A New ZVS Bidirectional DC-DC Converter With Phase-Shift Plus PWM Control Scheme

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Abstract: The current-voltage-fed bidirectional DC-DC converter can realize ZVS for the switches with the use of the phase-shift (PS) technology, however the current-fed switches suffer from high voltage spike and high circulating conduction losses. In order to solve these problems, a novel phase-shift plus PWM (PSP) control ZVS bi-directional DC-DC converter is proposed, which adopts active clamping branch and PWM technology. The novel converter can realize ZVS for all power switches from no load to full load. The operation principle is analyzed and verified by a 28V/270V conversion prototype rated at 1.5kW.

I. INTRODUCTION

In recent years, the development of high power isolated bidirectional dc-dc converters (BDC) has become an important topic because of the requirements of electric vehicle, uninterruptible power supply (UPS) and aviation power system [1-7]. In a typical UPS system, the battery is charged when the main power source is normal and the battery discharges to supply power in the event of lose of main power source. In the aircraft high voltage direct current (HVDC) power supply system, when the 270V HVDC generator is in gear, it charges the 28V battery and supplies the 28V key load by the BDC, and when the generator is in failure, the 28V battery discharges to supply 270V key load by the BDC. The high-low voltage conversion and electrical isolation are necessary in above-mentioned condition. The current-voltage-fed BDC is fit for such system due to it has a high voltage conversion ratio and low current ripple.

A dual active full bridge dc-dc converter was proposed for high power BDC [4, 5], which employs two voltage-fed inverters to drive each sides of a transformer. Its symmetric structure enables the bidirectional power flow and ZVS for all switches. A dual active half bridge current-voltage-fed soft-switching bidirectional dc-dc converter was proposed with reduced power components [6], however, the current-fed half bridge suffers from a high voltage spike because of the leakage inductance of the transformer. When the voltage amplitude of the two sides of the transformer is not matched, the current stresses and circulating conduction losses become higher in [4], [5], and [6]. In addition, these converters can not achieve ZVS in low-load condition. These disadvantages make it not suitable for large variation of input or output voltage condition. An asymmetry bidirectional dc-dc converter with Phase shift plus PWM (PSP) control was proposed in [7], the circulating conduction loss is reduced, however, it results a current bias which decreases the utilization of the transformer.

A current-voltage-fed PSP ZVS BDC based on an isolated dual boost converter and a half bridge converter is proposed, as shown in Fig.1 (a). The converter with an active clamping branch Sa1, Sa2 and Cc avoids the voltage spike, achieves ZVS of S1 and S2, and also restrains the start-inrush current [8]. By PWM control of S1 and S2, Vab and Vcd are well matched, which reduces circulating conduction losses, also realizes ZVS from no load to full load. The decoupling control of Phase-shift (PS) and PWM is realized by two independence close-loops control circuits. The operation principle is analyzed in detail. A 22-32V / 270V 1.5kW prototype is built to verify the operation principle of the proposed converter.

II. OPERATION PRINCIPLE

The BDC has two operation modes, the energy flowing from V1 side to V2 side is defined as Boost mode, and the counterpart is defined as Buck mode. Before the analysis, the following assumptions are given: 1) All the active power devices are ideal switches with parallel body diodes and parasitic capacitors, 2) The inductance L1 and L2 are large enough to be treated as two current sources with value of 0.5I1, 3) The transformer T is ideal one with series leakage inductor Lr, Fig.1 (b) shows the key waveforms in the Boost mode. One complete switching cycle can be divided into ten periods. Because of the similarity, only a half switching cycle is described in detail. The equivalent circuits are shown in Fig.2. Because the two sides of the topology are symmetrical, the operation principles in Buck mode are similar to those in Boost mode. Fig.1 (c) shows the key waveforms in the Buck mode.

1) Stage 0 [Before t0]: Refer to Fig.2 (a). S1, S2a and S4 are conducting. The current of the leakage inductor Lr is \( i_{Lr} = -I(0) \). The power flows from V1 side to V2 side.

2) Stage 1 [t0, t1]: Refer to Fig.2 (b). At t0, S2a is turned off. Lr, C2 and C2a begin to resonant, C2 is discharged and C2a is charged.

3) Stage 2 [t1, t2]: Refer to Fig.2 (c). At t1, the voltage across C2 attempts to overshoot the negative rail. D2 is therefore forward biased. During this period, S2 can be turned on at zero voltage. The voltage across C2a is clamped at Vcc. The current of the leakage inductor Lr is

\[
i_{Lr} = -I(0) + \frac{n_1 V_2 \theta}{2n_2 \omega L_r}.
\]
Fig. 1. The novel PSP ZVS BDC (a) Main circuit. (b) Key waveforms in the Boost mode. (c) Key waveforms in the Buck mode.

4) Stage 3 \([t_2, t_3]\): Refer to Fig. 2 (d). At \(t_2\), \(S_1\) is turned off. \(L_r\), \(C_1\) and \(C_{a1}\) begin to resonant, \(C_1\) is charged, \(C_{a1}\) is discharged. The current of \(L_r\) is

Fig. 2. Equivalent circuits of switching stages in the Boost mode.

\[
i_{Lr} = -I(0) + \frac{n_1 V_1 (2d - 1)\pi}{2n_2 \omega L_r} + \frac{n_1 V_2 \theta - (2d - 1)\pi}{n_2 \omega L_r}.
\]

5) Stage 4 \([t_3, t_4]\): Refer to Fig. 2 (e). At \(t_3\), the voltage across \(C_{a1}\) attempts to overshoot the negative rail. \(D_{a1}\) is
therefore forward biased. During this period, \( S_3 \) can be turned on at zero voltage. The voltage across \( C_1 \) is clamped at \( V_{CC} \). The current of \( L_r \) rises to a positive value.

6) Stage 5 \([t_4, t_5]\): Refer to Fig.2 (f). At \( t_4 \), the current of \( L_r \) is positive. \( D_3 \) turns on. During this period, \( S_3 \) can be turned on at zero voltage. The current of \( L_r \) is \( i_{Lr} = I_{Lr}(0) \). The power flows from \( V_1 \) side to \( V_2 \) side. At \( t_5 \), starting the second half cycle, which is similar to the first half cycle.

III. CHARACTERISTICS OF THE NOVEL BDC

A. Output Power

The phase shift angle \( \varphi \) (-0.5\( \pi \) \( \leq \) \( \varphi \) \( \leq \) 0.5\( \pi \)) between \( V_{ab} \) and \( V_{cd} \), which is defined to be positive when \( V_{ab} \) is leading to \( V_{cd} \) in phase, is used to control magnitude and the direction of the transmitted power. The pulse width \( d \) of \( S_1 \) and \( S_2 \) is used to match \( V_{ab} \) and \( V_{cd} \), means that the current \( i_{Lr} \) keeps horizontal in stage 0 and stage 5. The duty cycle of \( S_1 \) and \( S_2 \) are

\[
d = 1 - \frac{2n_2V_1}{n_1V_2}
\]

Under PS control, the output power is

\[
P = \frac{n_1V_1V_2}{2n_2\omega L_r} \cdot \frac{\varphi - [\varphi]}{2\pi}
\]

Under PSP control, the output power is

\[
P = \frac{\left(2n_2\omega L_r\right)^2}{\left(2n_2\rho \right)^2} \cdot \frac{\varphi}{2\pi}
\]

\[
\phi \in \left[-2(1-d)\pi,0\right]
\]

\[
2\left(n_2\omega V_1/2n_2\right)^2 \left(1-d\left(\varphi - (d-0.5)\pi\right)\right)/\omega L_r,
\]

\[
\phi \in \left[0,(2d-1)\pi\right]
\]

\[
\left(n_2\omega V_1/2n_2\right)^2 \left(2d-1\right)\pi(\phi - d\pi) + \phi(\pi - \phi)
\]

\[
\phi \in \left[2(2d-1)\pi,\pi\right]
\]

Fig.3 shows the relations between the output power and phase-shift angle under PS and PSP control. The bold curves are power versus \( V_1 \) under PSP control. The intersection curves are power versus \( V_1 \) under PS control. When \( V_1 \) and \( V_2 \) are matching \((V_1=32V, V_2=270V)\), the both curves are superposition under PS control and PSP control.

B. Circulating Current

When transmitted power is \( P_N \), the current RMS of \( L_r \) is

\[
I_{RMS} = \sqrt{\frac{2\pi}{\varphi}} \int_{\theta} i_{Lr}^2(\theta) d\theta / 2\pi
\]

Fig.4 shows the comparing of the current RMS of \( L_r \) under PS control and PSP control. In evidence, the circulating current is less under PSP control.

C. Range for Achieving Soft Switching

From the section II, it can be known that in order to achieve ZVS for all switches, equation (5) should be satisfied in Boost mode

\[
\begin{cases}
i_{Lr}(t_0) < -i_{Lr}(t_0) \\
i_{Lr}(t_2) < i_{Lr}(t_2) \\
i_{Lr}(t_4) > 0
\end{cases}
\]

Also, equation (6) should be satisfied in Buck mode

\[
\begin{cases}
i_{Lr}(t_1) < -i_{Lr}(t_1) \\
i_{Lr}(t_3) < i_{Lr}(t_3) \\
i_{Lr}(t_5) > 0
\end{cases}
\]

This converter can satisfy (5) or (6) well from no load to full load under PSP control. In other words, compared with the PS control, the PSP control can expand the ZVS range.

IV. CONTROL STRATEGY
The decoupling control of phase-shift angle \( \phi \) and duty cycle \( d \) is realized with two independence close-loop circuits, as shown in Fig.5. The phase-shift angle close-loop circuit adopts one port voltage (\( V_2 \)) regulated and another port (the battery port, \( V_1 \)) current regulated to realize the energy bidirectional transmitted freely. The duty cycle close-loop circuit realizes the matching of \( V_{ab} \) and \( V_{cd} \) when \( V_1 \) is variation.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

In order to verify the operation of the proposed converter, a 1.5kW prototype was built in laboratory.

1) The battery voltage of \( V_1 \) side: \( V_1=22-32 \text{VDC} \).
2) The rated voltage of \( V_2 \) side: \( V_2=270 \text{VDC} \).
3) Rated power: \( P_N=1.5 \text{kW} \).
4) The turns ratio of the transformer: \( n_2:n_1=2.1 \).
5) The leakage inductor of the transformer: \( L_r=1.2 \mu \text{H} \).
6) The inductors: \( L_1=L_2=15\mu \text{H} \).
7) The clamping capacitor: \( C_c=3\mu \text{F} \).
8) The capacitors: \( C_a=C_b=470\mu \text{F} \).
9) Switches S1 and S2: APT20M11JFLL.
10) Switches S3 and S4: APT77N60JC3.
11) Switches Sa1 and Sa2: APT20M16LFL.
12) Switching frequency: $f_s = 100\text{kHz}$.

Fig. 6 (a) and (b) show the experimental waveforms of the leakage inductor current $i_{Lr}$, the primary voltage $v_{ab}$, and the secondary voltage $v_{cd}$ at $V_1 = 32\text{V}$ in Boost mode with 1.5kW output power under PSP and PS control respectively. Since the voltage $V_1$ and voltage $V_2$ are match in this case, the maximum current of $L_r$ under PSP control and PS control is the same. Fig. 6 (c) and (d) show the experimental waveforms of the leakage inductor current $i_{Lr}$, the primary voltage $v_{ab}$, and the secondary voltage $v_{cd}$ at $V_1 = 22\text{V}$ in Boost mode with 300W output power under PSP control and PS control. In this case, voltage $V_1$ and voltage $V_2$ are not matched. Therefore, the current stress of $L_r$ with PS control is higher than that of PSP control.

Fig. 7 (a), (b) and (c) show the gate drive signal, voltage across the drain and source, and the drain current of the switches at full load and $V_1 = 30\text{V}$ in Boost mode. (a) $S_1$, (b) $S_3$, (c) $S_{a1}$.

Fig. 8 (a), (b) and (c) show the gate drive signal, voltage across the drain and source, and the drain current of the switches at full load and $V_2 = 300\text{V}$ in Buck mode. (a) $S_1$, (b) $S_3$, (c) $S_{a1}$.

Fig. 7 and Fig. 8 illustrate that all the switches realize ZVS. The experimental results are in agreement with the theoretical analysis well.
there are voltage $v_2$ and current $i_1$. When the voltage on $V_2$ port is higher than the reference value, the bidirectional dc–dc converter charges the battery. When the voltage on $V_2$ port drops, the battery turns to discharge and maintains the $v_2$ voltage as 270VDC. The experimental results convinced that the novel control strategy can control the energy conversion freely. The respond time of voltage rebuilding is 10ms. Therefore, this converter has the high steady and dynamic performance.

Fig.10 (a) shows the overall efficiency curves at different load and $V_1$ voltage under PSP control. Fig.10 (b) shows the efficiency curves of the converter under PSP control and PS control. It can be easily find that PSP control has higher efficiency than PS control, especially in low battery voltage.

VI. CONCLUSION

This paper proposed an novel ZVS bidirectional dc–dc converter with PS plus PWM control, which has the following advantages:

1) The converter avoids the voltage spike with the use of an active clamping branch $S_{a1}, S_{a2}$ and $C_c$.
2) The PS plus PWM control reduces circulating current and expands the ZVS range.
3) The decoupling control realizes the energy conversion freely, which has the high steady and dynamic performance.

REFERENCES