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AUXILIARY SWITCH CONTROL FOR BIDIRECTIONAL DC-DC CONVERTER

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Abstract: In this project the auxiliary switch control using a lookup table is proposed to improve the efficiency of the bidirectional dc/dc converter can be used in electric vehicle and performs soft switching. In the lookup table the auxiliary switch turn-on time is taken as reference. The control method properly controls the auxiliary switch turn-on time according to the required load current this auxiliary switch control brings more efficient control in generative and regenerative mode operation. To overcome the few drawbacks of the resonant converter, the zero voltage transition (ZVT) and zero current transition (ZCT) methods are proposed. The ZVT and ZCT methods can be applied to the conventional bidirectional dc–dc converter through adding auxiliary circuit to the converters. To solve this problem the auxiliary switch turn-on time is generated by a lookup table (LUT), which is composed of the load current and the turn-on time difference of the main and auxiliary switches. The proposed auxiliary switch control method of the bidirectional dc/dc converter satisfies the soft-switching condition for main, auxiliary switches, and diodes using an LUT The aim of this project are to introduce the auxiliary switch turn-on time control for the bidirectional dc/dc converter in an electric vehicle system.
Keywords: Auxiliary switch control, electric vehicle, lookup table (LUT), resonant type of bidirectional converter, soft switching.

I. INTRODUCTION

The importance of a bidirectional dc–dc converter is getting increased. Because the structure of the converter is simple and control is comparably easy, it is called as the topology of conventional bidirectional converter. However, the drawbacks of the conventional bidirectional dc–dc converter are the large switching losses and the long reverse recovery time of antiparallel diodes. Particularly, during the reverse recovery time of the diodes because it can cause circuit damage and electromagnetic interference problems due to high current spikes. Thus in order to improve the shortcomings of conventional pulse width modulation (PWM) methods and increase the efficiency of the system, the study using series resonance, parallel resonance and quasi-resonance methods have progressed. However due to the common characteristic of resonant converter, lots of conduction losses occur because of high circulating energy. To overcome the drawbacks of the resonant converter the zero voltage transition (ZVT) and zero current transition (ZCT) methods are proposed. The ZVT and ZCT methods are turning ON and turning OFF of the switches under zero voltage and zero current condition using resonance. The ZVT and ZCT methods can be applied to the conventional bidirectional dc–dc converter through adding auxiliary circuit to the converters. However since the added auxiliary circuit is operated under hard-switching condition the other losses will occur. It's necessary to operate under soft switching. Moreover lots of other circuits are weak in high resonant current and voltage and the range of load for resonant circuit is limited. The composition of the proposed resonant bidirectional dc/dc converter is an auxiliary circuit added to the conventional bidirectional buck–boost converter. The fundamental operation is same as the conventional bidirectional buck–boost converter. The resonance of the proposed converter is caused by the resonant capacitor and inductor of the auxiliary circuit. The auxiliary switch can be operated in boost mode and buck mode. The soft switching is carried out by the main switches, diodes and auxiliary switches. To perform the soft-switching action the conventional control method has to calculate the time difference between the gate signals of the main and auxiliary switches. But it is difficult to obtain the current data in the short resonant time due to the limit of the DSP ADC capacity. Therefore, in the conventional control method, the additional power loss occurs due to the fixed turn-on time of the auxiliary switch in the full load.

II. PROPOSED CONVERTER CONFIGERATION AND OPERATIONAL PROCESS

A. Proposed Converter Configuration

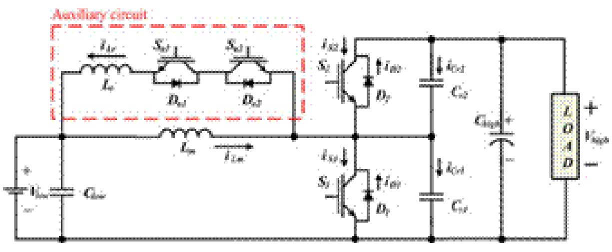

Fig.1. Proposed bidirectional soft-switching dc/dc converter

Fig.1 shows the proposed bidirectional dc–dc converter which is formed by adding one resonant inductor, two resonant capacitors and two switches to the conventional bidirectional converter circuit. The soft-switching operation is done by energizing inductor L_r in the auxiliary circuit with the voltage difference $V_{high}-V_{low}$ before turning ON the main switch. In order to maintain the voltage across inductor L_r with voltage $V_{high}-V_{low}$ before the main switch is turned ON the upper converter is operated in continuous conduction mode. The boost mode operation of the proposed system is given in the next section and has seven operational modes. The description of boost mode is provided, as well as the mathematical equations can be derived from an equivalent circuit of mode.

B. Operational process

MODE 1 ($t_0 \le t < t_1$): At $t=t_0$, both switches S_1 and S_{a1} are in turn-off state. When the S_{a1} is turned ON, mode 1 is started. Since inductor L_r is at resonance condition no current will be flowing through S_{a1} and the switch is turned ON under the ZCT condition. During this mode, current in inductor i_{Lr} is increased by the current flowing through L_m and the antiparallel diode of S_{a2}, and it can be described as (1)–(5). When the same amount of current is flowing though L_m and L_r this mode is finished.

$$i_{Lm}(t_0) = I_{Lm\_0}, \ i_{Lr}(t_0) = I_{Lr\_0} = 0 \quad (1)$$

$$V_{Cr1}(t_0) = V_{high}, V_{Cr2}(t_0) = 0 \quad (2)$$

$$i_{Lm}(t) = 1/L_m(V_{low} - V_{high})(t - t_0) + I_{Lm\_0} \quad (3)$$

$$i_{Lr}(t) = 1/L_r(V_{high} - V_{low})(t - t_0) + I_{Lr\_0} \quad (4)$$

$$i_{Lm}(t_1) = I_{Lm\_1}, \ i_{Lr}(t_1) = I_{Lr\_1} = I_{Lm\_1} \quad (5)$$

MODE 2 ($t_1 \le t < t_2$): When i_{Lr} is larger than i_{Lm}, mode 2 start to begin. Due to continuity of i_{Lr}, the resonance between S_1 and the output capacitor of S_2 will be started. Two switches S_1 and S_2 both are in turn-off state and as the capacitor C_{r1} is charged and discharged to i_{Lm} and resonant capacitor current flow through L_r. As a result the voltage across S_1 and S_2 is decreased and increased complementary due to the resonance. It can be described through (7). When the voltage across S1 becomes 0 V, and that of the switch S2 is equal to V_{high}, the resonance between capacitor C_{r1} and inductor L_r is finished. Moreover, i_{Lr} is getting decreased

$$i_{Lr}(t_1) = I_{Lr\_1} = I_{Lm\_1} \quad (6)$$

$$i_{Lm}(t_1) = I_{Lm\_1} = I_{Lm\_2} \quad (7)$$

$$i_{Lr}(t) = ((V_{high} - V_{low})/Z_r) \sin\omega r (t - t_1) + I_{Lr\_1} \quad (8)$$

$$V_{Cr1}(t) = V_{low} + (V_{high} - V_{low}) \cos(\omega r (t - t_1)) \quad (9)$$

$$V_{Cr2}(t) = V_{high} - V_{Cr1}(t) \quad (10)$$

$$C_r = C_{r1} + C_{r2} \quad (11)$$

$$\omega r = 1/\sqrt{L_r C_r}, \ Z_r = \sqrt{L_r C_r} \quad (12)$$

MODE 3 ($t_2 \le t < t_3$): Even though the current in inductor i_{Lr} is getting decreased from mode 2, it is still larger than current in L_m, the continuity of current is maintained. Since the surplus current is flowing through the antiparallel diode of S_1, the voltage across S_1 is equal to zero and the switch can be turned ON under the ZVT condition. In this mode current across both inductor i_{Lr} and i_{Lm} are depicted with following equations and when the same amount of current is flowing through those two inductors, L_m and L_r, mode 3 is finished.

$$i_{Lm}(t) = 1/L_m(V_{low}.(t - t_2)) + I_{Lm\_2} \quad (13)$$

$$i_{Lr}(t) = -1/L_r(V_{low}.(t - t_2)) + I_{Lr\_2} \quad (14)$$

$$i_{Lr}(t_3) = I_{Lr\_3} = I_{Lm\_3} \quad (15)$$

MODE 4 ($t_3 \le t < t_4$): In the beginning of this mode, the main switch S_1 is turned ON under the ZVT condition. As the main inductor current is increased linearly and the main switch current is also increased. At the end of this mode the resonant inductor is discharged completely and the current of the auxiliary switch becomes 0 A

$$i_{Lm}(t) = 1/L_m(V_{low}.(t - t_3)) + I_{Lm\_3} \quad (16)$$

$$i_{Lr}(t) = -1/L_r(V_{low}.(t - t_3)) + I_{Lr\_3} \quad (17)$$

MODE 5 ($t_4 \le t < t_5$): Since current is not flowing through S_{a1}, the current loop is same as that of the conventional bidirectional dc–dc converter in boost mode i.e the main inductor increases current is flowing through the switch S_1.During time $t=t_5$, the main switch S_1 is turned OFF under the ZVT condition due to the resonance of the capacitor C_{r1}, and the auxiliary switch S_{a1} is turned OFF under the ZCT condition. When these two switches are turned OFF, this mode is finished.

$$i_{Lr}(t_4) = 0 \quad (18)$$

$$i_{Lm}(t) = 1/L_m(V_{low}.(t - t_4)) + I_{Lm\_4} \quad (19)$$

MODE 6 ($t_5 \le t < t_6$): In this mode, the main inductor current is flowing through S_1 and C_{r1} consistently. The voltage across the main switch S_1 is increased meanwhile the voltage across S_2 is decreased and the equations are given below. When the voltage across S_1 is equal to output voltage the main switch S_2 is turned ON under the ZVT condition. It is to be noted that the C_r means $C_{r1}+C_{r2}$ as given in equation (11), and the parameter of these two capacitors should be almost same for correct ZVT condition

$$i_{Lm}(t) = I_{Lm\_5} = I_{Lm\_6} \quad (20)$$

$$i_{Lr}(t) = 0 \quad (21)$$

MODE 7 ($t_6 \le t < t_7$): When the antiparallel diode of main switch S_2 is conducted this mode is started. The main inductor current is decreased until S_{a1} is turned ON and it can is given in equation as (24). When current is flowing through the antiparallel diode of S_2, the ZVT turning-on and ZVT turning-off conditions are satisfied. Moreover since the current flows through the antiparallel diode of S_2 the current path is secured and loss is reduced i.e. the turning-on loss of the diode is larger than that of RDS (ON) conduction loss. This method is called the synchronous rectifying method and the method can be applied to the topology operating in boost mode and buck mode as well

$$i_{Lm}(t) = 1/L_m((V_{low} - V_{high})(t - t_6) + I_{Lm\_6} \quad (22)$$

$$i_{Lm}(t_7) = I_{Lm\_7} = I_{Lm\_0} \quad (23)$$

Fig. 2 shows the key waveforms of each component in the boost mode and each waveform depicts the operational characteristic of each component in the ideal condition.

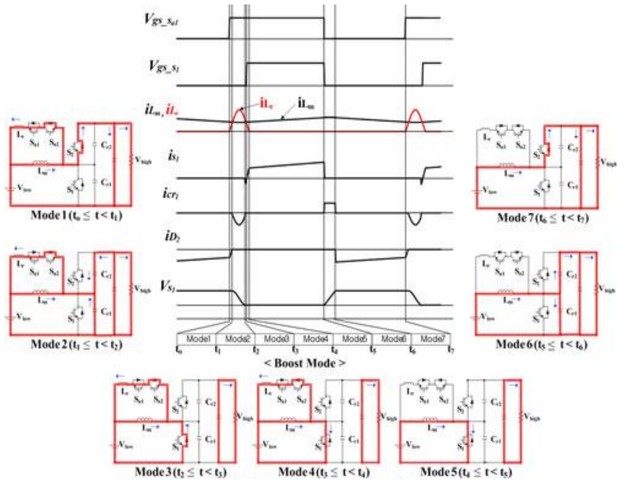
Fig.2. Operation mode and key waveforms of the proposed converter in boost mode.

Fig.3 shows the buck mode operation of the proposed bidirectional dc/dc converter. Similar to the boost mode the buck mode are also classified into seven modes. The operational characteristic is almost the same as that of the boost mode since the buck mode operates in complement with the boost mode. However the two switches *S*2 and *Sa*2 are activated in the buck mode operation.

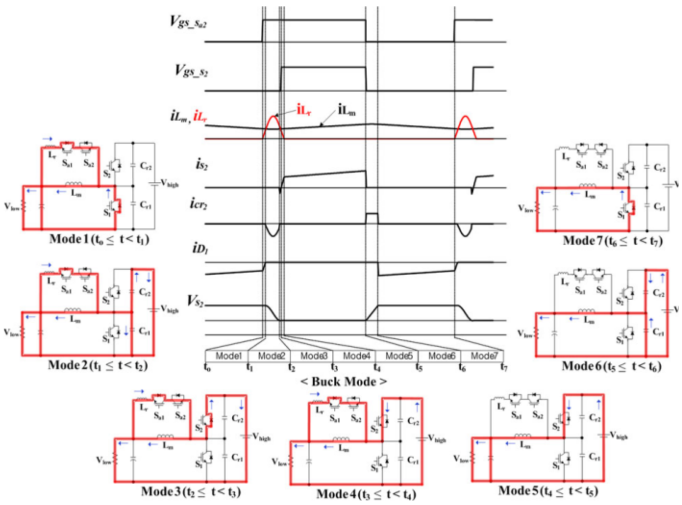
Fig.3. Operation mode and key waveforms of the proposed converter in buck

III. CONTROL CONFIGURATION

In a vehicle application, the bidirectional dc/dc converter can be operated either in buck mode or the boost mode depending up on the driving condition. The buck–boost control method using only one single voltage controller has an advantage of a soft mode that change according to the flow of the dc-link energy. But when the mode is changed the discontinuous period occurs due to the addition of the auxiliary circuit. If the voltage controller only applied in this system the soft-switching condition will not be operated. Therefore, it is operated with the buck mode and boost mode control separately for the soft switching. Fig.4 and Fig.6 shows the overall control diagram of the proposed bidirectional dc/dc converter. In the boost mode the output of the voltage controller is compared with a triangle wave and this duty signal controls the main switch *S*1.In Contrast to the boost mode in which controller is for voltage control the buck mode controller is for current control of the main inductor. In the buck mode main switch *S*2 is on–off switching for the current regulation of the main inductor. As the main switches, auxiliary switches are also controlled with the buck mode and boost mode operation. Auxiliary switch *Sa*1 is for soft-switching operation of boost mode and *Sa*2 is for the same operation of buck mode. The PWM signals of the auxiliary switches *Sa*1 and *Sa*2 are generated by each LUT.

IV. SIMULATION AND RESULTS

The simulation results are taken for Boost converter and Buck Converter using an R load and have a Vlow. The input source V_{low} with 30volts for both Boost and Buck Converter. The output voltage obtained is 136 volt for Boost converter and 14 volts for Buck Converter.

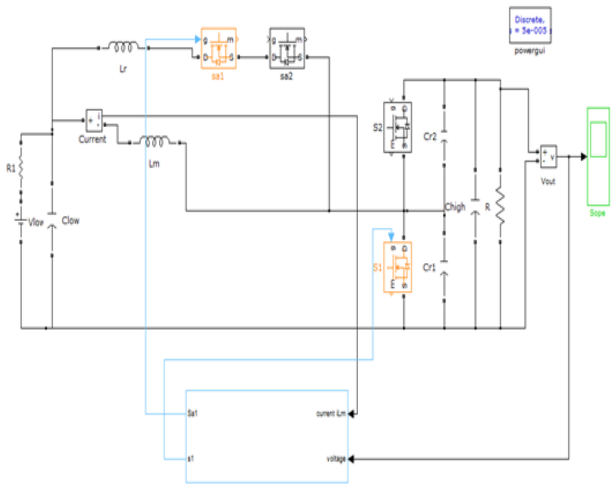
Fig.4. simulation of bidirectional dc-dc Boost converters

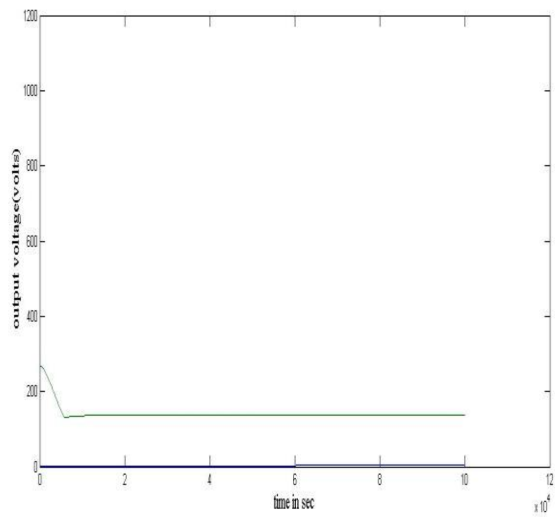

Fig.5. output waveform for boost converter

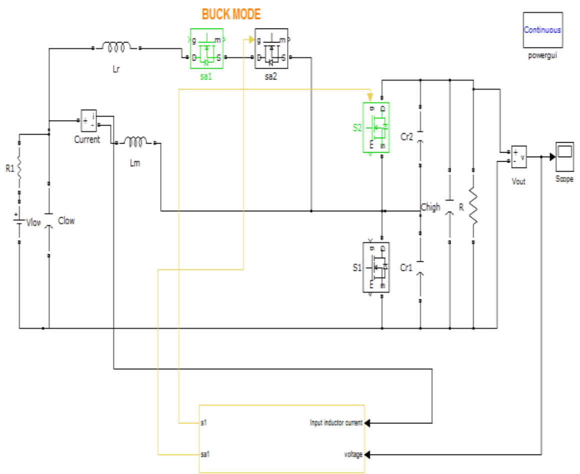

Fig.6 Simulation of bidirectional dc-dc buck converter

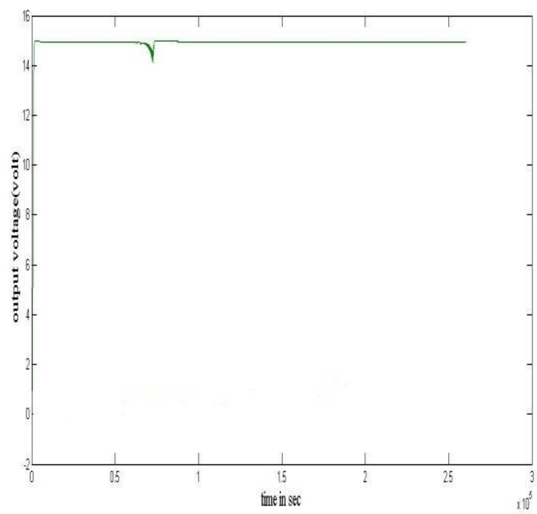

Fig.7. output waveform for buck converter

V. CONCLUSIONS

In this project, the auxiliary switch control method for the new bidirectional ZVT and ZCT converter is proposed. The two unidirectional ZVT and ZCT dc/dc converter topologies are combined by auxiliary circuit switches ZVT and ZCT bidirectional power flow is achieved by the proposed dc/dc converter. To control this bidirectional dc/dc converter with ZVT and ZCT condition buck and boost mode operation for a different voltage controller is described. Moreover to achieve more efficiency from a conventional ZVT and ZCT converter an auxiliary switch control method corresponding to the load condition is demonstrated. Because of the resonant current sensing problem the conventional control method cannot adapt this auxiliary switch control method. However with the LUT for auxiliary switch control the proposed converter has more efficiency than the conventional control method specifically under the rated load condition. The proposed control method and topology are checked with the mathematical analysis and simulation for experiment. From these results the new proposed bidirectional converter with the auxiliary control method achieves more efficiency than the conventional control method.

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