A New Buck-Boost DC/DC Converter of High Efficiency by Soft Switching Technique

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***Abstract*-In this paper, we study on a new buck-boost dc/dc converter of high efficiency by soft switching technique. The switching devices in the proposed converter are operated by soft switching with a new partial resonant circuit. The partial resonant circuit is designed to replacement of an energy storage inductor and a snubber circuit used in a conventional buck-boost converter, and then the configuration of the proposed converter is simplified. The switching control technique of the converter is also simplified for the switches to drive in a constant switching frequency. The results are that the switching power loss is very low and system efficiency is high. In addition, the output voltage of the converter is regulated by PWM control technique, and the discontinuous current flowing into the resonant inductor of the converter makes to simplify control method and control components. In comparison with the conventional buck-boost dc/dc converter, some simulation results on computer and experimental results are confirmed the validity of analytical results of the proposed converter.**

I. Introduction

Equipment and machinery which supply dc electricity energy requires the boost dc-dc converter of high efficiency by active switching modes to make the most use of the provided energy. The power converter must be increased the switching frequency in order to achieve small size, light weight, and low noise [1]-[3]. However, the switches in the converter are subjected to high switching power losses and switching stresses. As a result, the power system brings on low efficiency. Recently, to improve the efficiency, a large number of soft switching topologies including resonant circuits have been proposed [4]-[7]. But these converters increase the number of switches in power conversion circuit and complicate the sequence of switching operation.

This paper describes a new buck-boost dc/dc converter with high efficiency. The switching devices in the proposed converter are operated by a soft switching technique with a new partial resonant circuit. The partial resonant circuit makes use of a step-up inductor and a loss-less snubber capacitor regenerating accumulated energy into the input power source. The partial resonant operation makes zero current switching (ZCS) and zero voltage switching (ZVS) for the control switches without switching power losses so called “soft switching” [8], [9]. The resonant operation of the partial resonant circuit is partially enforced at only switching turn-on time or turn-off time. It reduces the losses and stresses of the resonant devices. The switching control technique of the proposed buck-boost dc/dc converter is simplified for the switches to drive in constant switching frequency [4], [10]. The output voltage of the converter is also regulated by the PWM control of switches. As a result, the proposed converter is operated with high efficiency by the soft switching and the partial resonant operation.

II. Circuit Configuration

Fig. 1 shows a conventional buck-boost dc/dc converter that is generally used. There are two control modes for this converter. One is the continuous conduction mode (CCM) of dc current and another is the discontinuous conduction mode (DCM) of dc current[10]. The output voltage of the converter is also regulated ted by the PWM control of the switch *S*. Specially, the turn-on of the switching device in the discontinuous mode is a ZCS. On the other hand, the device must be switched off at a maximum inductor current. Therefore, in order to relieve turn-off stress of the device, a snubber circuit is connected in parallel with the switch of the conventional converter.

However, the efficiency of the conventional converter is very low due to the power loss of the snubber circuit.

To improve the efficiency, a new buck-boost dc/dc converter with high efficiency is proposed in this paper and is shown in Fig. 2. The proposed buck-boost dc/dc converter is composed of controlling devices, a step up-down inductor L_r, and a snubber capacitor C_r used in similar way for the conventional converter. It is considered that the snubber circuit in the conventional converter is partly replaced to a partial resonant circuit in the proposed converter. The partial resonant circuit consists of a series connected switch-diode pair with a resonant capacitor, which is operated to a loss-less snubber capacitor.

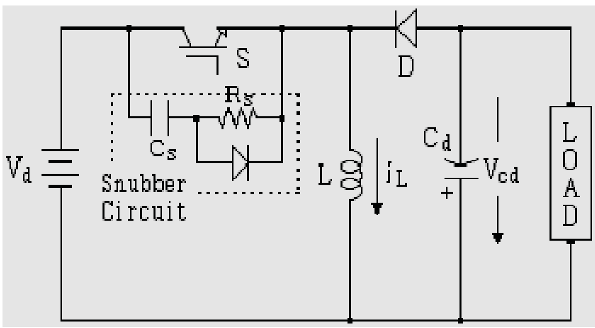


Fig. 1. Conventional buck-boost dc/dc converter.

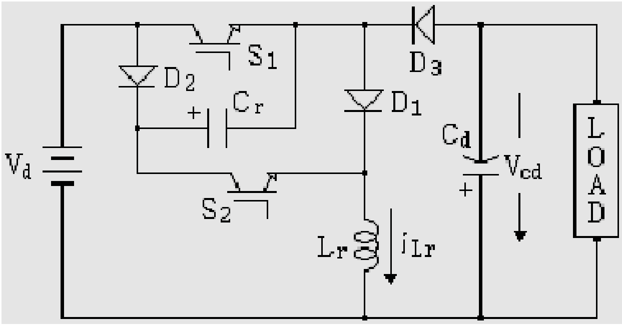


Fig. 2. Proposed buck-boost dc/dc converter.

The switching devices in the proposed converter are operated with the soft switching by partial resonance and with constant switching frequency. When the switching devices, S_1 and S_2, are turned off, the inductor L_r current charges the capacitor C_r by the partial resonant operation. Therefore, the turn-off of the S_1 and S_2 is ZVS. Since the current pulses in DCM converter always begin at zero, the turn-on of the S_1 and S_2 is ZCS. Furthermore, at the turn-on of the S_1 and S_2, it is for an accumulated energy in the snubber capacitor to regenerate into the input power source by partial resonant operation without the power loss of snubber circuit, which is generally produced in the conventional buck-boost dc/dc converter.

As a result, the proposed converter using a partial resonant circuit achieves the soft switching (the ZCS at turn-on and the ZVS at turn-off). The power losses of the switching devices are drastically decreased, and then the proposed converter is operated with high efficiency.

Ⅲ. OPERATION PRINCIPLE OF PROPOSED CONVERTER

Fig. 3 shows four equivalent circuits of each operational mode in one cycle switching of the proposed converter. At initial condition, the current flowing through inductor L_r is zero, Main switches S_1 and S_2 are off-state, and the capacitor C_r is charged to sum of the input voltage V_d and the output dc voltage V_{cd}.

1) Mode 1 (T_1 : $t_0 \le t < t_1$) : Mode 1 begins by turning on both S_1 and S_2 at the same time. The input voltage V_d and the capacitor voltage v_{cr} are added and applied to the inductor L_r. Then this mode takes the form of a series *LC* resonance circuit. The capacitor C_r discharges its electric charge through the inductor L_r. The turn-on of the switching devices occurs at zero current state. Hence this is ZCS. The capacitor voltage v_{cr} is expressed in (1) and the inductor current i_{Lr} increases according to (2).

$$v_{cr} = (2V_d + V_{cd})\cos\omega_r t - V_d \tag{1}$$

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

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

This mode ends when $v_{cr} = 0$. The time duration T_1 of this mode can be obtained by the following.

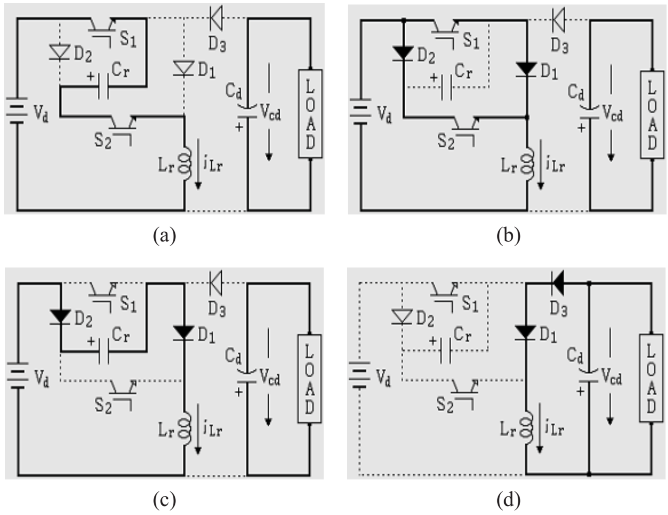


Fig. 3. Equivalent circuits of each operational mode in one cycle switching: (a) mode 1, (b) mode 2, (c) mode 3, and (d) mode 4.

$$T_1 = \sqrt{L_r C_r}\cos^{-1}\left(\frac{V_d}{2V_d + V_{cd}}\right) \tag{3}$$

The inductor current I_1 at the end of this mode is

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

2) Mode 2 (T_2 : $t_1 \le t < t_2$) : Mode 2 begins when the voltage across C_r becomes zero. Then the diodes D_1 and D_2 start conducting. The inductor current is divided into two paths of S_1-D_1 and D_2-S_2. The inductor current linearly increases as the following until the switches are turned off.

$$i_{Lr} = \frac{V_d}{L_r}t + I_1 \tag{5}$$

This mode ends when both S_1 and S_2 are turned off simultaneously. Then the time duration T_2 of this mode is expressed as

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

where T_{on} is the turn-on period of the switches S_1 and S_2, and the inductor current I_2 at the end of this mode can be obtained by the following.

$$I_2 = I_1 + \frac{V_d}{L_r}\left\{T_{on} - \sqrt{L_r C_r}\cos^{-1}\left(\frac{V_d}{2V_d + V_{cd}}\right)\right\} \tag{7}$$

3) Mode 3 (T_3 : $t_2 \le t < t_3$) : Mode 3 begins by turning off both S_1 and S_2 at the same time. The current flowing through L_r takes a route of D_2-C_r-D_1 and charges C_r. Then this mode takes the form of a series *LC* resonance circuit. The turn-off of S_1 and S_2 occurs at ZVS because the voltage of C_r is zero. In this mode, the voltage of C_r and the current of L_r are expressed as follows.

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

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

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 the capacitor voltage v_{cr} becomes equal to "$V_d + V_{cd}$" and the diode D_3 starts conducting, this mode ends. The time duration T_3 of this mode is expressed as (10) and the inductor current I_3 at the end of this mode is given by (11).

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

$$I_3 = \sqrt{I_2^2 - \frac{C_r}{L_r}(V_{cd}^2 - V_d^2)} \tag{11}$$

4) Mode 4 ($T_4 : t_3 \le t < t_4$) : By the conducting of the diode D_3, the inductor current i_{Lr} flows through the load side. The current linearly decreases as the next equation.

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

This mode ends when $i_{Lr} = 0$. The time duration T_4 of this mode is obtained by the following.

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

At the turn-on of both S_1 and S_2 simultaneously, another cycle starts.

IV. Computer Simulation and Experimental Results

The proposed converter was analyzed by *PSpice* simulation program. The circuit parameters for the simulation are listed in Table I. The output voltage V_{cd} of the simulation circuit is regulated at about dc 200V. The diodes are ideal, and every switch is replaced by an equivalent circuit consisting of a variable resistance and an ideal diode. Fig. 4 shows the waveforms of each part in one cycle switching for the proposed converter, in order to verify the partial resonant operation and the soft switching operation of the control devices.

In Fig. 4, the controlling switches, S_1 and S_2, of duty factor 40% are simultaneously turned on at t_0, and the capacitor C_r begins to discharge. The capacitor voltage v_{cr} becomes zero at t_1. At t_2, the controlling switches are simultaneously turned off and the capacitor C_r is charged by the inductor current i_{Lr}. The voltage of C_r becomes equal to "$V_d + V_{cd}$" at t_3. At t_4, the current i_{Lr} of the inductor reaches zero and the switches are kept off till the next cycle.

TABLE I
Circuit Parameters

Input voltage, V_d	100V	Output voltage, V_{cd}	200V
Resonant inductor, L_r	100μH	Smoothing capacitor, C_d	2000μF
Resonant capacitor, C_r	50nF	Load resistor, R_L	100Ω
Snubber resistor, R_s	50Ω	Switching frequency, f_c	40kHz
Snubber capacitor, C_s	0.47μF	Duty factor, D_C	40%

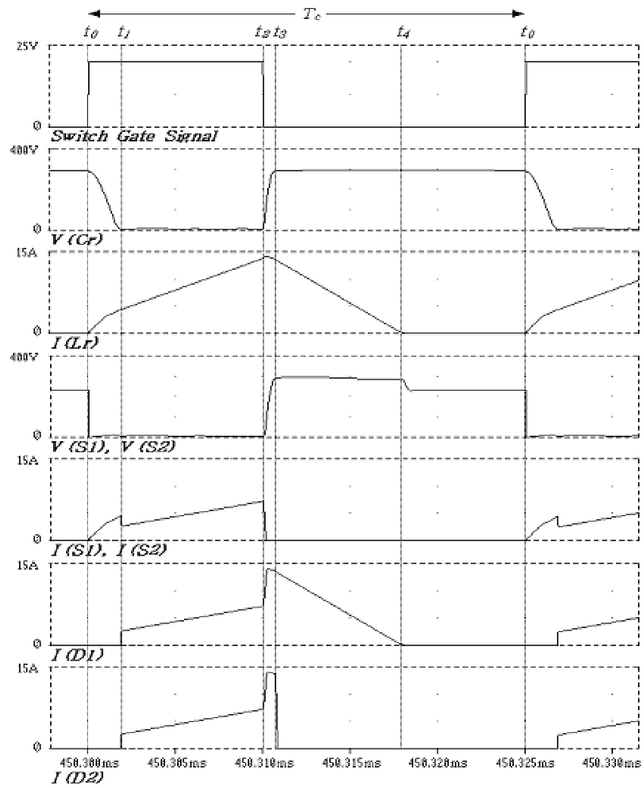
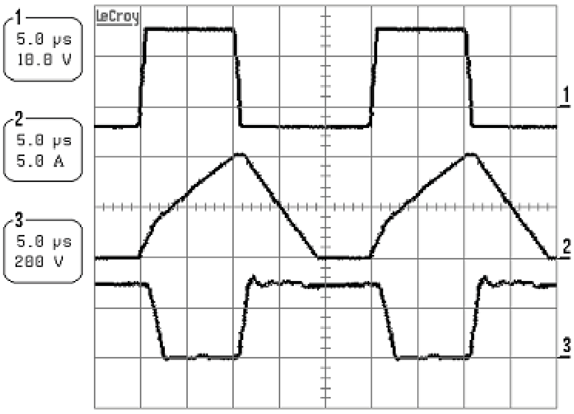


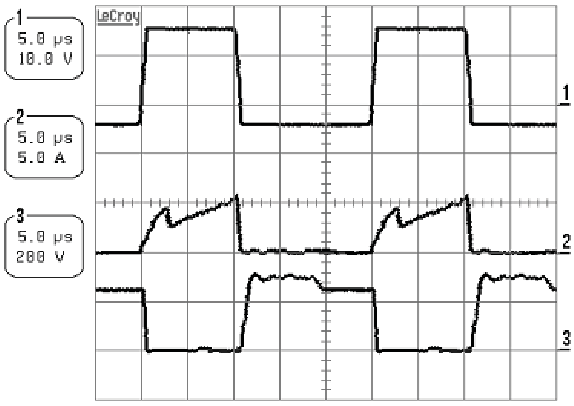
Fig. 4. Simulation waveforms in switching one cycle.

The indicated T_c is the period of one cycle of switching operation. In addition, as the current flowing through switches is zero at t_0, the switches are turned on at ZCS. As the voltage across switches is also zero at t_2, the switches are turned off at ZVS. The simulated results confirm the validity of theoretical results for each mode previously stated.

In order to confirm the feasibility, the proposed converter was built in the maximum output power of 1.0kW. The principal circuit devices in the proposed converter were designed on the basis of Table 1. Specifically, the output load was composed of a variable wiring resistor within the range of 10Ω to 1000Ω of 1.0kW rating. The used power switches were implemented by Fuji IGBT series 1MBH-60 (V_{CE}=600V, I_C=40A, and T_{off}=640ns rated for 20kHz switching frequency operation). Additionally, the power diodes were used to FRD (fast recovery diode) type. The control circuit of the converter was built in a Micom. package of Intel's 80c196kc processor.



(a)



(b)

Fig. 5. Experimental waveforms of each part for switching control signal [1]: (a) Inductor current i_{Lr} [2] and capacitor voltage v_{cr} [3], (b) Switch current i_s [2] and voltage v_s [3].

The switching signal was controlled with a programmed PWM data function table and a designed voltage-feedback circuit board through the A/D (analog/digital) converting port of the Micom.

Fig. 5 shows the waveforms of each part in one cycle switching for the proposed converter, in order to verify the partial resonant and soft switching operation of the control devices. Experimental values are obtained for the case of the load resistor $R_L = 100\Omega$, duty factor $D_c = 40\%$.

In Fig. 5, the switches used in the converter were operated with the soft switching, namely turn-on at zero current and turn-off at zero voltage, according to partial resonant operation. Particularly, the resonant operation of the partial resonant circuit was partially enforced at only switching turn-on time and turn-off time. It reduces the losses and stresses of the resonant devices. The above experimental results agree well with theoretical studies and computer simulation results previously stated.

The power losses of the main devices in the proposed converter are shown in Fig. 6, respectively. Fig. 7 shows the relation between a system efficiency and an output power. The output power was measured in the adjusted range of the variable resistor with PWM switching control for a fixed output voltage of dc 200V.

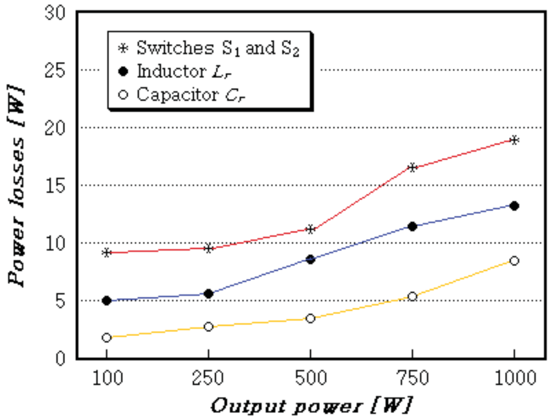


Fig. 6. Power losses of main devices in the proposed converter.

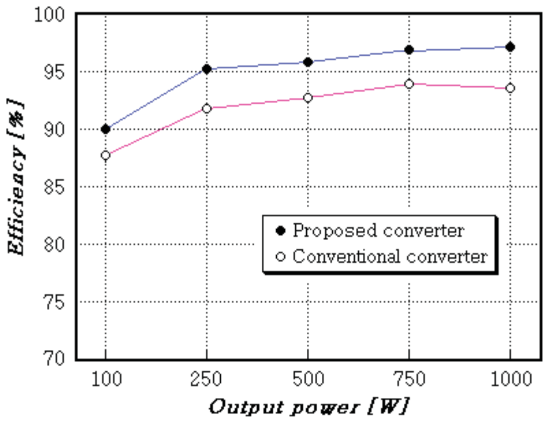


Fig. 7. Relationship between efficiency and output power.

The snubber circuit in the conventional converter was also composed of a snubber resistor of 50Ω and a snubber capacitor of 0.47μF, which was generally used in variable hard switching converters. The efficiency of the proposed buck-boost converter operated to soft switching was increased more than that of the conventional hard switching converter.

V. Conclusion

A new buck-boost dc-dc converter with high efficiency has been presented in this paper. To achieve the soft switching of the controlling switches, the proposed converter applied a partial resonant circuit using a step-up inductor and a loss-less snubber capacitor. That is, the partial resonant circuit was designed to replacement of an energy storage inductor and a snubber circuit which have been used in a conventional buck-boost converter, and then the configuration of the proposed converter was simplified. The accumulated energy in the loss-less snubber capacitor was regenerated into the input power source by the partial resonant operation. The partial resonant operation also conduced to the reduction of the losses and stresses of the resonant devices. The switching control technique and control components of the proposed converter were simplified for the switches to drive in a constant switching frequency with PWM and DCM. As a result, the proposed buck-boost dc/dc converter was that the switching power losses were very low and the system efficiency was high in comparison with the conventional buck-boost dc/dc converter.

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