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# A New Bidirectional DC-DC Converter with ZVT Switching

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***Abstract*- In this paper, a novel bidirectional DC-DC converter using improved ZVT method is proposed to overcome the drawbacks of the conventional bidirectional DC-DC converter using general PWM methods and resonance. In order to achieve ZVT operation, auxiliary circuit is added to the conventional topology. The added auxiliary circuit consists of one inductor and two capacitors, two switches for bidirectional operation and resonant circuit. In fact, the structure of the ZVT, the auxiliary switch is turned off hard switching. But, because the main switch is turn-on and turn-off with ZVS that decrease losses. Also, Main diode is a big advantage without reverse recovery phenomenon. In this paper, the operational characteristic of the topology is analyzed, and simulation and experiment are performed to verify the validity of the topology.**

## Ⅰ. INTRODUCTION

Recently the subject of power conversion technology in the power electronics has applied and used for variable area. The development of power sector, industrial machinery, telecommunications and household appliances ranging across all areas of human life has been very widely used. The future of the advanced information society, supporting the electrical energy in the world, acceptance of the increase in a variety of purpose by the smooth power conversion and control technologies and power loss minimization, and energy efficiency of a priority as power electronics technology is significantly expanding its area. Moreover, global warming is an environmental issue to be raised largely present, and high expectations are being further strengthened.

In general, power conversion system implements the system's compact and lightweight that can be obtained by increasing the switching frequency. However, by increasing the switching frequency, in proportion to the switching losses occur. Thus, limit factor of increasing switching frequency and overall system efficiency is reduced as factor. Therefore, high power density and efficiency of the entire system to improve with increasing the switching frequency is essential for reducing the switching losses. For this purpose, switching transients and to reduce switching losses occur in the resonant converters for a variety has been active in the study [1]-[2].

For example, to overcome the above shortcomings, ZVT (Zero Voltage Transition) and ZCT (Zero Current Transition) methods are proposed. ZVT and ZCT methods are that switches are turning on and turning off under zero voltage and zero current condition through using resonance. The ZVT and ZCT methods can be applied to the conventional bidirectional DC-DC converter through adding auxiliary circuit to the converters [3]-[7].

In this paper, a high efficiency bidirectional DC-DC converter using ZVT method is proposed to overcome the above mentioned problems. The proposed bidirectional DC-DC converter is the transformed type of conventional bidirectional converter. That is, the switches for operating in boost mode and buck mode, and auxiliary switches are added to the conventional bidirectional converter, and main switches are operated under soft switching condition. Moreover, through using switches instead of diodes, the main switches are operated under synchronous rectifying condition when the main switches are turning on and turning off. Therefore, switching losses and conduction losses come from switching devices can be reduced, and EMI can be minimized as well.

## Ⅱ. COMPOSITION OF TOPOLOGY

### *A. BESS*

Environmental issue through our worldwide interest in clean energy and alternative energy, while increasing in the developed countries, mainly in the country put a lot of effort into developing technology. These clean and alternative energy facilities of the stand-alone solar power system has received a great attention. When compared to other development facilities, the stand-alone solar power system is a difficult external powered from renewable energy and the battery in the power. But, through the use of photovoltaic equipment, during the day because the time constraints spend and the remaining surplus power battery save that extra time is needed to add facilities capable to load.

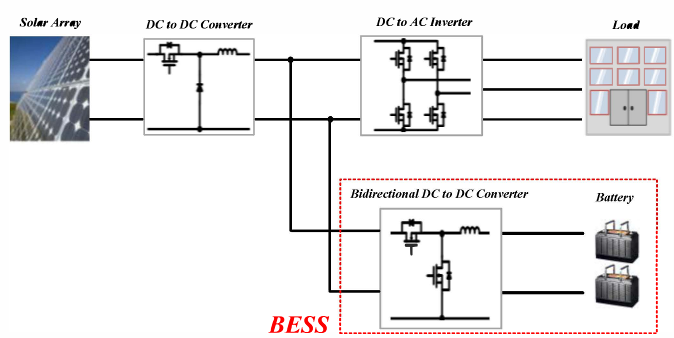


Fig. 1. BESS using bidirectional converter

This role is performed by BESS. Fig. 1 shows BESS using bidirectional converter.

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Recently, solar energy generation system with BESS (Battery Energy Storage System) and electric vehicle come into the spotlight due to environmental pollution. The systems need bidirectional DC-DC converter of high efficiency, small and lightweight. BESS is load-efficiency improvement, reverse power, voltage and frequency control, development and distribution equipment of investment delay effect, reliability of supply increased [8]-[10].

These development facilities in order to facilitate the delivery of power between BESS and bidirectional DC-DC is essential. In case of the power conversion device the same bidirectional DC-DC converter, high switching frequency to reduce volume. But, the general case of bidirectional DC-DC converter, due to hard switching operation according to switching frequency increases the loss caused by the switching action and in the end will be a lower efficiency power conversion devices.

*B. Proposed ZVT bidirectional DC-DC converter*

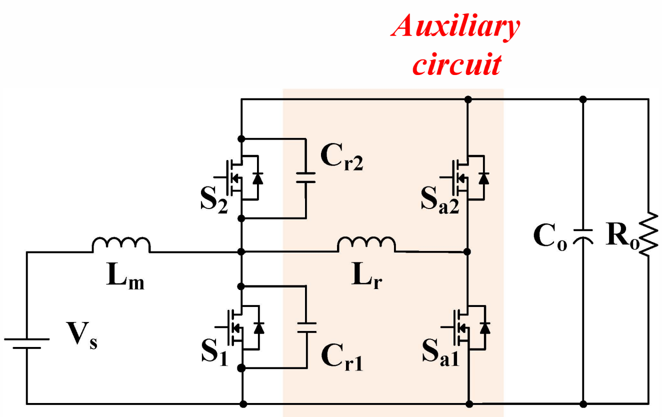


Fig. 2. Proposed ZVT bidirectional DC-DC converter

Fig. 2 shows the proposed ZVT bidirectional DC-DC converter. One resonant inductor, two resonant capacitors and two switches are added to the conventional bidirectional converter circuit.

The boost mode operation of the proposed system was depicted in fig. 3, and the operational mode can be divided into 7 modes.

*C. Mode analysis of the boost converter*

The description of each mode is provided with mathematical equations that represented each mode. The mathematical equations are able to derive from the equivalent circuit of each mode.

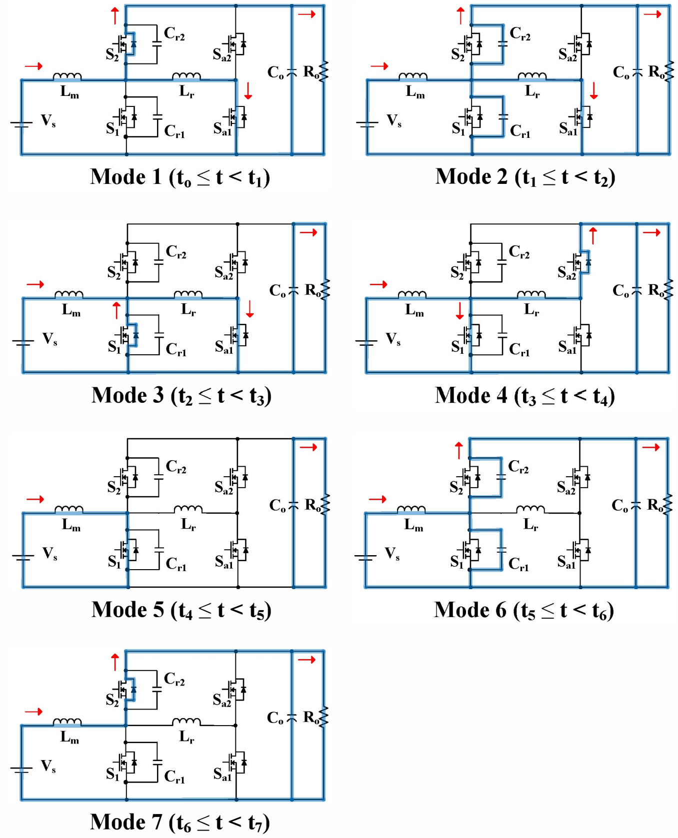


Fig. 3. Boost mode of proposed converter

MODE 1 ($t_0 \le t < t_1$): During the previous time $t_0$, the main switch ($S_1$) and auxiliary switch ($S_{a1}$) were turned off, and the energy that stored in the main inductor ($L_m$) flows through the reverse parallel diode of switch $S_2$. At this point, capacitor ($C_{r1}$) is charged with the output voltage $V_0$. Due to that reason, $S_{a1}$ is turned on under ZCS condition, and diode current $i_{D2}$ is increased linearly. At the end of this mode, same amount of current is flowing through main inductor and resonant inductor as well. The mathematical equations for describing this mode are presented.

$$i_{Lm} = \frac{1}{L_m}\int_{t_0}^{t_1}(V_s - V_o)\,dt = \frac{1}{L_m}(V_s - V_o)t + I_o \tag{1}$$

$$i_{Lr} = \frac{1}{L_r}\int_{t_0}^{t_1}(V_o - V_s)\,dt = \frac{1}{L_r}(V_o - V_s)t \tag{2}$$

$$i(0) = I_0,\quad i_{Lm}(t_1) = I_{M1},\quad i_{Lr}(t_1) = I_{r1} \tag{3}$$

$$V_{cr1}(t_1) = V_o,\quad V_{cr2}(t_1) = 0 \tag{4}$$

MODE 2 ($t_1 \le t < t_2$): After time $t_1$, $L_r$ and $C_{r1}$ resonant is stared. During this mode, resonant inductor and resonant capacitor are completely charged and then begin discharging. Since current is flowing through $C_{r1}$ and $C_{r2}$, the voltage of main switch is decreased from 400V to 0V. Although the current is flowing through two resonant capacitors, $C_{r1}$ is discharged while $C_{r2}$ is charged. Key equations that describe the operation of this mode are provided.

Note that in order to simplify the high order functions of this mode, an assumption was built. The assumption is that since the variation of current flowing through main inductor is too small to consider, the main inductor current is regarded as a current source($I_k$). Moreover, in order for recognizing resonant capacitors, following equations are provided.

$$i_{Lr} = I_k \cos\omega_r t - \frac{V_{Cr'}}{Z_r}\sin\omega_r t \tag{5}$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}},\quad Z_r = \sqrt{\frac{L_r}{C_r}},\quad C_{r'} = \frac{C_{r1}\cdot C_{r2}}{C_{r1}+C_{r2}} \tag{6}$$

$$i_{Lm}(t_2) = I_{M2} \approx I_{M1},\ i_{Lr}(t_2) = I_{r2} \tag{7}$$

$$V_{cr1}(t_2) = V_s - V_{cr}(t_1) - V_o\cos\omega_r t \tag{8}$$

$$V_{cr2}(t_2) = V_o - V_{cr1} \tag{9}$$

MODE 3 ($t_2 \le t < t_3$): When two resonant capacitors are charged and discharged at $t=t_2$, this mode begins. Accumulated energy in resonant tank is transferred through auxiliary switch and reverse parallel diode of main switch. Since main switch is received gate signal while the current is transferred through reverse parallel diode of $S_1$, the switch can be turned on under ZVS condition.

$$i_{Lm} = \frac{1}{L_m}V_s t + I_{M2} \tag{10}$$

$$i_{Lm}(t_3) = I_{M3},\ i_{Lr}(t_3) \approx I_{r2} \tag{11}$$

$$V_{cr1}(t_3) = 0,\ V_{cr2}(t_3) = V_o \tag{12}$$

MODE 4 ($t_3 \le t < t_4$): In previous mode, the main switch was turned on. So, current is flowing via main switch instead of reverse parallel diode of the main switch. Mode 4, since the front is $i_{Lr} > i_{Lm}$ that as reverse parallel diode conducts and back end conducts switch. At the end of this interval the current flowing through resonant tank ($i_{Lr}$) becomes zero.

$$i_{Lm} = \frac{1}{L_m}V_s t + I_{M3} \tag{13}$$

$$i_{Lr} = -\frac{1}{L_r}V_s t + I_{r3} \tag{14}$$

$$i_{Lm}(t_4) = I_{M4},\ i_{Lr}(t_4) = I_{r4} \tag{15}$$

$$V_{cr1}(t_4) = 0,\ V_{cr2}(t_4) = V_o \tag{16}$$

MODE 5 ($t_4 \le t < t_5$): Through $S_1$ and $L_m$, current flows and at this point, the accumulation is the inductive energy.

$$i_{Lm} = \frac{1}{L_m}V_s t + I_{M4} \tag{17}$$

$$i_{Lm}(t_5) = I_{M5},\ i_{Lr}(t_5) = 0 \tag{18}$$

$$V_{cr1}(t_5) = 0,\ V_{cr2}(t_5) = V_o \tag{19}$$

MODE 6 ($t_5 \le t < t_6$): Mode 6 with $S_1$, the ZVS condition turn-off starts. Since the main switch was turned off in mode 5, current path was changed. Consequently, all switches $S_1$ and $S_{a1}$, are turned off condition, and current is flowing through resonant capacitor $C_{r1}$. Therefore, the resonant capacitor is charged completely at the end of this mode. Time $t_6$, the voltage across the main switch is in the $V_o$, diode $D_2$ is turned on smoothly at the zero voltage state.

$$i_{Lm} = \frac{V_s + V_{cr} - V_o}{Z_m}\sin\omega_m t + I_{M5}\cos\omega_m t \tag{20}$$

$$i_{Lm}(t_6) = I_{M6},\ i_{Lr}(t_6) = 0,$$

$$\omega_m = \frac{1}{\sqrt{L_m C_r}},\ Z_m = \sqrt{\frac{L_m}{C_r}} \tag{21}$$

$$V_{cr2}(t_6) = V_o - V_{cr}(t_5) - V_s\cos\omega_m t,$$

$$V_{cr1}(t_6) = V_o - V_{cr2} \tag{22}$$

MODE 7 ($t_6 \le t < t_7$): In this mode, all switches are turned off condition and resonant components finished its operation as well. Therefore, current is flowing through the reverse parallel diode of buck mode main switch $S_2$. $L_m$ of the current free-wheeling diode of $S_2$ through the output capacitor ($C_o$) is charged. When the auxiliary switch is turned on, the first mode is started again.

$$i_{Lm} = \frac{1}{L_m}(V_s - V_o)t + I_{M6} \tag{23}$$

$$i_{Lm}(t_7) = I_{M7},\ i_{Lr}(t_7) = 0 \tag{24}$$

$$V_{cr1}(t_7) = V_o,\ V_{cr2}(t_7) = 0 \tag{25}$$

Fig. 4 shows the key waveforms of each component in boost mode, and each waveform were depicted the operational characteristic of each component in ideal condition.

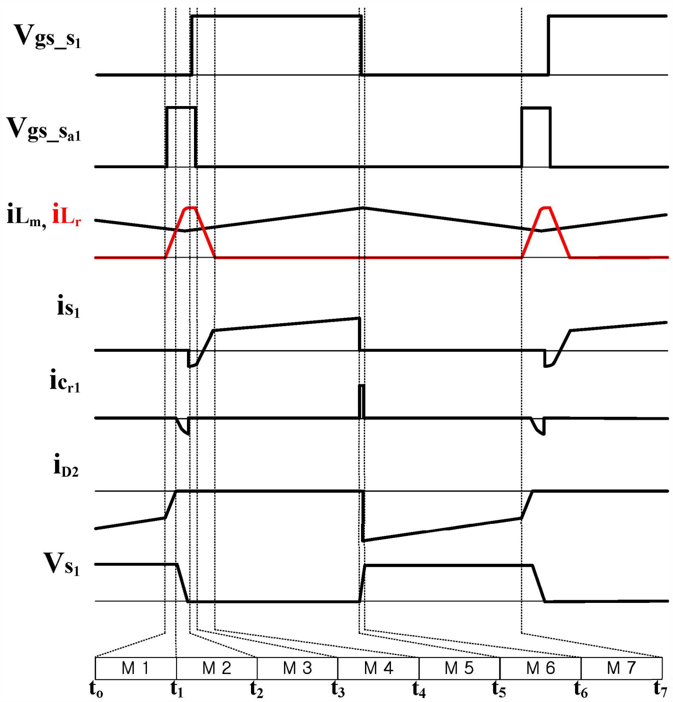

Fig. 4. Key waveforms of the boost mode operation

*D. Mode analysis of the buck converter*

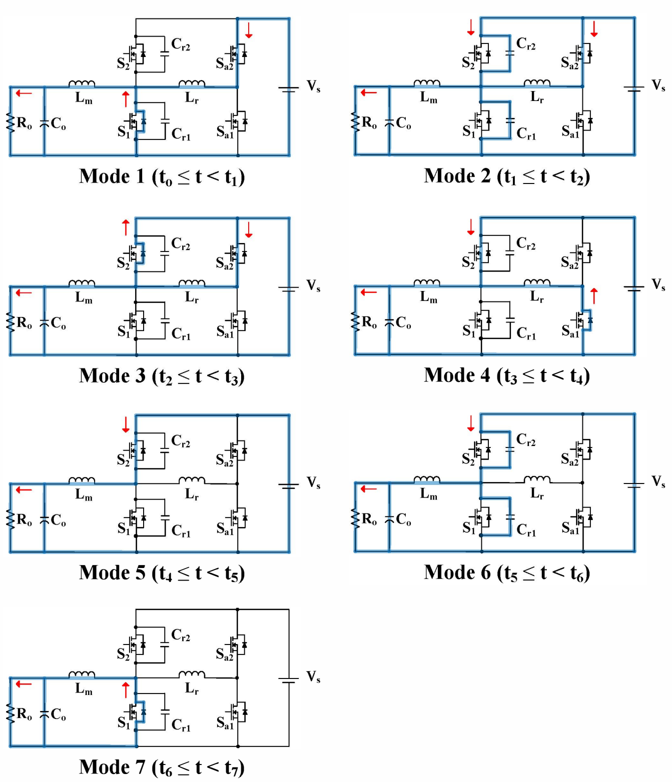

Fig. 5. Buck mode of proposed converter

Fig. 5 shows the buck mode operation of the proposed bidirectional DC-DC converter. With same manner of boost mode, the modes are able to be divided into 7 modes. The operational characteristic is almost same as boost mode. Since buck mode operates complementary with bidirectional converter. However, two switches $S_2$ and $S_{a2}$, are activated for buck mode operation.

## III. SIMULATION RESULTS

In this paper, the simulation of the proposed bidirectional DC/DC converter was performed with PSIM 9.0.3 program. The parameters used for simulations are shown in Table. 1. The simulation was performed under a 30kHz switching frequency and a input voltage is fixed as 200V. Moreover the duty ratio of the simulation is 0.5.

TABLE I
SIMULATION PARAMETER

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Input voltage | $V_{in}$ | 200 | [V] |
| Output voltage | $V_o$ | 400 | [V] |
| Capacity | $P_o$ | 1 | [kW] |
| Main inductor | $L_m$ | 1 | [mH] |
| Resonant inductor | $L_r$ | 100 | [μH] |
| Resonant capacitor1 | $C_{r1}$ | 3.3 | [nF] |
| Resonant capacitor2 | $C_{r2}$ | 3.3 | [nF] |
| Output capacitor | $C_o$ | 1000 | [μF] |
| Switching frequency | $f_{sw}$ | 30 | [kHz] |

Fig. 6, 7 shows the waveforms of each component in boost mode and buck mode as well. Moreover, the waveforms indicate the ZVS turn-on and turn-off operation occurs at the main switch and ZCS turn-on operation occurs at the auxiliary switch.

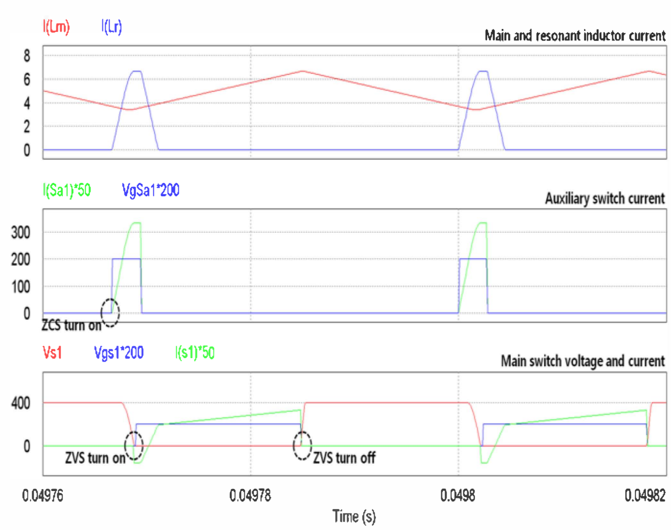

Fig. 6. Boost soft switching operation waveforms

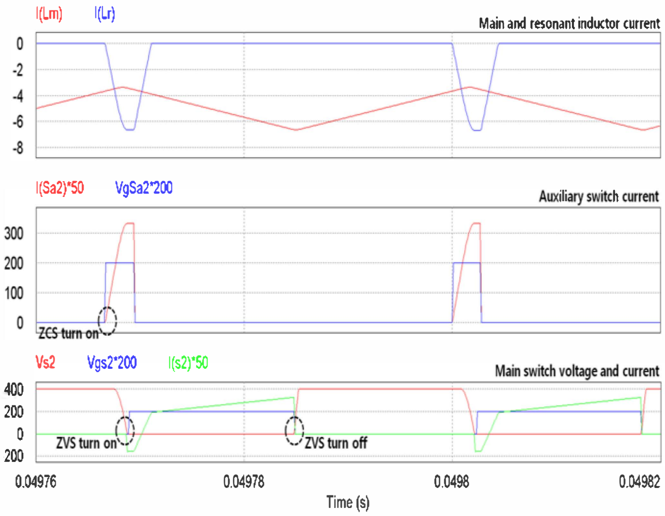


Fig. 7. Buck soft switching operation waveforms

## IV. Circuit Design

In order for the optimized performance of the proposed converter, resonant components have to be designed appropriately.

### A. Switch PWM signal

In order to achieve the ZVS condition, delay time is required, and the delay time depends on the $D_aT$. That is, the auxiliary switch must be on state while the resonant capacitors $C_{r1}$ and $C_{r2}$, are charged and discharged complementary. Moreover, the minimum turn off time of auxiliary switch is that the switch must be turned off when the current flowing through the reverse parallel diode of main switch. If this condition is qualified, the main switch PWM signal is overlapped with the auxiliary switch PWM signal. The PWM signals of the auxiliary and main switch are shown in fig. 8.

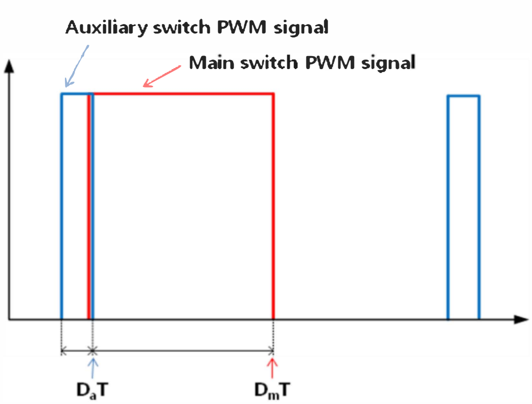


Fig. 8. PWM signals of the auxiliary and main switch

### B. Resonance condition and design

TABLE 2
SWITCHING CONDITIONS OF SWITCHING DEVICES

| Semiconductor device | Turn on condition | Turn off condition |
|---|---|---|
| Switch $S_{a1}$, $S_{a2}$ | ZCS | - |
| Switch $S_1$, $S_2$ | ZVS | ZVS |

Fig. 9 shows the resonant inductor current, main inductor current, main switch current, signal and voltage, and resonant capacitor current respectively. Auxiliary switch turn-on of the resonant inductor current to switch on the secondary sector is the primary difference between the inductor current becomes more minutes than the resonant capacitor of the current state of by discharge to create the ZVS. After this extra current free-wheeling diode conduction of the switch gate signal is on while the main switch turn-on is implemented by ZVS.

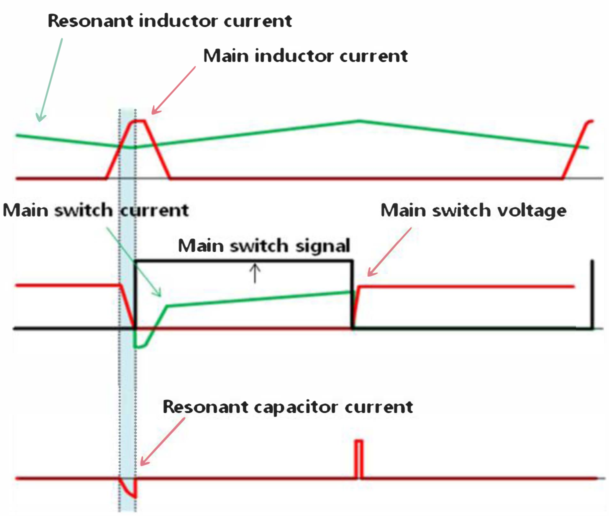


Fig. 9. Key waveforms of the resonance condition

To satisfy the resonant condition, the resonant inductor current range should be greater than the main inductor current. Thus, resonant inductor maximum peak current is greater than main inductor minimum current, so this equation (31) can be expressed.

$$I_L = \frac{Pin}{Vin\_min} = 5 \tag{26}$$

$$\Delta I_L = \frac{I_L}{1.7} = 2.94 \tag{27}$$

$$I_{L\_max} = I_L + \frac{\Delta I_L}{2} = 6.47 \tag{28}$$

$$I_{L\_min} = I_L - \frac{\Delta I_L}{2} = 3.53 \tag{29}$$

$$L = \frac{Vin\_min\, T_{on}}{2} = 1.13mH \tag{30}$$

$$\dot{i}_{Lr\_peak} > \dot{i}_{Lm\_min} \tag{31}$$

$$\frac{1}{C_r}\int(\dot{i}_{Lr\_peak} - \dot{i}_{Lm\_min})\,dt > 400 \tag{32}$$

$$\dot{i}_{Lr\_peak} = K\dot{i}_{Lm\_min} = 8.411 \tag{33}$$

$$Z_o = \frac{V_{cr\_peak}}{i_{Lr\_peak}} = \frac{V_o}{i_{Lr\_peak}} = 87.16 \tag{34}$$

$$C_r > \frac{T_r}{2\pi Z_o} = 20.29\,nF \tag{35}$$

$$L_r > Z_o^{\,2} C_r = 84.1\mu H \tag{36}$$

100% load conditions calculated to satisfy the resonant condition of the maximum value for the resonant inductor resonant capacitor is calculated to 84.1μH, 20.29nF. In the experiment and simulation devices for ease of selection were given an extra 100μH, 3.3nF were selected.

### C. The control algorithm

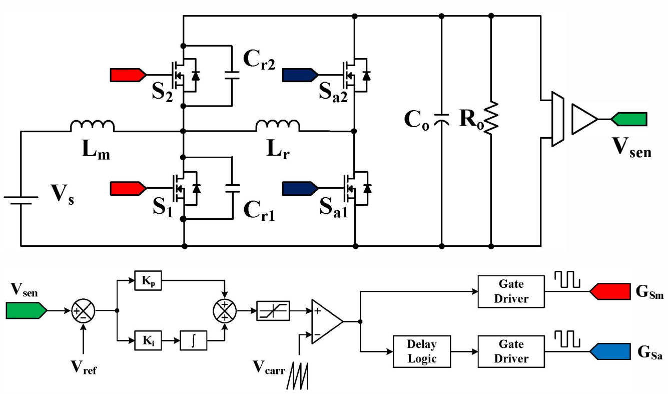


Fig. 10. Control block diagram

The system block of the proposed soft ZVT bidirectional DC-DC converter is illustrated in Fig. 10. The auxiliary switch and main switch have a difference of a time which two switches are turned on. Thus, delay logic is essential at this system. A delay logic can be obtained by shifting a switch on time. The carrier waveform has to be a sawtooth waveform for designing a fixed switch on time. The output voltage is sensed to carry out a constant voltage (CV) control and this sensed voltage is compared with the voltage reference. A PI controller is compared with a carrier waveform. The output signal sets the duty ratio. This output signal gets into the main switch after via a gate driver. And a signal passed through the delay logic is used in the auxiliary switch.

## V. Conclusion

In this paper, ZVT bidirectional DC-DC converter with auxiliary circuit was proposed. The proposed bidirectional DC-DC converter consists of additional resonant inductor and resonant capacitors, auxiliary switches and passive devices. In fact, the structure of the ZVT, the auxiliary switch is turned off hard switching. But, through using the additional switching and passive devices, main switches are operated under ZVS soft switching condition. Therefore, switching losses were reduced. Also, Main diode is a big advantage without reverse recovery phenomenon. Through theoretical analysis, the operating principle of the proposed converter was testified, and through the simulation and experimental results, the validity of the proposed converter was verified.


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