An Improved Soft Switching Bi-directional PSPWM FB DC/DC Converter

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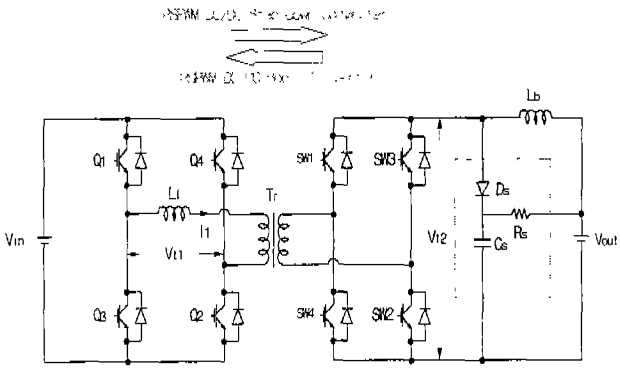
ABSTRACT - A new soft switching isolated bi-directional phase shifted pulse width modulation (PSPWM) dc/dc converter is presented. Due to the use of the energy recovery snubber, the isolated bi-directional PSPWM dc/dc converter has a significant reduction of switching losses in the switching devices of the primary and secondary side bridge, respectively. The proposed soft switching bi-directional PSPWM FB dc/dc converter provides an energy recovery snubber which consists of two fast recovery diodes, a resonant capacitor and a resonant inductor. The complete operating principles and simulation results will be presented.

1. INTRODUCTION

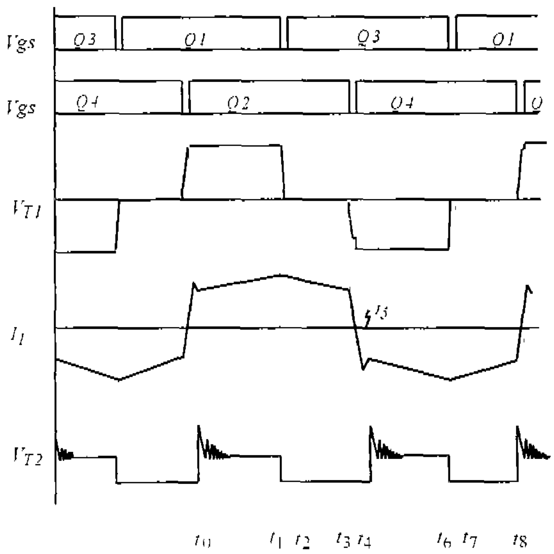
High frequency switching bi-directional isolated type dc/dc converters have been widely used for electrical insulation in the battery charger-discharger system and other applications. Forward power conversion of the bi-directional PSPWM FB dc/dc converter is operated as a step down converter and the gate signal of the primary bridge IGBT pairs (Q_1,Q_3 and Q_2,Q_4) are each operated at a fixed frequency with 50% duty-ratio. By controlling the phase shift between the IGBT pairs as shown Fig. 1(b), square wave PWM primary voltage (V_{T1}) is produced. Also, the gate signal of the secondary bridge IGBT pairs (SW_1, SW_4 and SW_3, SW_2) are turned off, and the secondary bridge IGBT pairs are only operated as a rectifier to supply output power through the isolated high frequency transformer and the IGBT anti-parallel diodes.

The operating mechanism of the PSPWM step down bi-directional FB dc/dc converter is the same as the conventional ZVS FB dc/dc converter. Soft switching in the primary bridge can be achieved by using the energy stored in the leakage inductance of the transformer. But, in the secondary bridge, the leakage inductance of the high-frequency transformer and the parasitic capacitance of the switching device cause parasitic ringing and switching surge voltages in the switching devices. To absorb the energy stored in the transformer leakage inductance and suppress the surge voltage, RC or RCD snubbers are generally used in the secondary side of the converter as shown Fig. 1(a). However, the converter with these snubbers can't be used for high operating frequencies and high output voltage because the absorbed energy during the turn-on or turn-off is dissipated in the snubber resistor. Also, to increase the output voltage (V_{out}) of the secondary side to the higher input voltage of the primary side in reverse power conversion operation of the bi-directional PSPWM FB dc/dc converter, the dc/dc converter must be operated as a step up boost converter.

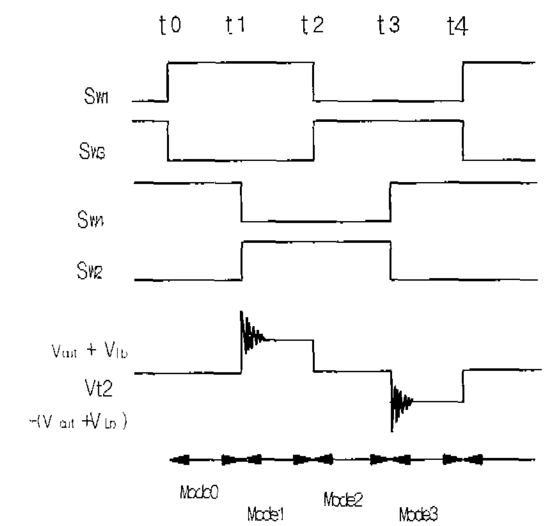
The operating mechanism of the step up phase-shifted switching in the secondary bridge is shown in the timing waveforms of Fig. 1(c). When SW_1 and SW_4 (or, SW_3 and SW_2) are simultaneously turned on, the step up PSPWM dc/dc converter is operated in the boost mode and energy is stored in the boost inductor L_b due to the current flowing through the switching devices, output source V_{out}, and boost inductor L_b. When SW_1 and SW_2(or, SW_3 and SW_4)) are turned on, the step up PSPWM dc/dc converter is operated in powering mode and energy is transferred to the primary side through a high frequency transformer.



(a) A hard switching bi-directional dc/dc converter with RCD snubber



(b) Waveforms of the step down operation in the bi-directional dc/dc converter



(c) Waveforms of the step up operation in the bi-directional dc/dc converter

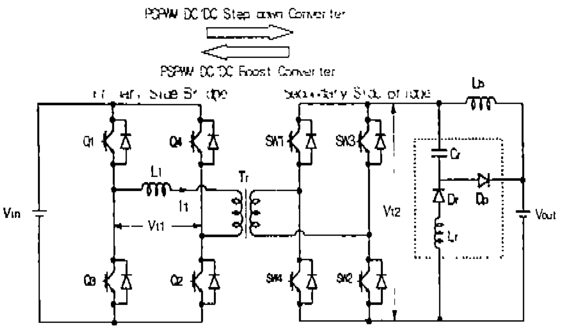
Fig 1. A hard switching bi-directional dc/dc converter utilizing RCD Snubber

But, at time(t_1, t_3) of transition from boosting mode to powering mode, the current of the boost inductor L_b will not just simply flow to the high frequency transformer due to the leakage inductance of transformer. Therefore, in the secondary bridge, the boost inductor and the parasitic capacitance of the switching devices causes parasitic ringing and switching surge voltages in the switching devices.

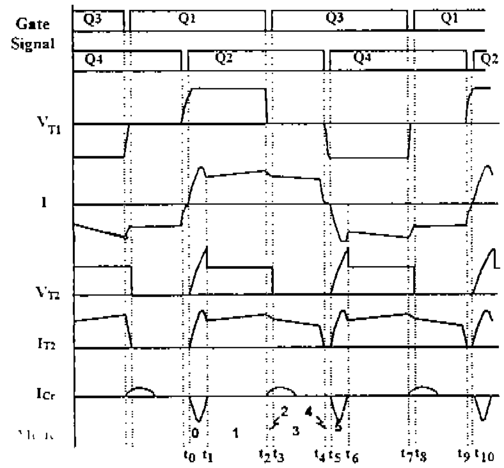
So, the switching devices may be damaged by voltage surges and noise in the secondary bridge link during the transition mode. Therefore an RCD snubber needs to be applied for the transition from the current of the boost inductor to an alternate path of low-impedance. But, the application of the RCD snubber has the disadvantage of increasing the losses of the snubber when the leakage inductance of the high frequency transformer and the snubber capacitor are larger, and input voltage and switching frequency is higher. Therefore, in this paper, to minimize the switching losses and parasitic ringing during the forward and reverse power conversion operation in the bi-directional isolated type FB dc/dc converter, an energy recovery snubber can be used as shown in Fig 2(a). Due to the use of the energy recovery snubber, the isolated bi-directional PSPWM dc/dc converter has a significant reduction of switching losses in all the switching devices during the switching operation of the primary and secondary side bridge, respectively. The proposed soft switching bi-directional PSPWM dc/dc converter provides an energy recovery snubber which consists of two fast recovery diodes, a resonant capacitor and a resonant inductor.

2. The Proposed Soft Switching Bi-directional DC/DC Converter Using an Energy Recovery Snubber

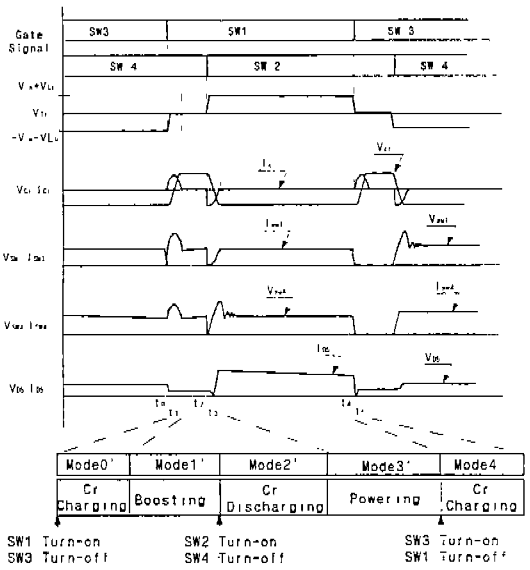
As shown in Fig. 2(a), the proposed converter is constructed by using energy recovery snubber in parallel with the secondary bridge link of the conventional bi-directional FB dc/dc converter. Due to the use of the energy recovery snubber in the secondary, the proposed converter achieves zero-voltage switching for all switching devices without switching losses and anti-parallel diode recovery losses during the forward and reverse power conversion operation. The operation modes in the proposed circuits are illustrated in Fig. 2 (b), (c).



(a) Soft switching bi-directional PSPWM dc/dc converter using an energy recovery snubber



(b) Waveforms of the step-down operation in the soft switching bi-directional dc/dc converter



(c) Waveforms of the boost operation in the soft switching bi-directional dc/dc converter

Fig. 2. An improved bi-directional PSPWM FB dc/dc converter using an energy recovery snubber

2.1 Step-down Operation of the Soft Switching Bi-directional DC/DC Converter

Figure 2(b) shows the step down operation of bi-directional dc/dc converter. Operating mechanism of the proposed step down bi-directional dc/dc converter is same as the hard switching bi-directional dc/dc converter above mentioned. Primary switching devices of each leg are operated with 50% duty ratio and phase shifted value between two legs determine the operating duty cycle of the converter. Secondary bridge IGBT pairs are turned-off and only operated as rectifiers. In initial condition, the primary circulating current is flowing through the body diode of Q_1 and Q_4, high frequency transformer. The snubber capacitor is charged up to $-V_{out}$ and inductor current I_{Lb} is freewheeling through the anti-parallel diodes of switching devices(SW_4, SW_1 and SW_4, SW_1), L_b and C_o.

Mode 0 (t_0 - t_1): At time t_0, when switching device Q_1 and Q_4 are turned-on, transformer primary and secondary voltages are produced. At this point, because the sum of snubber capacitor voltage V_{cr} and output voltage V_{out} is zero, anti-parallel diodes in the secondary bridge are turned-off by zero voltage switching. During mode 0, the transformer secondary current I_1/n begins to flow to the energy recovery snubber C_r, D_p and V_{out} through the transformer and anti-parallel diodes in the secondary bridge. And then, the polarity of V_{cr} is reversed and the secondary snubber capacitor C_r is evenly charged up to the transformer secondary voltage V_{t2} and is held there until the operating mode 2 is reached.

Mode 1 (t_1 - t_2): After the snubber capacitors C_r is charged up to V_{t2} at time t_1, resonant current I_{cr} flowing through the snubber circuit becomes zero and the converter only transfers input power to the load.

Mode 2 (t_2 - t_4) : At time t2, when the switching device Q1 is turned-off, the circulating current starts to flow through anti-parallel diode of Q3 and Q2, thus solving the problem of parasitic ringing in the primary bridge during the time interval of t3 - t4. When the primary and secondary voltage become zero, the charged snubber capacitor C_r is discharged to the output load and is recharged up to output voltage $-V_{out}$.

Mode 3 (t_5 - t_6) : Switch Q_4 is also turned-on with ZVS by transformer leakage inductance energy at time t_5. Like mode 0, at this point, anti-parallel diodes in the secondary bridge are turned-off by zero voltage switching because the sum of snubber capacitor voltage V_{cr} and output voltage V_{out} is zero. The reflected primary current I_1/n begins to flow to the energy recovery snubber C_r, D_p and V_{out} through the transformer and anti-parallel diodes in the secondary bridge, and the input power is transferred to the load.

By use of the energy recovery snubber, step-down bi-directional dc/dc converter can reduce the secondary parasitic ringing and diode reverse recovery losses.
So, the proposed converter can increase the switching frequency due to the reduced switching losses and the improved system efficiency

2.2. Step-up Operation of the Soft Switching Bi-directional DC/DC Converter

The operating mechanism of the step up phase-shifted switching in the secondary bridge is shown in the timing waveforms of Fig. 2(c). This converter has five operating modes in a switching cycle. If the snubber capacitor voltage V_{cr} is initially charged up to V_{Lb}, the five operating modes are as follows:

Mode 0 (t_0 - t_1) : At time t_0, when SW_1 and SW_4 are simultaneously turned on, the step up PSPWM dc/dc converter is operated in the boost mode and energy is stored in the boost inductor L_b due to the current flowing through the switching devices (SW_1 and SW_4), output source V_{out} and boost inductor L_b. During this mode, the current I_{sw1}, I_{sw4} flowing through the switching devices (SW_1 and SW_4) is the sum of the inductor current I_{Lb} and resonant current I_{cr}. At this time, a snubber capacitor C_r is resonantly charged through SW_1, SW_4 and L_r, D_r until the polarity of V_{cr} is reversed, and then the secondary side snubber capacitor C_r is evenly charged up to the output voltage $-V_{out}$ and is held there until the operating mode2 is reached.

Mode 1 (t_1 - t_2): After the snubber capacitor C_r is charged up to $-V_{out}$ at time t_1, the resonance between capacitor C_r and snubber inductor L_r is stopped, and inductor current is only flowing through the SW_4, SW_1 and L_b, C_o.

Mode 2 (t_2 - t_3) : At time t2, when SW_1 and SW_2 are turned on, the summed voltage (V_{out}+V_{Lb}) of the output voltage and inductor voltage will be applied to the secondary transformer of the step up PSPWM FB dc/dc converter and energy will be transferred to the primary side through a high frequency transformer and anti-parallel diodes of the primary bridge. But, at time(t_1) of transition from boosting mode to powering mode, the current of the boost inductor L_b flows to the low-impedance path of snubber capacitor C_r instead of flowing through the high frequency transformer due to the leakage inductance of transformer. Therefore, IGBT pairs in the secondary bridge are turned-off in a zero-voltage switching form due to the discharging of the snubber capacitor C_r which is charged to the output voltage $-V_{out}$. Thus, the inductor current I_{Lb} is commuted through the snubber capacitor C_r, the commutation diode D_p, and the output inductor L_b. Then, the snubber capacitor voltage V_{cr} goes from $-V_{out}$ to V_{Lb}.
Due to the use of the energy recovery snubber, the isolated step-up bi-directional PSPWM dc/dc converter has a significant reduction of switching losses in all the switching devices at time(t_1, t_3) of transition from boosting mode to powering mode.

Mode 3 (t_3 - t_4) : This mode begins when the snubber capacitor voltage V_{cr} is charged up to V_{Lb}. The summed voltage(V_{out}+V_{Lb}) of the output voltage and inductor voltage is applied to the secondary transformer of the step up PSPWM dc/dc converter and energy is transferred to the primary side through a high frequency transformer and anti-parallel diodes of the primary bridge.

Mode 4 (t_4 - t_5) : Like mode 0, at time t_4, when SW_1 is turned-off and SW_3, SW_2 are simultaneously turned on, the step up PSPWM dc/dc converter is operated in the boost mode and energy is stored in the boost inductor L_b due to the current flowing through the switching devices (SW_3 and SW_2), boost inductor L_b and output source V_{out}.

3. SIMULATION RESULTS

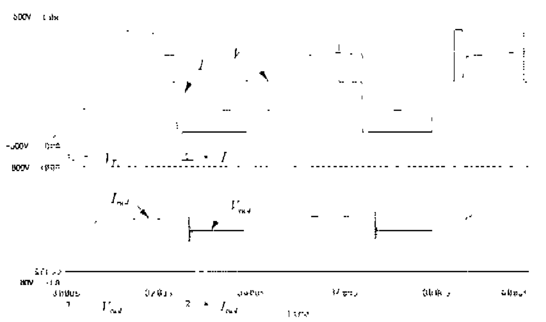
Operation characteristics of the proposed energy recovery snubber associated with bi-directional PSPWM dc/dc converter of Fig. 2(a) was verified by simulation. The following parameters have been used for simulation.

Input voltage : $400V_{DC}$, Output voltage : $200V_{DC}$
Snubber capacitor C_r : 0.1uF, Snubber inductor L_b : 10uH
Output capacitor C_o : 500uF, Output inductor L_b : 200uH
Transformer L_1,L_2 : 300uH, 200uH
Transformer leakage inductance : 2uH
Switching frequency : 40kHz

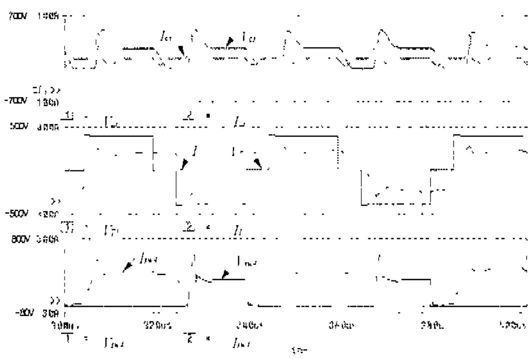
Fig. 3 and Fig. 4 show simulation waveforms of the voltage and current of the primary transformer and switching device SW_4 in the hard switching bi-directional dc/dc converter and the proposed converter with an energy recovery snubber, respectively. Comparing Fig. 3 with Fig. 4, it can be seen that by using an energy recovery snubber, the isolated bi-directional PSPWM FB dc/dc converter has a significant reduction of switching losses in all the switching devices during the forward and reverse power conversion operation. Also, the proposed bi-directional isolated type dc/dc converter generates low noise output compared with the conventional hard switching bi-directional isolated type dc/dc converter, because the short current and the switching noise due to the reverse recovery characteristic of the secondary side rectifier diodes are reduced.

4. Conclusion

An improved soft switching topology of a bi-directional full bridge PWM DC/DC converter is proposed.The proposed converter can minimize the switching noise and losses in the switching devices. Also, by applying an energy recovery snubber, the converter achieves zero voltage switching. An analysis was performed to verify the proposed topology.

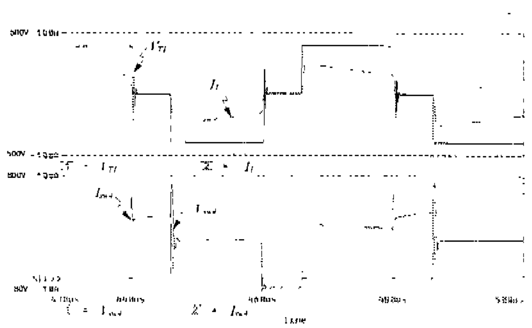


(a) Voltage and current waveforms of the primary transformer and switching device SW_4 in the converter with an RCD snubber

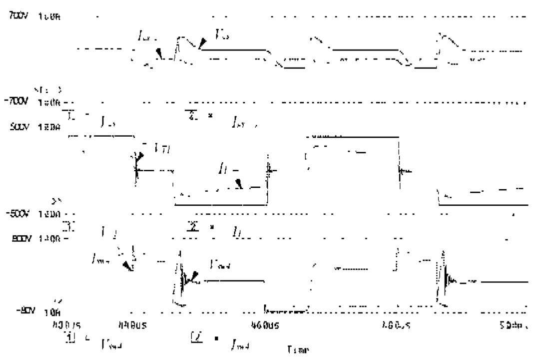


(b) Voltage and current waveforms of the primary transformer and switching device SW_4 in the converter with an energy recovery snubber

Fig. 3. Simulation waveforms in step-down operation of bi-directional dc/dc converter



(a) Voltage and current waveforms of the primary transformer and switching device SW_4 in the converter with an RCD snubber



(b) Voltage and current waveforms of the primary transformer and switching device SW_4in the converter with an energy recovery snubber

Fig. 4. Simulation waveforms in step-up operation of bi-directional dc/dc converter

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