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Soft-switching PWM boost full-bridge converter

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Abstract: This paper proposes a family of PWM modulation strategies for boost full-bridge (FB) converters. The modulation strategies can be classified into two kinds according to the turn-on sequence of the diagonal switches. The concept of leading switches and lagging switches is introduced to realize soft-switching. According to the soft-switching realized by the leading switches and the lagging switches, two kinds of soft-switching techniques for PWM boost FB converters yield: zero-current-switching (ZCS) and zero-current and zero-voltage-switching (ZCZVS). Simulation results verify the analysis.

Key words: PWM; boost; full-bridge converters; zero-current-switching; zero-voltage-switching

The isolated buck full-bridge (FB) converter is widely used in medium and high power supplies due to its simple construction, low cost and high reliability. Its topologies and modulation strategies, especially its soft-switching modulation strategies, have been extensively researched[1-3]. The isolated boost FB converter is attractive in applications such as single-stage power factor correction (PFC) with isolation requirements and electric vehicle chargers with high output voltage[4,5]. Resonant boost FB converters realize soft-switching for switches but the design of their magnetic components is difficult due to the varying switching frequency[6].

This paper systematically discusses soft-switching technologies for PWM boost FB converters. It proposes a family of control strategies including nine strategies. The control strategies can be classified into two kinds according to the turn-on sequence of the diagonal switches. The concept of leading switches and lagging switches is introduced to realize soft-switching. This paper proposes two kinds of soft-switching techniques for PWM boost FB converters: zero-current-switching (ZCS) and zero-current and zero-voltage-switching (ZCZVS). Simulation results verify the analysis.

1 PWM Modulation Strategies for Boost FB Converter

The basic boost FB converter is shown in Fig.1(a) and includes: boost inductor L_b, FB inverter (switches Q_1 to Q_4 and free-wheeling diodes D_1 to D_4), output filter capacitor C_f, high-frequency transformer T_r, and output rectified diodes D_{R1} and D_{R2}. The boost inductance is assumed to be sufficiently large so that I_{in} is constant, and the transformer is ideal. By modulating the four switches Q_1 to Q_4, the primary current i_p is an AC square current, the amplitude of which is I_{in}. A secondary current appears, and is rectified to i_{rect} by the output rectifier diodes D_{R1} and

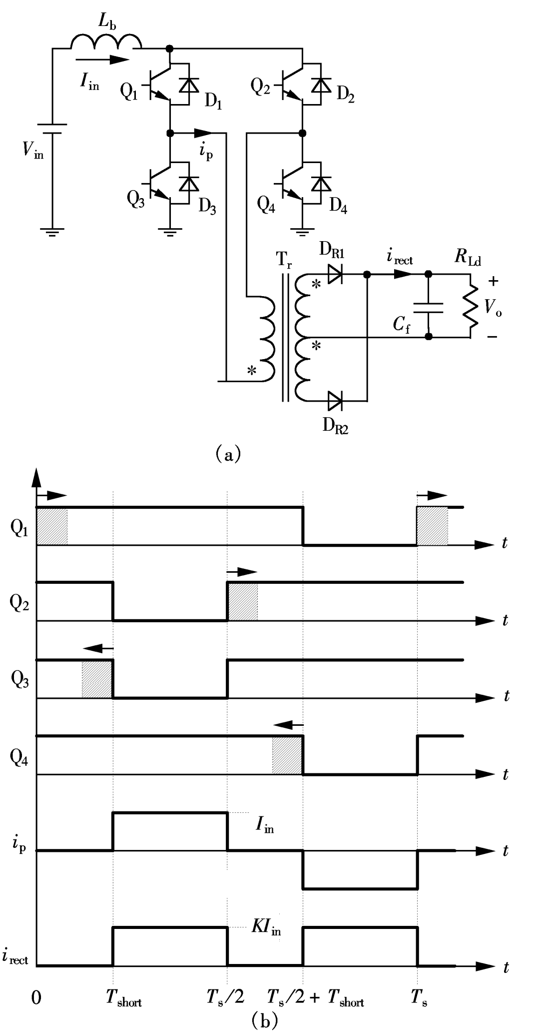

Fig.1 PWM boost FB converter. (a) Main circuit; (b) Control strategy

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D_{R2}. i_{rect} is a DC square current pulse the amplitude of which is KI_{in}, where K is the primary and secondary winding ratio. By filtering, we can get the DC output voltage V_o.

In order to get i_{rect}, the fundamental modulation strategy is shown in Fig.1(b). The pairs of diagonal switches are turned on or off simultaneously with a duty ratio of more than 50 percent over a switching cycle T_s. When all the four switches are on, primary current is zero. The short time of inverter bridge is T_{short} when the boost inductor is restoring energy, and the output voltage $V_o = V_{in}/[K(1-D)]$, where cycle duty $D = T_{short}/(T_s/2)$.

In fact, only one leg of switches needs to be on simultaneously when the boost inductor is restoring energy. We can keep the duty cycle of primary current i_p alternating square current unchanged by changing the modulation strategies of four switches through the following three ways:

1) Keep on-time of Q_1 and Q_2 unchanged, push the off-time of Q_3 and Q_4 forward or even make their on-time be $T_s/2$;

2) Keep on-time of Q_3 and Q_4 unchanged, push the on-time of Q_1 and Q_2 backward or even make their on-time be $T_s/2$;

3) Push the on-time of Q_1 and Q_2 backward or even to make their on-time be $T_s/2$, and at the same time push the off-time of Q_3 and Q_4 forward or even make their on-time be $T_s/2$.

Based on this thought, we can get a family of nine modulation strategies for boost FB converters as shown in Fig.2. Modulation strategy (a) is the fundamental modulation strategy, and modulation strategy (i) is phase-shifted modulation strategy.

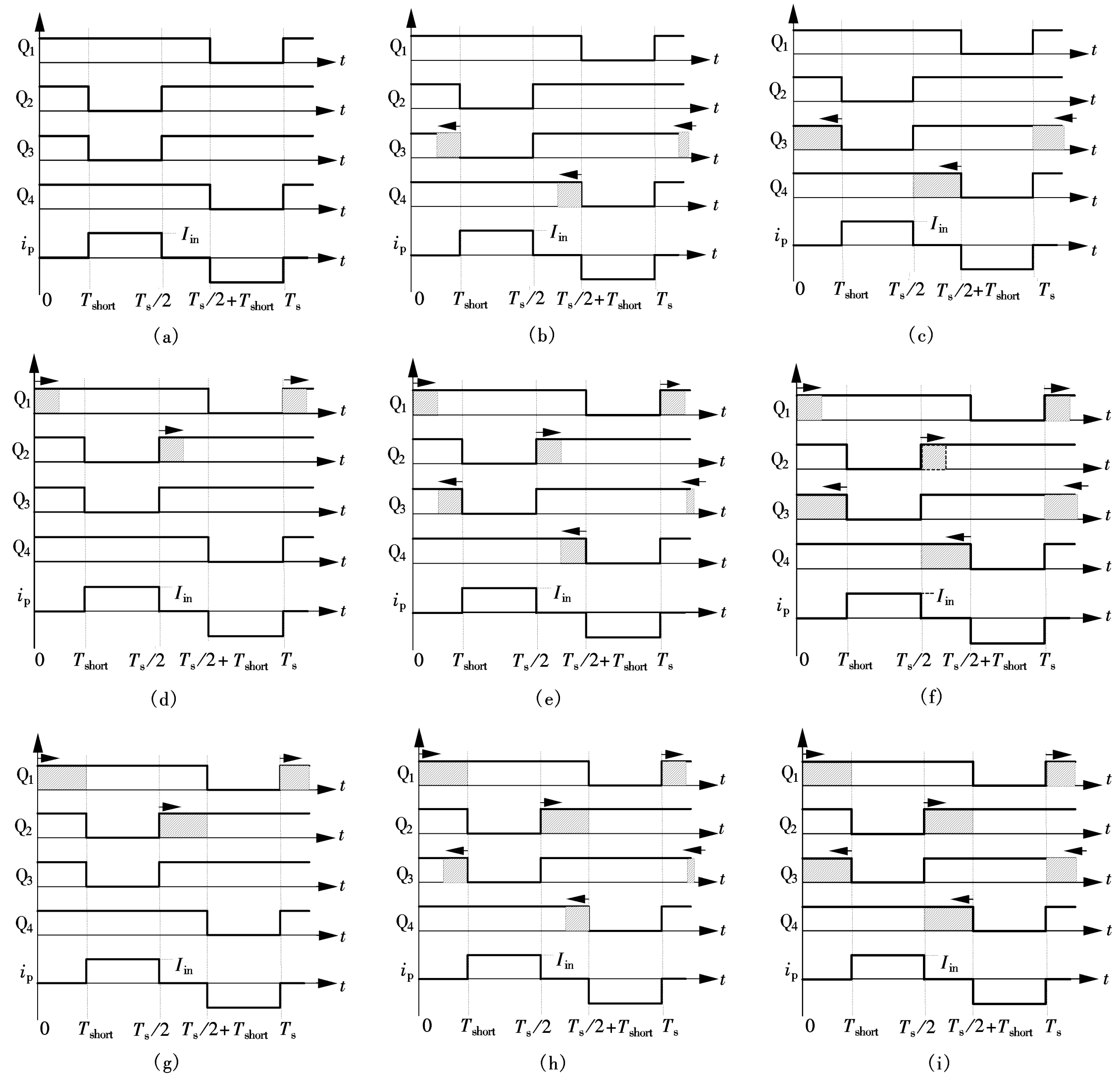

Fig.2 Nine control strategies. (a)Modulation strategy 1; (b) Modulation strategy 2; (c) Modulation strategy 3; (d) Modulation strategy 4; (e) Modulation strategy 5; (f) Modulation strategy 6; (g) Modulation strategy 7; (h) Modulation strategy 8; (i) Modulation strategy 9

2 Two Kinds of Modulation Strategies

The nine modulating strategies can be classified into two categories according to the turn-on sequence of the diagonal switches.

1) The diagonal switches are turned on simultaneously. Modulation strategies (a), (b) and (c) belong to this category.

2) The turn-on instants of the diagonal switches are staggered, one switch turning on before another. Modulation strategies (d) to (i) belong to this category.

Fig.3 shows the circuit and its main waveforms under the first kind of modulation strategy. C_{TR} is the parasitic capacitor of the transformer. L_{r1} to L_{r4} and D_1 to D_4 are in series with Q_1 to Q_4, respectively. When Q_2 and Q_3 are turned on simultaneously at t_0, the voltage KV_o of C_{TR} makes i_1 and i_4 reduce and i_2 and i_3 rise. So Q_2 and Q_3 are ZCS turn-on. When i_2 and i_3 rise to I_{in} at t_1, i_1 and i_4 reduce to zero. D_1 and D_4 prevent i_1 and i_4 from flowing in reverse direction during the zero state, which provides ZCS turn-off condition for switches Q_1 and Q_4. However, if Q_1 and Q_4 are turned off at t_1, i_p will be an AC square current, the duty cycle of which is 1. If Q_1 and Q_4 are not turned off at t_1, v_{CTR} will reduce to zero at t_2, then C_{TR} resonates with L_{r1} to L_{r4}. Q_2 and Q_3 are hard turn-on at t_3. So, if one pair of diagonal switches is turned on simultaneously, soft-switching cannot be realized.

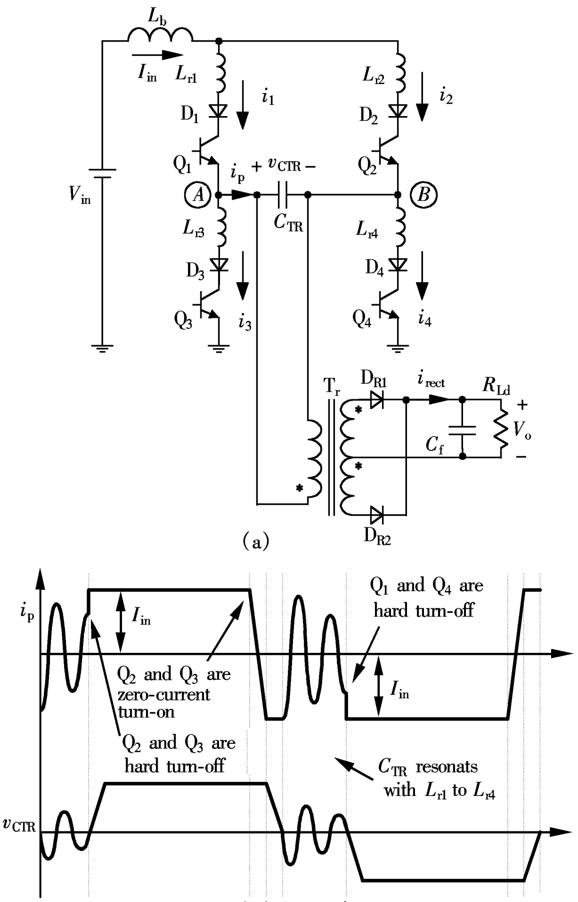

Fig.3 The diagonal switches simultaneous transition. (a) Main circuit; (b) Relevant waveforms

If the turn-on instants of the two diagonal switches are staggered, one switch turning on before the other, the switching transition will be improved. In general, the lower switches Q_3 and Q_4 are turned on before the upper switches Q_1 and Q_2, respectively, so we can define Q_3 and Q_4 as the leading switches, Q_1 and Q_2 as the lagging switches.

3 Soft-Switching for the Leading Switches and the Lagging Switches

3.1 Soft-switching for the leading switches

Before t_0, Q_1 and Q_4 are on, Q_3 and Q_2 are off, $i_p = I_{in}$, the rectifier diode D_{R1} is on, $v_{CTR} = KV_o$. In order to realize ZCS for leading switches, L_{r3} and L_{r4} are in series with Q_3 and Q_4. At t_0, Q_3 is turned on firstly. C_{TR} is in parallel with output capacitor C_f, the voltage of which is constant. v_{CTR} makes i_3 rise and i_4 reduce lineally. As i_3 rises to I_{in}, i_4 reduces to zero, $i_p = 0$. Then we can turn off Q_4 with ZCS due to D_4. Similarly, Q_4 can turn on and Q_3 can turn off with ZCS when Q_4 is turned on firstly.

Before the leading switches are turned on, C_{TR} is in parallel with the output capacitor C_f and v_{CTR} keeps constant. So the leading switches can only realize ZCS and easily realize ZCS because the energy of both C_{TR} and C_f is used.

3.2 Soft-switching for the lagging switches

When two switches in the same leg are on, for example, Q_1 and Q_2 are on, $i_p = 0$, we can operate the converter under two modes if certain devices and/or elements are added in the main circuit. One is voltage constant mode, in which v_{CTR} remains constant. The other is voltage reset mode, in which v_{CTR} is forced to zero and then remains at zero.

If the zero state operates in voltage constant mode, the voltage of the parasitic capacitor C_{TR} is KV_o before Q_2 is turned on. L_{r1} and L_{r2} are in series with lagging switches Q_1 and Q_2, respectively, as shown in

Fig.3(a). After Q_2 is turned on, i_2 rises and i_1 reduces due to v_{CTR}. Then Q_2 is ZCS turn-on and Q_1 can be turned off with ZCS when $i_1 = 0$. Similarly, Q_1 is ZCS turn-on and Q_2 can be turned off with ZCS when Q_1 is turned on. In a word, if the zero state operates in voltage constant mode, the lagging switches can realize ZCS. However, only the energy in C_{TR} is used to realize the ZCS for lagging switches. In a heavy load condition, the energy of C_{TR} may not be enough to realize the ZCS for lagging switches.

If zero state operates in voltage reset mode, L_{r1}, L_{r2}, D_1 and D_2 should be removed from Fig.3(a). Q_2 is ZVS turn-on when $v_{CTR} = 0$. Q_1 is ZVS turn-off because C_{TR} limits the rising rate of voltage. Similarly, when Q_1 is turned on, Q_1 is ZVS turn-on and Q_2 is ZVS turn-off. In a word, if zero state operates in voltage reset mode, the lagging switches can realize ZVS.

3.3 Kinds of soft-switching for PWM boost FB converter

According to the soft-switching type of the lagging switches, the soft-switching PWM boost FB converter can be divided into two kinds:

1) ZCS PWM boost FB converter, in which zero state operates in constant voltage mode, both the leading switches and lagging switches realize ZCS;

2) ZCZVS PWM boost FB converter, in which zero state operates in voltage reset mode, the leading switches realize ZCS, and the lagging switches realize ZVS.

4 ZCS and ZCZVS PWM Boost FB Converter

4.1 ZCS PWM boost FB converter

The typical topology of ZCS PWM boost FB converter using phase-shift control shown in Fig.3(a) can be simplified as Fig.4. A resonant inductor is in series with primary winding of the transformer, which can take the place of the four inductors which are in series with four switches. In order to use the leakage inductance of the transformer, a capacitor is in parallel with secondary winding of transformer, which resonates with leakage inductance and the resonant inductor. So all the switches realize ZCS[7].

4.2 ZCZVS PWM boost FB converter

The zero state of ZCZVS PWM boost FB converter using phase-shift control operates in voltage reset mode. A reset current source should be placed in

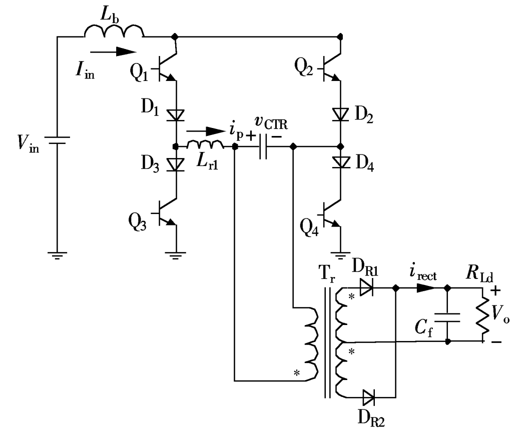

Fig.4 Simplified ZCS PWM boost FB converter

parallel with primary winding to make v_{CTR} reduce to zero in the interval of zero state as shown in Fig.5. The current source is positive when $i_p = I_{in}$, and it is negative when $i_p = -I_{in}$. When i_p reduces to zero, the rectifier diodes D_{R1} and D_{R2} do not conduct and v_{CTR} reduces to zero because of the current source discharging C_{TR}. The reset current source can be obtained by placing an inductor in parallel with primary or using the magnetizing inductance. The current source i_{reset} rises when Q_1 and Q_4 are on, reduces when Q_2 and Q_3 are on, and keeps unchanged when the converter operates in zero state, which makes v_{CTR} reset. After v_{CTR} resets, it must be kept zero. So anti-parallel diodes of Q_1 and Q_2 are added, which can offer a path for i_{reset} and offer ZVS for lagging switches.

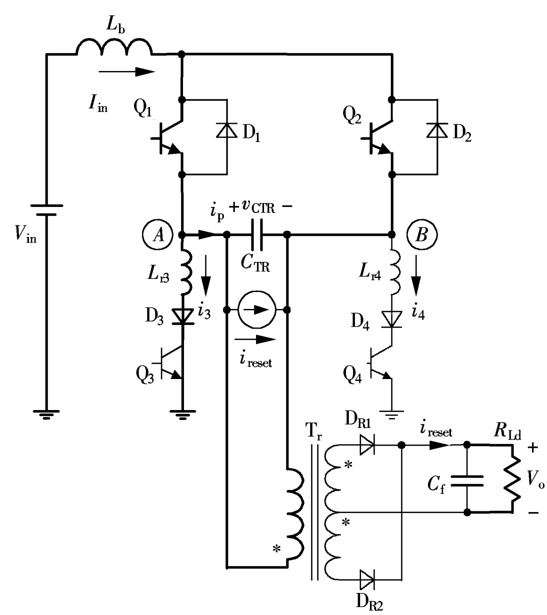

Fig.5 ZCZVS PWM boost FB converter

5 Simulation Results

In order to verify the operational principle of the

ZCS PWM boost FB converter shown in Fig.4 and ZCZVS PWM boost FB converter shown in Fig.5, the simulation is done by using Pspice with the main circuit parameters as follows: input DC voltage V_{in} = 300 V, output DC voltage V_o = 48 V, output current I_o = 10 A, switching frequency f = 50 kHz, the ratio of primary and secondary K = 8, input filter inductance L_b = 2 mH, resonant inductance L_r = 30 μH, L_{r3} = L_{r4} = 6 μH.

Fig.6(a) shows the waveforms of the gate singles and their collector currents for the leading switch Q_1 and the lagging switch Q_3 in the ZCS PWM boost FB converter under full load. It illustrates the leading switches and the lagging switches are all ZCS turn-on and ZCS turn-off. Fig.6(b) shows the gate signal v_{GE1} and its collector-emitter voltage v_{CE1} for the lagging switch Q_1 and gate signal v_{GE3} and its collector current i_{C3} for the leading switches Q_3 in ZCZVS PWM boost FB converter under full load. It illustrates that the leading switches achieve ZCS and the lagging switches achieve ZVS.

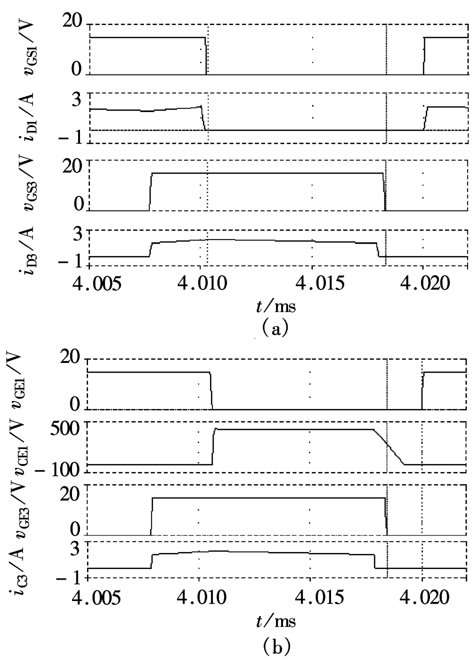

Fig.6 Main simulation waveforms. (a) ZCS PWM boost FB converter; (b) ZCZVS PWM boost FB converter

6 Conclusions

1) There are nine modulation strategies for PWM boost FB converters;

2) We can classify these modulation strategies into two categories according to the turn-on sequence of the diagonal switches: one is that the diagonal switches turn-on simultaneously, the other is that the turn-on instant of the diagonal switches is staggered, one switch turning on before the other.

3) When the diagonal switches turn on simultaneously, they cannot realize soft-switching unless auxiliary circuits are added.

4) When the turn-on instant of the diagonal switches is staggered, they can realize soft-switching. The leading switches can realize ZCS only, and they easily realize ZCS. The lagging switches can realize ZCS and ZVS.

5) According to the soft-switching type of the lagging switches, the soft-switching PWM boost FB converters can be divided into two categories: ① ZCS PWM boost FB converters, in which both the leading switches and lagging switches realize ZCS; ② ZCZVS PWM boost FB converters, in which the leading switches realize ZCS, and the lagging switches realize ZVS.

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软开关 PWM boost 全桥变换器

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摘　要　本文系统提出 boost 全桥变换器的一族共 9 种 PWM 控制方式.根据一对斜对角开关管开通情况的不同,将这 9 种 PWM 控制方式分成 2 类切换方式.为了实现软开关,引入超前管和滞后管的概念.在此基础上,将软开关 PWM boost 全桥变换器分成 ZCS 和 ZCZVS 两类.计算机仿真结果证实了所做的分析.

关键词　脉宽调制；boost；全桥变换器；零电流开关；零电压开关

中图分类号　TM46