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Research on Characteristics of Soft Switching Bidirectional Converter Based on Electric Vehicle

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ABSTRACT

A practical soft switch bidirectional converter for EV is presented, which can realize the bidirectional flow of energy between the energy storage battery and the motor of the EV. By choosing an appropriate resonant circuit, the soft switch characteristics of the converter in Buck mode and boost mode are analyzed, and a prototype is made. The waveform of the power tube switch state is collected by an oscilloscope, which improves the energy conversion efficiency of the converter and verifies the rationality of the design.

Keywords: *Electric vehicle, Soft switch, Bidirectional converter, Mode*

1. INTRODUCTION

With the increasingly prominent environmental and energy issues, the development of electric vehicles is particularly important [2].Electric vehicle can work in both electric and feedback braking state when working. The stability of voltage and charging using braking energy cannot be separated from the help of bidirectional DC/DC converter [1]. However, there are still many problems in the bi-directional converter currently used. For example, in the process of power transmission, because the switch tube of the bi-directional converter works in hard switch state, there is a large switch loss. Some bidirectional converters are complex in structure and unstable in operation, and others have problems such as spontaneous combustion due to unreasonable design. For this reason, the soft switch converter with high energy efficiency and simple structure has become a technology that must be tackled in the development of electric vehicle. Based on this, a soft switch bi-directional converter for electric vehicle is designed, which improves the efficiency of the converter and has a simple structure, showing good performance.

2. CIRCUIT TOPOLOGY AND WORKING PRINCIPLE

Soft-switch two-way converter connects the motor and battery of the electric vehicle separately and acts as an interface for energy exchange between them. The circuit topology of the soft-switch bidirectional converter is shown in Figure 1. V_{in} is the DC voltage of the motor, V_o is the battery voltage, $S_1$and S_3 are the main switches of the soft-switching bidirectional converter, S_2 and S_4 are the auxiliary switches of the soft-switching bidirectional converter, D_1 and D_4 are the reverse parallel diodes of the switch tube, L is the main inductance, L_{r1} and L_{r2} are the resonant inductance, C_r is the resonant capacitor, which work together to realize the soft-switching function of the bidirectional converter.

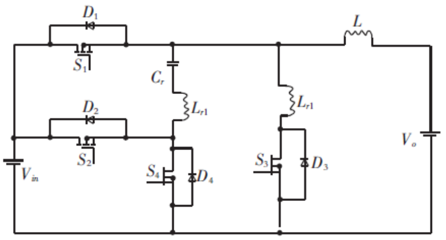

Figure1 Soft switching bidirectional converter circuit topology

The soft-switch bidirectional converter consists of two working modes, buck mode and boost mode [3].When the motor brakes in reverse, the motor charges to the battery through a soft-switch bidirectional converter, which operates in Buck mode. When the motor drives the electric vehicle normally, the battery supplies power to the motor through a soft-switch bidirectional converter, which works in boost mode. Due to the existence of resonant inductance and capacitance, the switch in soft-switching bidirectional converter always works in zero-current state, that is, soft-switching state.

When the soft switch bi-directional converter is in Buck mode, the switch S_1 and S_2 are in working state, and S_3 and S_4 are always in off state. The buck mode of the converter can be divided into four stages.

Stage 1 ($t_0 < T < t_1$): When buck mode starts t = t_0, switches S_1 and S_2 are turned off, and the output current is stored by inductance and supplied to the battery port through the inverse shunt diode D_3 of switch S_3.

Stage 2 ($t_1 < T < T_2$): When t = t_1, switch S_1 is on and S_2 is off. The capacitance C_r resonates with the inductance L_{r1}, forcing the current in diode D_3 to gradually decrease to zero, creating a zero-current switch condition for switch S_1, the soft-switch condition. The current expressions of the voltage at both ends of the resonant capacitor C_r and the resonant inductance L_{r1} are:

$$V_{Cr}(t) = -V_{Cr\max}\cos(\omega_0(t - t_1)) \qquad (1)$$

$$I_{Lr1}(t) = I_L + \frac{V_{Cr\max}}{Z_0}\sin(\omega_0(t - t_1)) \qquad (2)$$

Among

$$Z_0 = \sqrt{L_{r1}/C_r} \qquad (3)$$

$$\omega_0 = 1/\sqrt{L_{r1}C_r} \qquad (4)$$

In the formula: V_{Cr} is the voltage at both ends of capacitor C_r, I_{Lr1} is the current of inductance L_{r1}, V_{Crmax} is the peak voltage at both ends of capacitor C_r, I_L is the current of inductance L, L_{r1} is the inductance value of inductance L_{r1}, and C_r is the capacitance value of capacitor C_r.

Stage 3 ($t_2 < T < t_3$): When t = t_2, capacitance C_r and inductance L_{r1} stop resonance, switch S_1 is on, the converter is in Buck operation, and the motor supplies power to the battery through the converter.

Stage 4 ($T_3 \leqslant T < T_4$): when t = T_3, the switch S_2 is turned on, the capacitor C_r and the inductor L_{r1} begin to resonate, and the voltage at both ends of the capacitor C_r reaches the peak after half a cycle. The resonance between capacitor C_r and inductor L_{r1} forces the current in switch S_1 to zero gradually, which creates zero current switching condition for switch S_1, that is soft switching condition. In this stage, the expressions of the voltage at both ends of the resonant capacitor C_r and the current of the resonant inductor L_{r1} are as follows:

$$V_{Cr}(t) = V_{Cr\max}\cos(\omega_0(t - t_3)) \qquad (5)$$

$$I_{Lr1}(t) = \frac{V_{Cr\max}}{Z_0}\sin(\omega_3(t - t_3)) \qquad (6)$$

When the soft-switch bidirectional converter is in boost mode, the switches S_3 and S_4 are in working state, and S_1 and S_2 are always in off state. The boost mode of the converter can be divided into six stages.

Stage 1 ($t_0 < T < T_1$): When t = t_0, the current of the main inductance L_1 flows through the inductance L_{r2} and the switch S_3, the inductance L_{r2} is in the energy storage state, and the switch S_3 zero current is on.

Stage 2 ($t_1 < T < t_2$): When boost mode starts, t = t_1, and the current in inductance L_{r2} reaches its peak. Inductance L_{r1}, inductance L_{r2} and capacitance C_r produce resonance. The current expressions for the voltage at both ends of the capacitor Cr and the inductance L_{r2} are:

$$V_{Cr}(t) = V_{Cr\max}\cos(\omega_0(t - t_1)) \qquad (7)$$

$$I_{Lr2}(t) = I_L + \frac{V_{Cr\max}}{Z_0}\sin(\omega_0(t - t_1)) \qquad (8)$$

Among

$$Z_0 = \sqrt{(L_{r1} + L_{r2})/C_r} \qquad (9)$$

$$\omega_0 = 1/\sqrt{(L_{r1} + L_{r2})/C_r} \qquad (10)$$

Stage 3 ($t_2 < T < T_3$): When $t = t_2$, the circuit of the capacitor C_r becomes zero and the resonance in the converter stops. The main inductance L is in the state of energy storage.

Stage 4 ($t_3 < T < t_4$): When $t = t_3$, the switch S_4 is on, the inductance L_{r1}, L_{r2} and capacitance C_r are always in resonance state, and when $t = t_4$, the current in inductance L_{r1} is zero.

Stage 5 ($t_4 < T < t_5$): When $t = t_4$, the resonance in the converter stops, the main inductance current I_L charges the capacitor C_r, and the voltage at both ends of the capacitor C_r increases linearly. When $t=t_5$, the voltage at both ends of the capacitor C_r reaches the battery voltage V_o. The expression of the voltage at both ends of the capacitor C_r at this stage is:

$$V_{Cr}(t) = V_{Cr}(t_4)\frac{I_L}{C_r}(t - t_4) \qquad (11)$$

Stage 6 ($t_5 < T < t_6$): When the voltage at both ends of the capacitor C_r reaches the DC voltage of the motor V_{in}, the diode D_1 is turned on under soft switch condition, and the converter is in the state of energy output. When $t=t_6$, the switch S_3 is switched on again to start the next working cycle.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Based on the soft-switch bi-directional converter structure proposed above, a prototype with power of 1 kW has been made. The prototype's motor DC voltage V_{in}= 400V, battery voltage V_o= 400V, operating frequency f = 100kHz.The inductance values of L_{r1} are L_{r1} = 10 μ H, L_{r2} = 1 μ H, and C_r = 10 nF. For experimental observation, the voltage waveform amplitude is reduced to 1/100 when the sample is measured. For current waveform measurement, the corresponding current probe is used and the current waveform amplitude is reduced to 1/10 [4].The experimental circuit waveforms are shown in Figure2, Figure3, Figure4 and Figure 5.

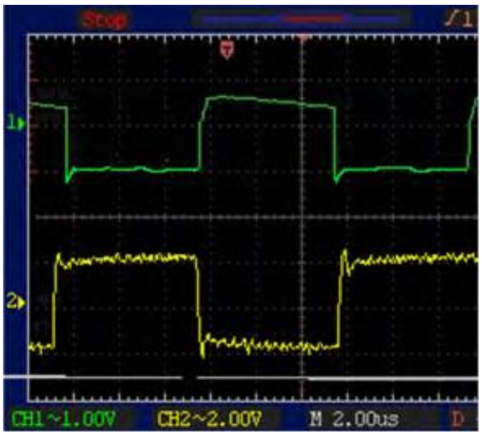

Figure 2 Voltage waveform and current waveform of switch S_1

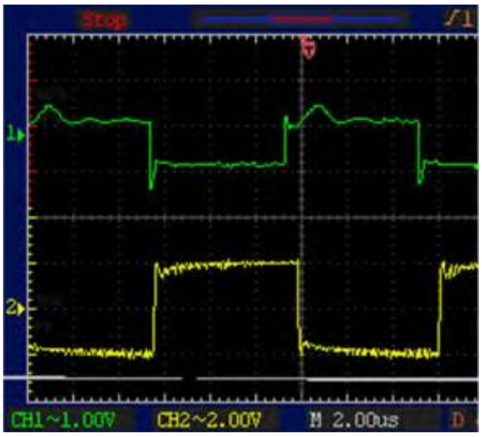

Figure3 Voltage waveform and current waveform of switch S_2

The voltage and current waveforms of the main switches S_1 and S_3 of the soft switch bidirectional converter are shown in Figure2 and Figure4.As shown in the diagram, the switches S_1 and S_3 have achieved zero current shut-off, and the switches operate in the Zero Current Switch (ZCS) state completely during the shut-off process. The voltage and current waveforms of the auxiliary switches S_2 and S_4 of the soft switch bidirectional converter are shown in Figure3 and Figure5. The diagram shows that the switch also works in the zero current switch state.

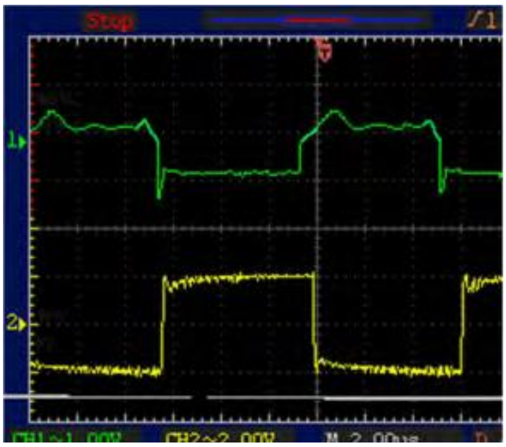

Figure4 Voltage waveform and current waveform of switch S_3

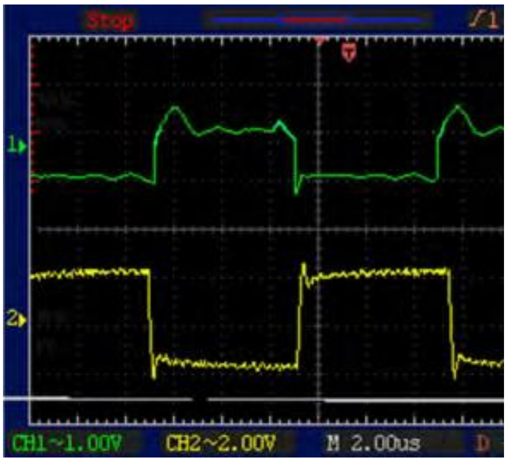

Figure5 Voltage waveform and current waveform of switch S_4

4. Conclusion

The soft switch bi-directional converter of the electric vehicle can be used as the interface between the energy storage battery of the electric vehicle and the energy exchange of the motor. When the electric vehicle is running normally, the converter is in boost mode, and the energy flows from the energy storage battery to the motor. When the electric vehicle is in braking state, the converter is in Buck mode, and the energy flows from the motor to the energy storage battery. The converter has designed a related resonant circuit, so that the switches in the converter can achieve soft switch, which greatly improves the efficiency of the converter [5].

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