REVIEW OF ZERO-CURRENT SWITCHING FLYBACK PWM DC-DC CONVERTERS

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Abstract: Zero-current (ZC) switching pulse-width-modulated (PWM) flyback DC-DC converter is an extended version of the single switch flyback converter with an additional active circuit. The purpose of the active circuit is to turn-off the main switch with zero-current switching (ZCS) condition to reduce the turn-off switching loss. This paper presents an overview of the ZCS flyback PWM DC-DC converters. The general principle of operation of the ZCS flyback converters is summarized. Relative merits and demerits of the ZCS flyback converter topologies are given. This work benefits the power supply designers in selecting an appropriate ZCS flyback PWM DC-DC converter for a certain application.

Key Words: Auxiliary Circuit, Flyback Converters, Power Conversion and Zero-Current Transition

I. INTRODUCTION

Pulse-width modulated (PWM) DC-DC converters are widely used in audio systems, alternative energy sources, back-up power supplies, battery chargers, communication equipments, computers, display units, hybrid electric vehicles, laptops, television sets, and many other commercial, industrial and military applications. PWM DC-DC converters are also used in power-factor correction (PFC) circuits as they provide tighter output voltage regulation and faster transient response.

A typical DC-DC converter is comprised of active switches such as MOSFETs or IGBTs, diodes, magnetic components such as inductors and transformers, and static devices such as capacitors. Magnetic components are heavier and occupy more volume than any other parts in a power electronic converter. The size of the magnetic components is inversely proportional to the switching frequency of the converter. In order to decrease the volume and weight of a DC-DC converter, higher switching frequency must be chosen. Increasing the switching frequency leads to increased switching losses which in turn reduces the converter efficiency. Soft-switching techniques are used in PWM DC-DC converters to reduce switching losses and electromagnetic interference (EMI).

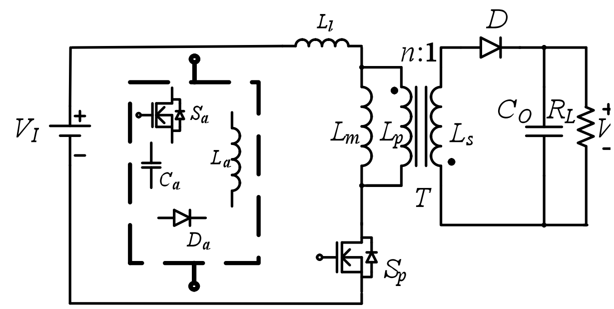

Fig. 1. Model of flyback PWM DC-DC converter with an auxiliary circuit.

Soft-switching is categorized as 1) zero-voltage switching (ZVS), 2) zero-voltage transition (ZVT) switching, 3) zero-current switching (ZCS), 4) zero-current transition (ZCT) switching, 5) zero-voltage-zero-current switching (ZVZCS), and 6) zero-voltage-zero-current transition (ZVZCT) switching. Soft-switching PWM converters in which the resonant periods of the voltage/current of the switching device are comparable to the converter switching period are classified as ZVS, ZCS, or ZVZCS converters, whereas converters in which the resonance occurs around the switching transitions are called as ZVT, ZCT, or ZVZCT converters. Several topologies of ZCT PWM DC-DC converters are studied in [1]-[25]. A comparative study of ZCT boost PWM DC-DC converters of [1]-[13] is presented in [14]. A ZCZVT boost PWM converter is introduced in [7]. In [1], [4], [17]-[21], a new ZCT PWM commutation cell is proposed, and is extended to other basic topologies of PWM DC-DC converters to form a family of ZCT PWM DC-DC converters.

Flyback converters are isolated versions of buck-boost converters and are widely used in low to medium power applications. They are relatively simple and have very few components. Recently, a few ZCS flyback converters are proposed to reduce the switching losses [22]-[24]. This paper presents an overview of the ZCS flyback converters. The principle of operation of the ZCS switching cell in a flyback converter is presented. A comparative study of ZCS flyback converters presented in [22]-[24] is performed, and the relative merits and demerits of each ZCS flyback converter are stated. Simulation results of two of the most recent ZCS flyback converters are given.

II. ZCS PWM SWITCHING CELL

Fig. 1 shows a model of a conventional flyback converter with an auxiliary ZCS switching cell. The auxiliary circuit consists of a minimum of one active switch, diode(s), and passive elements such as capacitor(s) and inductor(s). The auxiliary circuit is usually placed in parallel with the main switch of the converter. The role of each component in the auxiliary circuit is as follows [14]:

- an active switch activates the auxiliary circuit during the turn-off switching transition;
- an inductor-capacitor combination provides resonance to deviate the current in the main switch to the auxiliary circuit;
- diode(s) restrict the flow of current in a certain path.

In isolated DC-DC converters such as in flyback converters, the transformer leakage inductance can be used as the inductor of the auxiliary circuit. The parasitic leakage inductance also limits the rate of rise of current through the main switch, leading to soft turn-on of the switch and hence reduced turn-on switching losses. In order to incorporate the soft turn-on feature in the nonisolated DC-DC converters, an additional inductor is required in the auxiliary circuit such that it is placed in series with the main switch. The additional inductor is often referred to as snubber inductors [24]. The drawback of the snubber inductor is that it causes a voltage spike across the main switch when the switch is turned off. Therefore, a switch with higher voltage blocking capability must be selected for the main switch, which results in additional conduction losses. An ideal soft-switching scheme using an auxiliary circuit must be able to achieve the following [17]:

- reduce the switching losses without increasing the voltage or current stresses of both the main and the auxiliary switches;
- curtail the current spike in the diodes due to reverse recovery;
- contain fewer additional components;
- contain a ground referenced auxiliary switch;
- requires a simpler control scheme to activate and deactivate the auxiliary switch.

The general principle of operation of the ZCS flyback converter is as follows: The main switch is turned on and the energy is transferred from the DC input source to the magnetizing inductance of the flyback transformer. Just before the main switch is turned off, the auxiliary switch is turned on to create a resonance between the auxiliary capacitor and the additional resonant inductor. In some topologies, the leakage inductance of the flyback transformer is used in place of an additional inductor. Due to the resonance, the voltage across the auxiliary capacitor reduces and the main current is diverted to the auxiliary circuit. The main switch is turned off when the body diode or the antiparallel diode of the main switch is conducting. The auxiliary switch is turned off when the resonant current of the auxiliary inductor reaches zero. After the auxiliary switch is turned off, the auxiliary capacitor voltage begins to build towards its steady-state value. During the rest of the period, the rectifier diode commutates the magnetizing current to the output before the main switch is turned on at the beginning of the next switching cycle.

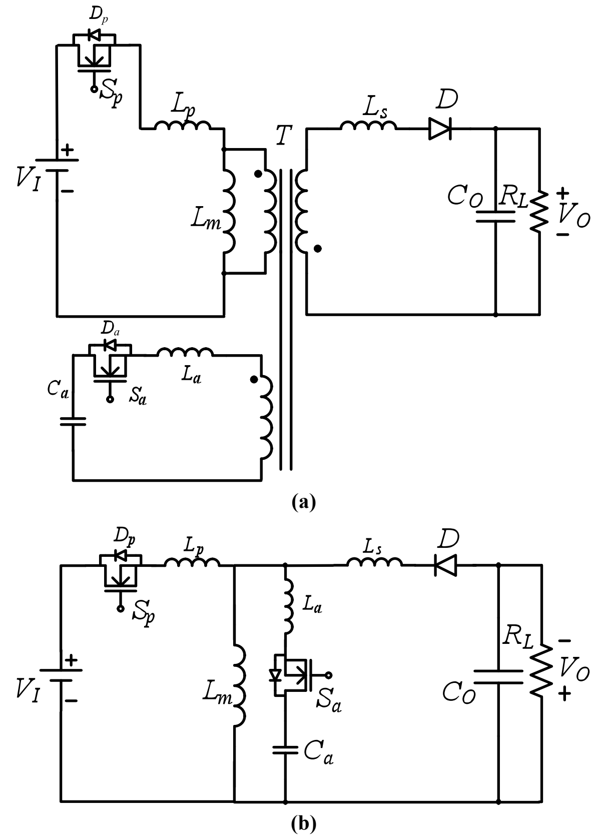

Fig. 2. (a) ZCS PWM flyback converter with a simple auxiliary circuit proposed in [21], [22]. (b) Equivalent circuit.

III. ZCS PWM FLYBACK CONVERTER WITH AN AUXILIARY SWITCH [21], [22]

The circuit of the first ZCS PWM flyback converter proposed in [21], [22] is shown in Fig. 2(a). The main switch S_p, the secondary side rectifier diode D, and the flyback transformer T form a part of the power circuit responsible for the power transfer. The auxiliary circuit consisting of a switch S_a and a capacitor C_a are linked to the main circuit through an additional winding. The auxiliary winding is reflected to the secondary side of the flyback transformer. The equivalent circuit of the converter is shown in Fig. 2(b). The body diodes of S_p and S_a are denoted by D_p and D_a, respectively. The leakage inductance of the primary, secondary, and the auxiliary windings are denoted by L_p, L_s, and L_a, respectively. The magnetizing inductance L_m of the transformer is reflected to the primary side of the transformer.

The operation of the converter is as follows: When the main switch S_p is on, L_m is charged by the input voltage source and the converter operation is same as that of a conventional hard-switched flyback converter. The auxiliary switch S_a is turned on just before S_p is turned off resulting in resonance between the leakage inductors L_p, L_a, and the auxiliary capacitor C_a. The main switch current is diverted to the auxiliary circuit to discharge C_a. When the resonant current through S_p reverses, the body diode D_p begins to conduct. When the diode D_p seizes conduction, the current through S_p is zero thereby creating a ZCS condition for S_p. The main switch S_p is turned off during this time period. The resonance between L_a, and C_a continues as the switch S_a remains on. The diode D turns on when the voltage across C_a falls below the output voltage thereby creating resonance between L_a, L_s, and C_a. When the resonant current through S_a reverses, the body diode D_a begins to conduct. When the diode D_a seizes conduction, the current through S_a is zero thereby creating a ZCS condition for S_a. The auxiliary switch S_a is turned off during this time period. The diode D commutates the magnetizing inductance current to the output until S_p is turned on in the next switching cycle.

Strengths: All the semiconductor devices are turned on softly and turned off with ZCS condition. The auxiliary circuit is simple as it comprised of only one active and one passive component.

Weaknesses: Longer conduction period of the auxiliary switch leads to more current circulating in both the auxiliary and the main circuits which lead to the following:

- Additional current stresses in the main switch and the rectifier diode due to increased peak currents.
- Additional conduction loss in the main switch.
- Additional voltage stress in the main switch, auxiliary switch, and the rectifier diode.

The turn-on and turn-off instants of the auxiliary switch is different from that of the main switch, i.e., the gate-to-source control voltage of the auxiliary switch is neither in phase nor complementary to the gate-to-source control voltage of the main switch. Also, since the source terminal of the auxiliary switch is not referenced to the ground, a floating isolated gate driver is required to drive the auxiliary switch. Thus, the control circuit is very complex in this converter. Since the auxiliary circuit is linked to the main circuit by additional winding, the flyback transformer becomes bulkier.

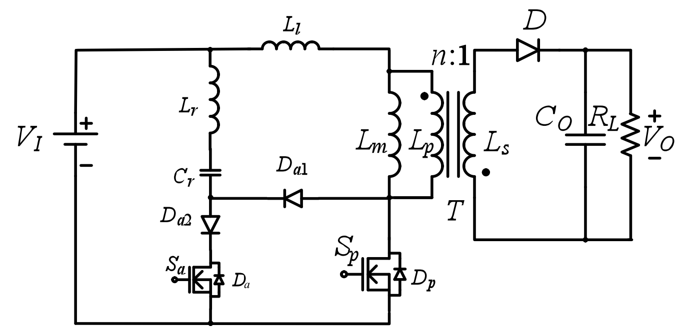

Fig. 3. ZCS PWM flyback converter with ZCS-PWM commutation cell proposed in [23].

IV. ZCS-PWM FLYBACK CONVERTER WITH ZCS-PWM COMMUTATION CELL [23]

The circuit of the ZCS-PWM flyback converter with a ZCS-PWM commutation cell proposed in [23] is shown in Fig. 3. The power circuit consists of the main switch S_p, the secondary side rectifier diode D, and the flyback transformer T. The ZCS-PWM switching cell is comprised of an auxiliary switch S_a, the resonant capacitor C_r, the resonant inductor L_r, and two auxiliary diodes D_{a1}, D_{a2}. The total leakage inductance L_l and the magnetizing inductance L_m of the flyback transformer are referred to the primary side.

The operation of the converter is as follows: When the main switch S_p is on, L_m and L_l are charged by the input voltage source and the converter operation is same as that of a conventional hard-switched flyback converter. The auxiliary switch S_a is turned on just before S_p is turned off resulting in resonance between L_r and C_r. The resonant capacitor C_r is discharged by the resonant current in the auxiliary circuit. When the resonant current reaches zero, the diode D_{a2} seizes conduction and stops the flow of resonant current through S_a. The resonant current now flows through D_{a1} and charges C_r. When the resonant current through S_p reverses, the antiparallel diode D_p begins to conduct. When the diode D_p seizes conduction, the current through S_p is zero thereby creating a ZCS condition for S_p and S_a. The switches S_p and S_a are turned off during this time period. When the switches are turned off, the resonance between L_l, L_r, and C_r begin, and the resonant current continues to charge C_r. The output rectifier D is forward biased and the magnetizing inductance current is transferred to the load. When the energy stored in L_r and L_l is transferred to C_r, the diode D commutates all of the magnetizing inductance current to the output until S_p is turned on in the next switching cycle.

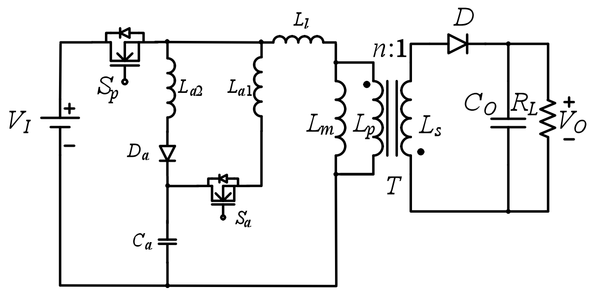

Fig. 4. ZCT PWM flyback converter proposed in [24].

Strengths:

- All the semiconductor devices are turned on softly and turned off with ZCS condition.
- The circulating current flows only through the auxiliary circuit and hence there is no additional current stress on the main switch.
- The auxiliary switch conducts for a very small period of time resulting in reduced conduction losses due to circulating current.
- The auxiliary switch is referenced with respect to the ground making it easier to drive.
- The auxiliary switch is turned off at the same time instant as that of the main switch making the control logic somewhat simpler than the ones found in the other two circuits.

Weaknesses:

- When both the switches are turned off, the parasitic output capacitance of the main switch, auxiliary switch, auxiliary diode D_{a1}, and the rectifier diode D participate in the resonance of L_l, L_r, and C_r, due to which the voltage stresses across S_p, S_a, D_{a2}, and D are significantly increased.
- Since the voltage across C_r swings from -4V_I to 6V_I, the stresses of C_r can be very large in high input voltage applications.
- The ZCS-PWM commutation cell needs an additional inductor L_r for the resonance. Also two additional auxiliary diodes are required for proper ZCS operation.

V. ZERO-CURRENT TRANSITION PWM FLYBACK CONVERTER [24]

The circuit of the ZCT-PWM flyback converter proposed in [24] is shown in Fig. 4. The main circuit consists of the switch S_p, the secondary side rectifier diode D, and the flyback transformer T. The auxiliary circuit is comprised of the switch S_a, the resonant capacitor C_a, the two resonant inductors L_{a1}, L_{a2}, and the auxiliary diode D_a. The total leakage inductance L_l and the magnetizing inductance L_m of the flyback transformer are referred to the primary side.

The operation of the converter is as follows: When the main switch S_p is on, L_m and L_l are charged by the input voltage source and the converter operation is same as that of a conventional hard-switched flyback converter. The auxiliary switch S_a is turned on just before S_p is turned off resulting in resonance between L_{a1} and C_a. The resonant capacitor C_a is discharged by the resonant current in the auxiliary circuit. When the resonant current through S_p reverses, the body diode D_p begins to conduct. When the diode D_p seizes conduction, the current through S_p is zero thereby creating a ZCS condition for S_p. The main switch S_p is turned off during this time period. The resonant current continues to discharge C_a until the rectifier diode D is forward biased. Resonant current due to resonance between L_l, L_{a1}, and C_a continues to discharge C_a. When the resonant current through S_a reverses, the body diode D_a begins to conduct. When the diode D_a seizes conduction, the current through S_a is zero thereby creating a ZCS condition for S_a. The auxiliary switch S_a is turned off during this time period. The stage during which D_a conducts is omitted in [24]. Resonance between L_l, L_{a2}, and C_a begins and the rectifier diode D continues to conduct. When the voltage across C_a reaches zero, the auxiliary diode D_{a2} seizes conduction, removing the auxiliary circuit from the main circuit. The diode D commutates all of the magnetizing inductance current to the output until S_p is turned on in the next switching cycle. When the main switch S_p is turned on, resonance between L_{a2} and C_a begins. The main switch current begins to build towards the magnetizing inductance current and the rectifier diode current falls to zero, thus ending one complete switching period.

Strengths: All the semiconductor devices are turned on softly and turned off with ZCS condition.

Weaknesses:

- Additional current stresses in the main switch and the rectifier diode due to increased peak currents.
- Additional conduction loss in the main switch.
- Additional voltage stress in the main switch, auxiliary switch, and the rectifier diode.
- The source terminal of the auxiliary switch is not referenced to the ground. Hence, a floating isolated gate driver is required to drive the auxiliary switch.
- Apart from the leakage inductance of the flyback transformer, the auxiliary circuit needs two additional inductors L_{a1} and L_{a2} for the resonance. Also an additional auxiliary diode is required for proper ZCS operation.

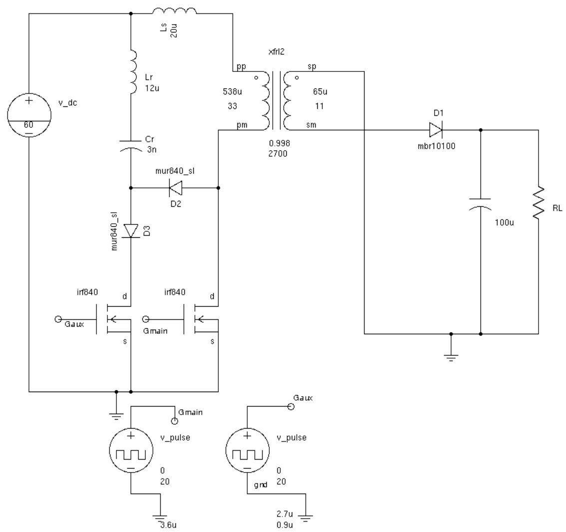

Fig. 5. Circuit of the ZCS PWM flyback converter with ZCS-PWM commutation cell used in Saber Sketch simulation.

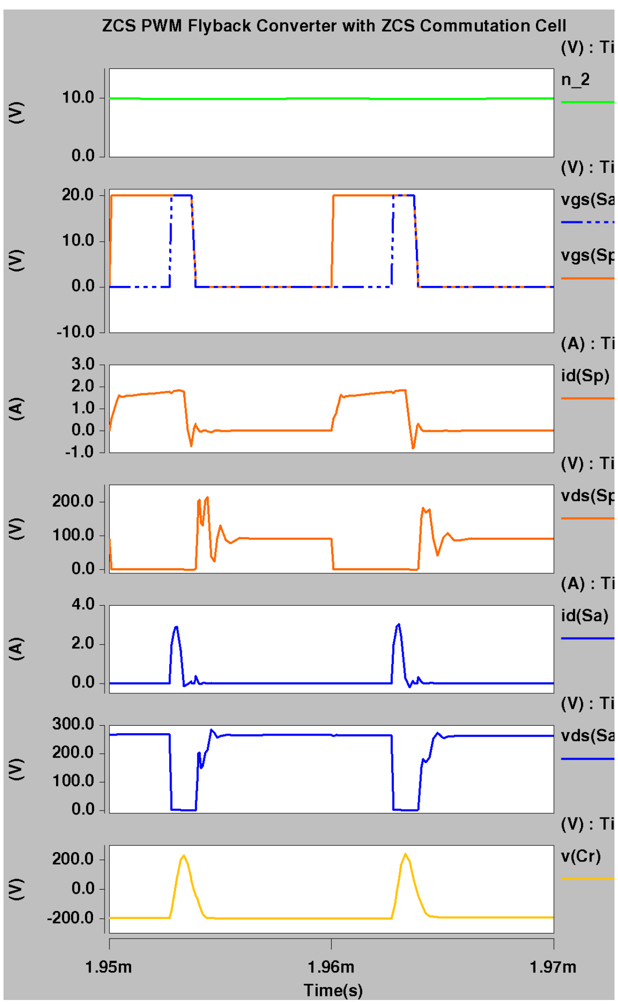

Fig. 6. Simulated waveforms of the voltages and currents of the ZCS PWM flyback converter with ZCS commutation cell.

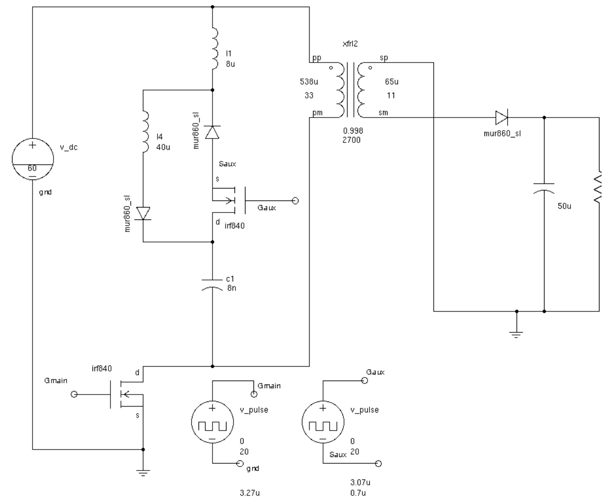

Fig. 7. Circuit of the ZCT PWM flyback converter used in Saber Sketch simulation.

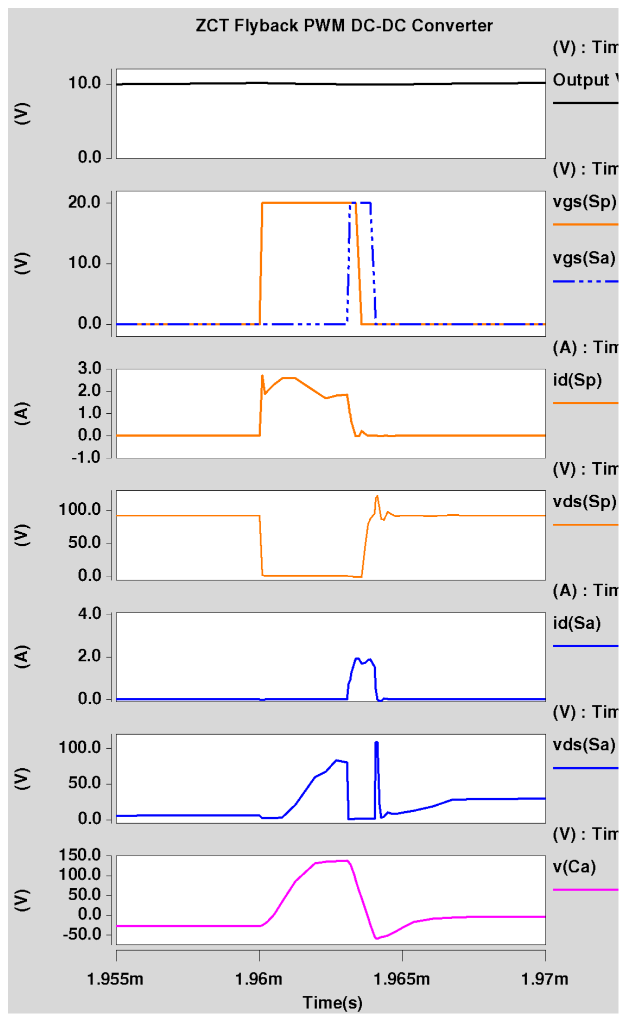

Fig. 8. Simulated waveforms of the voltages and currents of the ZCT PWM flyback converter.

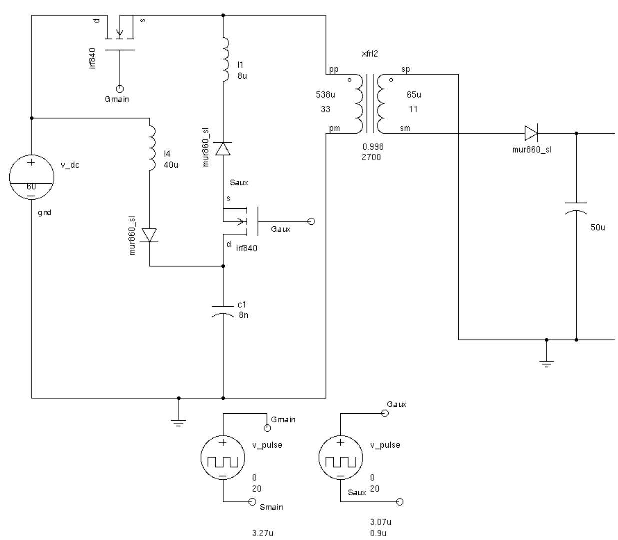

Fig. 9. Alternative circuit of the ZCT PWM flyback converter used in Saber Sketch simulation.

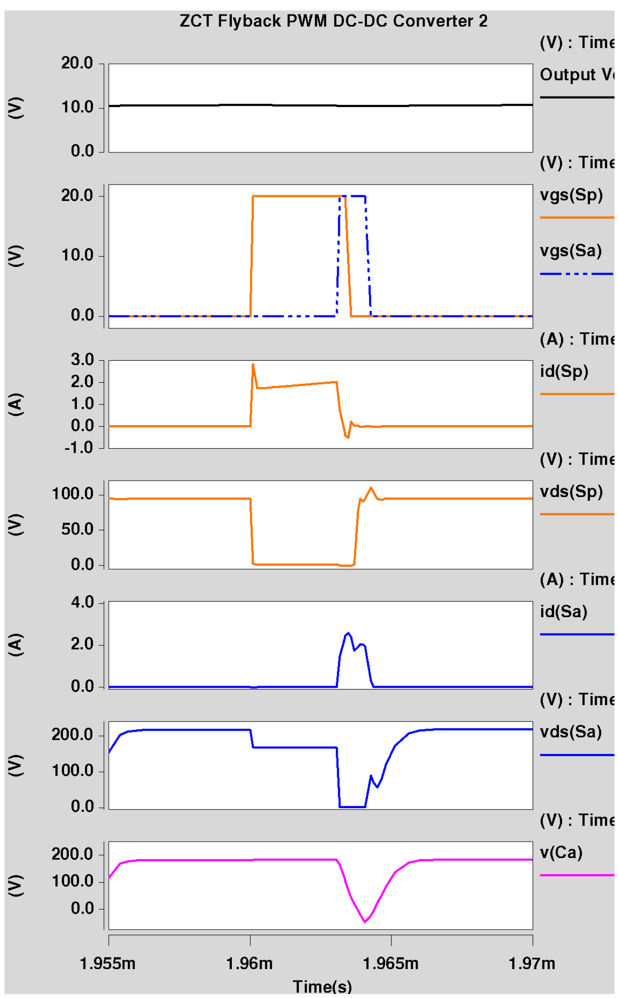

Fig. 10. Simulated waveforms of the voltages and currents of the alternative circuit of the ZCT PWM flyback converter.

TABLE I
LIST OF COMPONENTS IN THE AUXILIARY CIRCUIT OF THE ZCS FLYBACK CONVERTERS

Component	ZCS Flyback [22]	ZCS Flyback [23]	ZCT Flyback [24]
Auxiliary switch	1	1	1
Resonant capacitor	1	1	1
Resonant inductor	0	1	2
Auxiliary diode	0	2	1
Auxiliary winding	1	0	0
High-side driver	1	0	1
Total	**4**	**6**	**6**

VI. SIMULATION RESULTS

The design procedure presented in [23] and [24] are used to design the ZCS and ZCT flyback converters, respectively, for the following specifications:

- Input voltage: 60 VDC
- Output voltage: 10 VDC
- Maximum output power: 30 W
- Switching frequency: 100 kHz
- Transformer turns ratio N_1:N_2 = 33/11
- Primary side magnetizing inductance L_m = 526 µH
- Total leakage inductance L_l = 2 µH

The circuits of the ZCS and ZCT flyback converters used in Saber Sketch simulation are shown in Figs. 5 and 7, respectively. The simulated voltage and current waveforms of the converters shown in Figs. 5 and 7 are shown in Figs. 6 and 8, respectively. The circuit and the simulation results of an alternative circuit of the ZCT flyback converter proposed in [24] are shown in Figs. 9 and 10, respectively. The alternative ZCT flyback converter has reduced main switch current stress but the voltage stresses of the auxiliary switch and the capacitor are increased. From the main switch current waveforms obtained from the simulations, it is clearly seen that the ZCS operation of the flyback converters are achieved. Table 1 lists the number of components of the auxiliary circuits of the ZCS flyback converters.

VI. CONCLUSIONS

A comparative study of ZCS flyback converters is presented. The strengths and weaknesses of each ZCS flyback converter are given in detail. The conclusions drawn from the comparison are as follows:

1. The ZCS flyback converters of Figs. 2(a) or 4 are better suited for high input voltage applications as they have lower voltage stresses in the main and the auxiliary switches.
2. The ZCS flyback converter of Fig. 3 is better suited for low voltage high current applications

as it has lower current stresses but higher voltage stresses in the main and the auxiliary switches.

3. The ZCS flyback converter of Fig. 3 is the simplest among the three ZCS flyback converters as it has very few additional magnetic components and a simpler gate drive circuit.

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