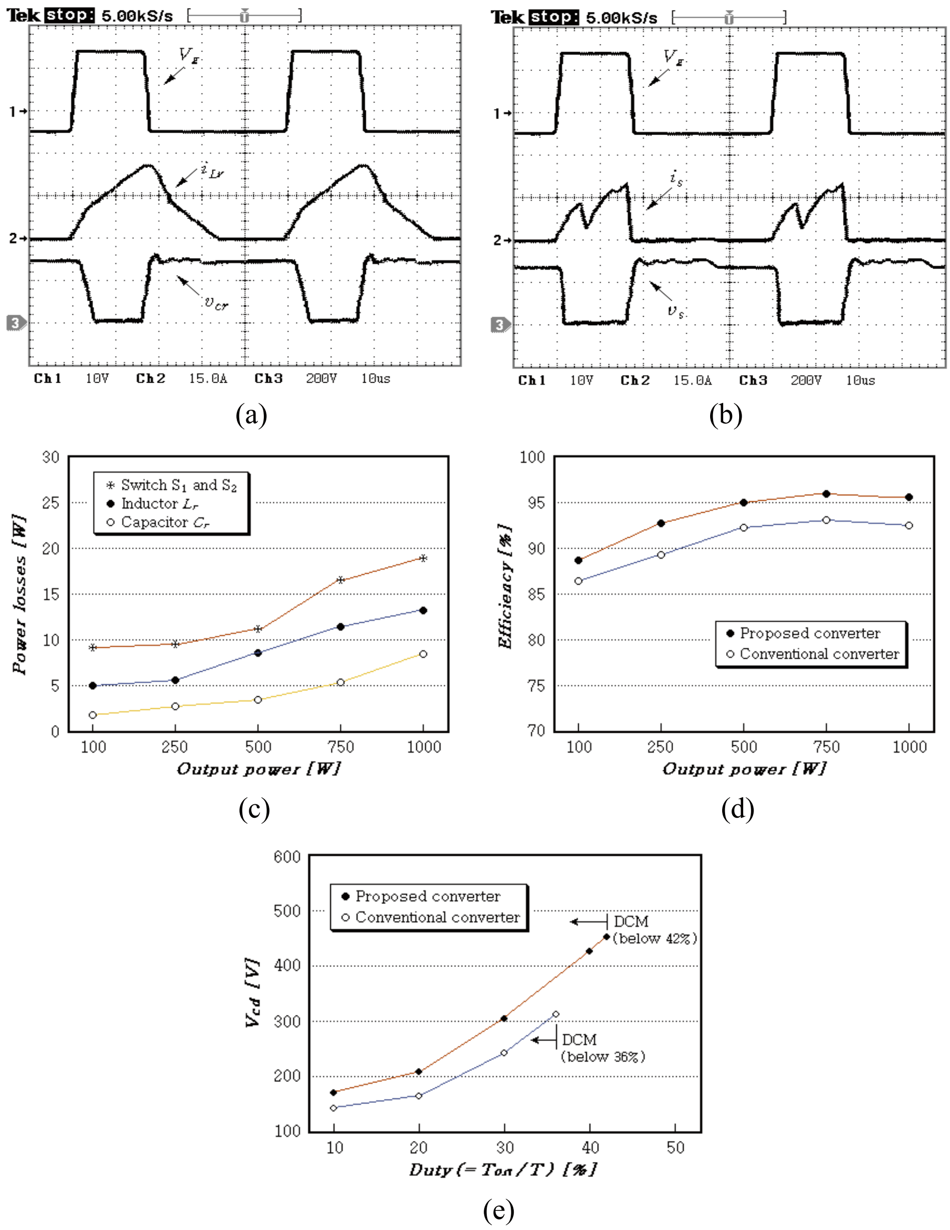

Fig. 3. Experimental waveforms in one cycle switching: (a) inductor current and capacitor voltage, (b) voltage and current of switch. (c) Power losses of main devices, (d) Measured efficiency comparison, and (e) Measured output voltage comparison with DCM.

42% and 36%, respectively, under the experimental condition.

4 Conclusion

A new boost dc-dc converter with high efficiency has been presented in this paper. To achieve the soft-switching of the controlling switches, the proposed boost converter applied a partial resonant circuit using a step-up inductor and a loss-less snubber capacitor. The accumulated energy in the loss-less snubber capacitor was regenerated into the input power source by the partial resonant

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