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배터리 충전기용 영전압 PWM 컨버터

정 규 범

ZVS PWM Converter For Battery Charger

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요 약

본 논문에서는 일정한 주파수로 동작하는 영전압 스위칭 방식의 PWM 컨버터를 제안하였다. 제안된 컨버터에서 컨버터의 주 스위치는 항상 영전압에서 스위칭을 하며, 보조 스위치는 항상 소프트 스위칭을 한다. 또한, 컨버터 스위치의 전압 및 전류 스트레스는 기존의 PWM 컨버터와 같이 적다. 제안된 컨버터는 배터리 컨버터로 적용하기 위하여 buck 형 컨버터로 구현하였다. 컨버터의 스위칭 특성은 실험적으로 확인하였다.

ABSTRACT

Zero Voltage Switched (ZVS) Pulse Width Modulation (PWM) converter which operates a fixed frequency is proposed in this paper. The main switches of the converter are always switched at zero voltage, and the auxiliary switches are softly switched. The voltage and current stresses of the switches are minimized as low as in conventional PWM converters. The suggested buck typed converter is analyzed, designed for a battery charger. The designed characteristics are experimentally verified by the results of the buck type converter.

Key Words:ZVS((zero voltage switched) Converter, Battery Charger, Soft Switching, DC/DC Converter, High Efficiency

1. INTRODUCTION

Pulse Width Modulation (PWM) converters have been used predominantly in industrial applications because they have simple topologies, they are easy to control, and they do not create high current and voltage stresses in switches. Due to the demands of high power density converters, resonant converters [1-5] have been introduced and improved. However, resonant converters generally increase voltage and/or current stresses which cause an increase in conduction losses.[1-5]

In the viewpoint of this, PWM control of converters and soft switching of devices is very desirable. They realize high efficiency, the minimum switching losses of devices, and easy PWM control at high frequency operation. Recently, soft switched PWM converters which do not much increase conduction losses have been researched in order to obtain higher power density system[6-7].

A zero voltage switching PWM converter[6] with modular switch concepts satisfies soft switching with PWM control. One disadvantage is conduction losses due to the series connection of their switches. Zero Voltage Transition (ZVT) PWM converters[7] without serial connections of their switches was suggested. They have also good characteristics in main switches. However, the auxiliary switches are turned off under hard switching conditions.

This paper presents ZVS PWM converter which operates a fixed frequency. The main switches are turn on and off at zero voltage, and auxiliary switches are softly switched at zero voltage or zero current conditions. Therefore, the hard switching of the auxiliary switch for the conventional converter[7] is improved..

The buck typed ZVS PWM converter is selected to implement battery charger with high power density. High power density system is very applicable for the space applications[8]

The suggested converter is analyzed, and an operation method is selected to get minimized reverse recovery effect of auxiliary diodes for the battery charger. The designed characteristics are experimentally verified by the results of the converter for the battery charger.

2. PROPOSED CONVERTER

Fig. 1 shows the overall configuration of the proposed ZVS PWM buck converter for a battery charger. The basic configuration is the similar to the conventional PWM buck converter. The proposed converter additionally has an auxiliary switch, two diodes, an inductor, and two capacitors with small ratings of current or voltage. The converter operates at a fixed frequency controlled by PWM scheme, and all of the switches, including auxiliary switches, are only turned on and off at zero voltage and/or zero current.

The operation of the converter is divided into eight different modes as shown in Fig. 2. The typical

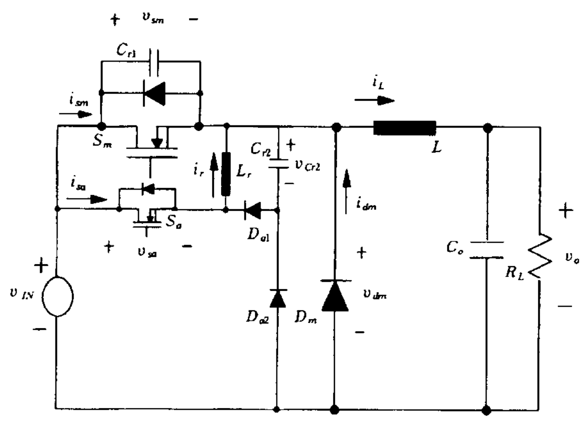

Fig. 1 Overall configuration of proposed ZVS PWM converter.

waveform of ZVS PWM buck converter is shown in Fig. 3. At mode 0, and mode 6, the switching of the main switches is the same to the switching of them for the conventional PWM converter. The main switches have a turn on process during from mode 1 to mode 5, and a turn off process during mode 7. For a battery charger, the mode 5 can omits to reduce reverse recovery effects without adding an saturable inductor in series with L_r. For omitting mode 5, C_{r2} should be as larger as possible.

In this analysis, the inductor current i_L, and the input voltage V_{IN} are assumed to be constant values which are I_L and V_{IN}, respectively.

The resonant frequencies ω_1, ω_2 and impedances Z_1 and Z_2 of the related resonant circuits are used in this paper. They are

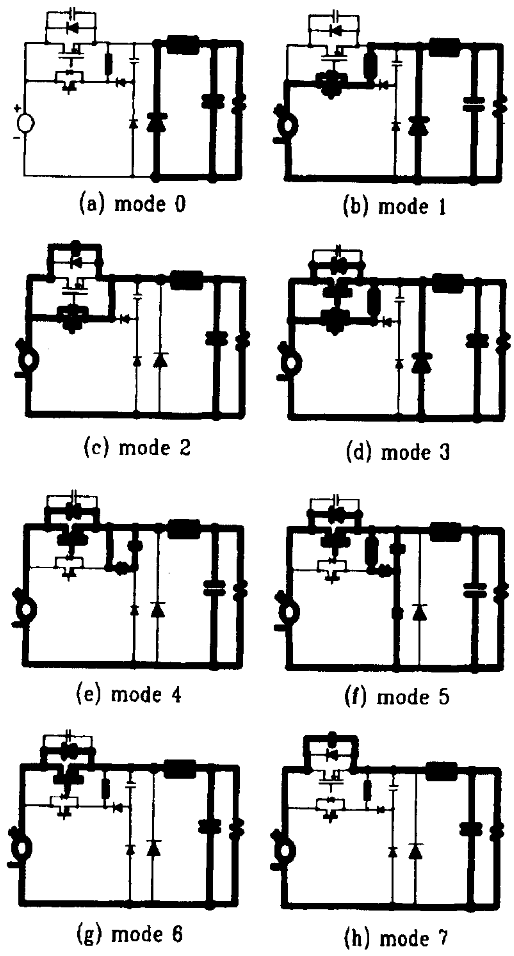

Fig. 2 Switch modes of ZVS PWM converter.

$$\omega_1 = \frac{1}{\sqrt{L_r C_{r1}}} \quad (1)$$

$$\omega_1 = \frac{1}{\sqrt{L_r C_{r2}}} \quad (2)$$

$$Z_1 = \sqrt{\frac{L_r}{C_{r1}}} \quad (3)$$

$$Z_2 = \sqrt{\frac{L_r}{C_{r2}}} \quad (4)$$

The descriptions of the modes are summarized as follows.

(1) Mode 0 (t_0-t_1) : The main diode D_m is conducting, all other switches are turned off as shown in Fig. 2(a). Therefore, the inductor current i_L is transferred to the load. The inductor current i_r remains zero, and the voltage v_{cr2} of the capacitor C_{r2} continues to be zero.

(2) Mode 1 (t_1 - t_2) : To turn on the main switch S_m, mode 1 is started when the auxiliary switch S_a is triggered at time t_1. The equivalent circuit is shown in Fig. 2(b). The inductor current i_r is increased to I_L in this mode. The L_r and V_{IN} determine the increasing rate of i_r as

$$\frac{di_r}{dt} = \frac{V_{IN}}{L_r} \quad (5)$$

The main diode current i_{dm} is decreased by the rate of (5). Therefore, S_a is softly turned on at zero current with the increasing rate of (5) as shown in Fig. 3.

(3) Mode 2 (t_2-t_3) : When i_r goes to I_L at time t_2, D_m is naturally turned off at zero voltage and zero current. The equivalent circuit becomes Fig. 2(c). Thus L_r and C_{rl} resonate until the capacitor voltage , v_{Crl}, is equal to zero. The current i_r and the voltage v_{Crl} are derived as follows.

$$i_r = I_L + \frac{V_{IN}}{Z_1} \cdot \sin[\omega_1 (t - t_2)] \quad (6)$$

$$v_{Cr1} = V_{IN} \cos[\omega_1 (t - t_2)] \quad (7)$$

(4) Mode 3 (t_3 - t_4) : When v_{Crl} reaches zero at time t_3, the internal diode of S_m is softly turned on at zero voltage. The current i_r and i_{sm} remain constant in this mode as the following values.

$$i_r(t) = I_L + V_{IN} / Z_1 \quad (8)$$

$$i_{sm}(t) = -V_{IN} / Z_1 \quad (9)$$

During this period, the gate signal of S_m has to be triggered to turn on S_m at zero voltage.

(5) Mode 4 (t_4-t_5) : When S_a is turned off, i_{sm} becomes I_L. The energy of L_r is transferred to C_{r2} until the voltage reaches V_{IN} by the resonance of L_r and C_{r2}. The equivalent circuit is shown in Fig. 2(e). i_r and v_{Cr2} are derived by resonance of L_r and C_{r2}.

$$i_r = (I_L + V_{IN} / Z_1) \cos[\omega_2 (t - t_4)] \quad (10)$$

$$v_{Cr2} = (I_L + V_{IN} / Z_1) Z_2 \ \sin[\omega_2 (t - t_4)] \quad (11)$$

The diode D_{al} is turned on at zero voltage because v_{Cr2} is zero at t_4

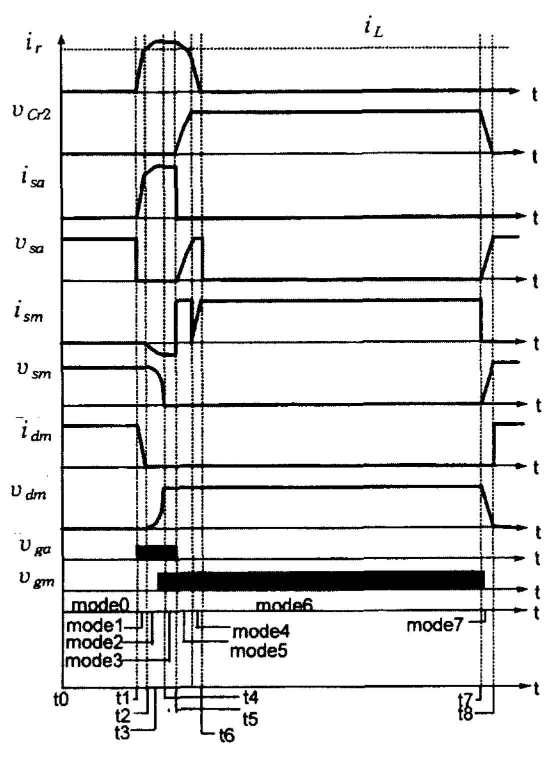

Fig. 3 Typical waveform of ZVS PWM converter.

(6) Mode 5 (t_5 - t_6) : When v_{Cr2} becomes V_{IN} at time t_5, the energy of L_r is transferred to the input as shown in Fig. 2(f). Then, i_r is decreased to the following equation.

$$i_r(t) = i_r(t_5) - \frac{V_{IN}}{L_r}(t - t_5) \tag{12}$$

Then,

$$i_{sm}(t) = I_L - i_r(t) \tag{13}$$

If the v_{cr2} does not reach to V_{IN} in mode 4, this mode shall be omitted.

(7) Mode 6 (t_6 - t_7): The diodes D_{al} and D_{a2} are naturally turned off at zero current when i_r decreases to zero. The main active switch is turned on as shown in Fig. 2(g).

(8) Mode 7 (t_7 - t_8) : At t_7, S_m is turned off. The slope of the voltage is determined by parallel capacitors C_{r1} and C_{r2}. The slope is

$$\frac{dv_{sm}}{dt} = \frac{1}{(C_{r1} + C_{r2})} \cdot I_L \tag{14}$$

During the mode 4, the voltage v_{cr2} can be lower than V_{IN}. When the mode If the mode 5 omits, the initial slope is

$$\frac{dv_{sm}}{dt} = \frac{I_L}{C_{r1}} \tag{15}$$

Then, the voltage slope is changed by (14), when v_{sm} is equal to v_{cr2}.

3. CHARACTERISTICS OF BATTERY CHARGER

One switching cycle of PWM operation is completed from mode 0 to mode 7, the next cycle is repeated by the same processes.

3.1 Operation of Switches

From switch mode analysis in section II, all switches satisfy soft switching conditions as shown in Table I. When load current becomes low or C_{r2} designs large, the maximum of v_{cr2} in (11) can be lower than V_{IN}. In this condition, the mode 5 can be skipped because i_r becomes zero before v_{Cr2} reaches the input voltage. But soft switching characteristics of the switches can not be varied.

Table 1. Switching conditions of switching devices.

Switches	Turn on conditions	Turn off conditions
Sm	ZVS	ZVS
Dm	ZVS	ZVS and ZCS
Sa	ZCS	ZVS
Dal	ZVS	ZCS
Da2	ZVS	ZVS and ZCS

The internal diode of main switch, S_m, is turned on at zero voltage and small current of V_{IN} /Z_1 from (9). Turning on signal of the main MOSFET is triggered during on state of the internal diode. The main switch S_m is turned off with the slope of (14) or (15). The main diode D_m is turned on with the slope of (14) or (15), also. The auxiliary switch S_a is turned on at zero current by L_r, and turned off at zero voltage by C_{r2}. D_{al} and D_{a2} are turned on at zero voltage by C_{r2}, and turned off at zero current by L_r.

3.2 Reverse Recovery Current of Diodes

Reverse recovery current of main diode D_m is determined by L_r. However, the current is not much because the diode is zero voltage transition turned off, which is due to resonant operation of L_r and C_{rl}, for mode 2. The reverse recovery current of the auxiliary diodes, D_{al} and D_{a2}, are also limited by L_r. When the auxiliary diodes are turned off with zero current, the current slope is determined by (12). To reduce the reverse recovery current, a saturable inductor shall be added in series with L_r, therefore.

In this paper, a new operation mode is suggested to reduce the reverse recovery current of auxiliary diodes without adding a saturable inductor. To operate the battery charger at this situation, C_r have to increase to some value. Then, the maximum voltage v_{cr2}, V_{cr2}, is lower than the input voltage V_{IN}. V_{cr2} can be calculated by (11) as follows.

$$V_{Cr2} = (I_L + V_{IN} / Z_1)Z_2 \tag{16}$$

When V_{cr2} is much lower than V_{IN}, we can reduce reverse recovery current of D_{a1} and D_{a2} without adding a saturable inductor.

3.3 Output Voltage Characteristics

Control of the output voltage is determined by duty ratio which is the ratio of turn on period(T_{on}) of main and auxiliary active switch with the total period(T). To maintain the soft switching condition, the minimum duty ratio is needed because turn on process from mode 1 to mode 4 is required. The minimum turn on time is determined by mode analysis, and simplified as follows.

$$T_{on,\min} = \frac{\pi}{2}\cdot(\sqrt{L_r C_{r1}} + \sqrt{L_r C_{r2}}) + LI_{L,\max} / V_{IN} \qquad (17)$$

where I_{Lmax} is the maximum current of inductor L, and $t_4 - t_3$, which is the period of mode 3, is assumed by 800 ns.

Fig. 4 represents the minimum duty ratio condition for soft switching of auxiliary switches for variations of L_r and C_{r2}. In this figure, switching frequency f_s, I_{Lmax}, and V_{IN} are assumed 100 kHz, 5 A, and 40 V, respectively. And, C_{r1} assumes very smaller than the capacitance of C_{r2}. As C_{r2} or L_r increases, the soft switching region is decreased due to the increasing resonant period. As increasing output load, or decreasing V_{IN}, the last term of (17) increases. The soft switching region is decreased, therefore.

Fig. 5 represents output transfer function as a function of duty ratio D for 100 kHz switching frequency. In eqn (17), 0.8㎲ period of mode 4 is considered, practically. In Fig. 5, C_{r2}, L_r, V_{in} and I_{Lmax} are 470 nF, 2.5 ㎌H, 40 V and 5 A, respectively. The dashed line is the soft switching region and dotted line is the hard switching region of the switches. Although the switches are operated by hard switching region at small duty ratio, the auxiliary circuit operates as the lossless snubber.

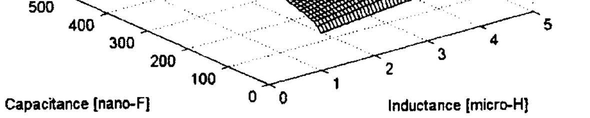

Fig. 4 Minimum duty ratio condition for soft switching of auxiliary switches for variations of L_r and C_{r2}

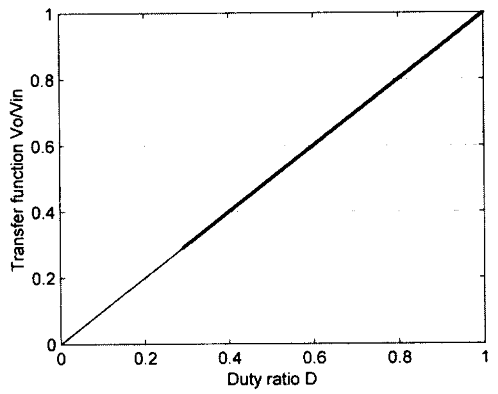

Fig. 5 Output transfer function for duty ratio

4. RESULTS OF EXPERIMENT

Battery charger was designed to supply maximum of 5 A for charging 22 battery cells in series connection. The controlled battery voltage shall be from 20 V to 32 V for control region. Therefore, the range of duty ratio of battery charger is from 0.5 to 0.8 for 40 V input bus line. A ZVS PWM buck converter has been implemented to demonstrate the operation. The power circuit, as shown in Fig. 1, consists of the following components:

V_{in} = 40 V	S_a : *IRF*132
L = 125 μH	D_m : *FE6D*
L_r = 2.5 μH	D_{a1} : *FE1D*
S_m : *IRFP*150	D_{a2} : *FE1D*

In Fig. 1, the filter C_o and load R replaces to 22 V of battery voltage. The battery charger is experimented has 0.55 of duty ratio for 4 A constant current charging, in this paper.

Because the turn off of D_m is zero current switching as well as zero voltage switching by resonant circuit, capacitance C_{r1} can be selected only internal capacitance switch S_m. The minimize C_{r1} reduces circulating energy of L_r-C_{r1} resonant circuit. Capacitance C_{r2} is designed as large as 470 nF to guarantee soft switching of auxiliary switch for 0.3 - 1.0 of duty ratio in Fig. 5. This region of duty ratio is enough to charge for normal operation of battery, which has 22 battery cell in series connection. Although the switches are operated by hard switching region at small duty ratio, the auxiliary circuit operates as the lossless snubber.

Fig. 6 represents voltage v_{sm} and current i_{sm} of main switch S_m. The S_m is always turned on and off at zero voltage. The turn on/off slopes depend on internal capacitor of S_m and L_r. For a high voltage input application, the turn off slope of S_m should be increased, an additional capacitor in parallel with S_m should be added to smooth the slope.

Fig. 7 shows the voltage v_{sa} and the current i_{sa} of the auxiliary switch S_a. S_a is turned on at zero current with a slope, and turned off at zero voltage. Soft switching of the switch S_a is satisfied. When D_{a1} is turn off, we know V_{cr2} is about 5 V. Therefore, the reverse recovery problem should be reduced with no adding saturable inductance.

Fig. 8 represents main diode voltage v_{dm} and inductor current i_L. The D_m is always turned on and off at zero voltage. The filter current i_L is increasing for on period

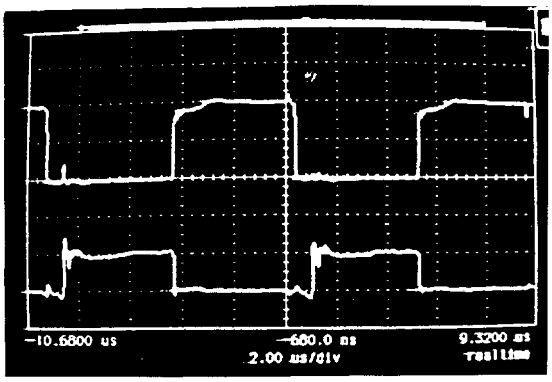

Fig. 6 Voltage and current waveform of main switch S_m. upper trace : v_{sm}- 20 V/div ; lower trace : i_{sm}- 2 A/div ; time scale : 2 μsec/div

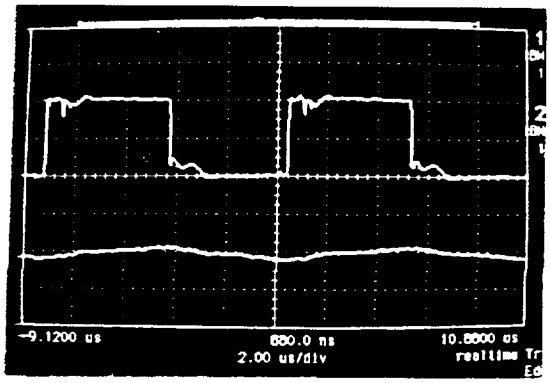

Fig. 8 Voltage waveform of main diode D_m and current waveform of inductor. upper trace : v_{dm}- 20 V/div ; lower trace : i_L - 2 A/div ; time scale : 2 μsec/div

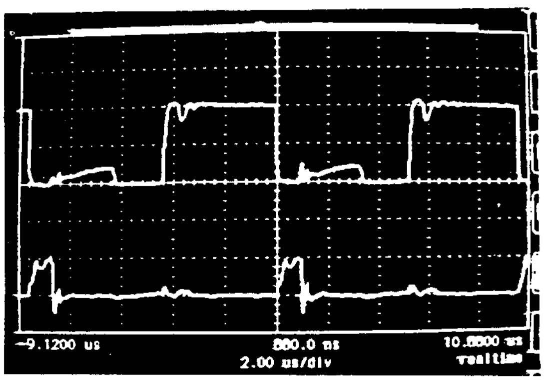

Fig. 7 Voltage and current waveform of auxiliary switch S_a. upper trace : v_{sa}- 20 V/div ; lower trace : i_{sa}- 2 A/div ; time scale : 2 μsec/div

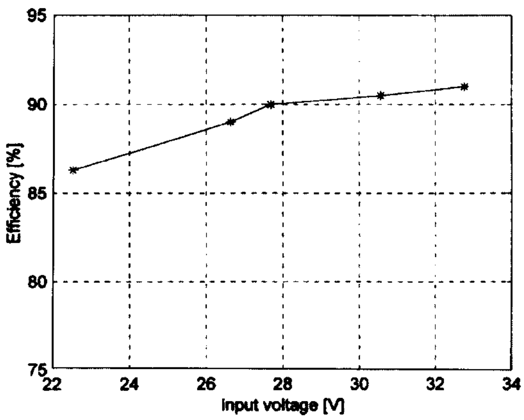

Fig. 9 Efficiency for battery voltage variations

of D_m, and decreasing for off period of D_m.

Fig. 9 shows efficiency for battery charger. The efficiency for higher than 26 V 88 - 91 %. At low input voltage, efficiency is lowered because the portion of conduction loss for switches is increased. Although, the efficiency is ranged from 86 to 91 %, battery voltage is normally charged more than 28 V, the operating efficiency of battery charger is higher than 90 %, practically.

5. CONCLUSIONS

The ZVS PWM converter that has soft switching characteristics of all switches including auxiliary devices is proposed. The proposed converter has similar good characteristics as conventional PWM converters in the following features[1-2]:

- PWM control with fixed frequency, similar device voltage and current stresses
- Similar model characteristics,

The proposed converter improves also upon conventional PWM converters in the following features:

- much lower switching losses of all the switches
- possible to operate higher frequency
- reducing reverse recovery current of auxiliary diode without adding additional saturable inductor

The characteristics of the converter is experimentally verified for battery charger.

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