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Circuit Properties of Zero-Voltage-Transition PWM Converters

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ABSTRACT

A zero-voltage-transition (ZVT) pulse width modulated (PWM) converter is a PWM converter with a single main power switch that has an auxiliary circuit to help it turn on with zero-voltage switching (ZVS). There have been many ZVT-PWM converters proposed in the literature as they are the most popular type of ZVS-PWM converters. In this paper, the properties and characteristics of several types of ZVT-PWM converters are reviewed. A new type of ZVT-PWM converter is then introduced, and the operation of a sample converter of this type is explained and analyzed in detail. A procedure for the design of the converter is presented and demonstrated experimentally. The feasibility of the new converter is confirmed with results obtained from an experimental prototype. Conclusions on the performance of ZVT-PWM converters in general are made based on the efficiency results obtained from the experimental prototypes of various ZVT-PWM converters of different types.

Keywords: Zero-voltage transition, PWM converters, Switch-mode power supplies, High-frequency converters

1. Introduction

High switching frequencies are used in power converters to reduce the size and weight of their magnetic and filter components, thus reducing overall converter size and weight. Operating at higher switching frequencies, however, increases switching losses, which reduces converter efficiency. Converters operating with high switching frequencies are, therefore, typically implemented with zero-voltage switching (ZVS) to minimize these problems. With ZVS, converter switches are made to operate with a zero-voltage turn-on and turn-off.

In recent years, the most widely used single-switch pulse-width modulated (PWM) ZVS power converters have been so called zero-voltage-transition (ZVT) PWM converters. There have been many previously proposed ZVT-PWM converters (i.e. [1]-[14]) and they all share certain common properties. These converters have an auxiliary circuit connected in parallel to the main switch to help it turn on with ZVS and a snubber capacitor to help the switch turn off with ZVS, as shown in Fig. 1. They operate in the same manner as regular PWM converters, but with reduced switching losses. This reduction is due to the fact that the auxiliary circuit operates for only a small portion of the switching cycle and is activated just before the main converter switch is about to be turned on. Since the auxiliary circuit is on for such a short time, a device with better switching characteristics than that used as the main switch can be chosen, as conduction losses are not an issue.

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The objectives of this paper are as follows:

(i) To review the basic circuit properties of ZVT-PWM converters for design engineers who may not be familiar with them;

(ii) To determine if it is possible to maximize the efficiency of these converters using these circuit properties.

In this paper, the properties and characteristics of several types of ZVT-PWM converters are reviewed. A new type of ZVT-PWM converter is then introduced and the operation of an experimental converter of this type is then demonstrated. The feasibility of the new converter is confirmed with results obtained from an experimental prototype. Conclusions on the performance of the converter and on the performance of ZVT-PWM converters in general are made based on efficiency results obtained from experimental prototypes of other ZVT-PWM converters that are representative of different types.

2. Non-Resonant and Resonant Auxiliary Circuits in ZVT-PWM Converters

There have been many auxiliary circuits that have been previously proposed for use in ZVT-PWM converters [14]. With few exceptions, auxiliary circuits in ZVT-PWM converters are generally one of three types: non-resonant circuits, resonant circuits that have an LC resonant network placed in series with the auxiliary circuit switch, or dual circuits that are a combination of the first two types. The operation of a ZVT-PWM boost converter with an experimental non-resonant and an experimental resonant auxiliary circuit is reviewed in this section of the paper.

The operation of a ZVT-PWM boost converter with an experimental dual circuit will be reviewed in the next section.

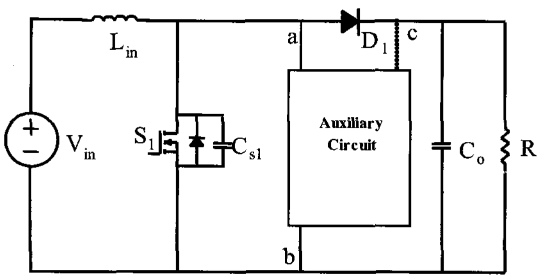


Fig. 1 General structure of a ZVT PWM boost converter

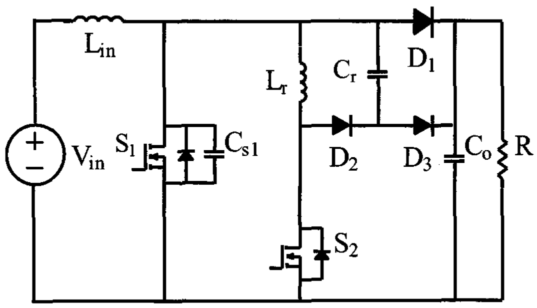


Fig. 2 ZVT-PWM boost converter with non-resonant auxiliary circuit

2.1 Non-Resonant Auxiliary Circuit

Consider the converter shown in Fig. 2 which is an example of a ZVT-PWM converter with a non-resonant auxiliary circuit [1]. The auxiliary circuit consists of a switch, S_2, an inductor, L_r, a capacitor, C_r, and two diodes, D_2 and D_3. The circuit is a non-resonant circuit because there is no capacitor in series with the auxiliary circuit inductor.

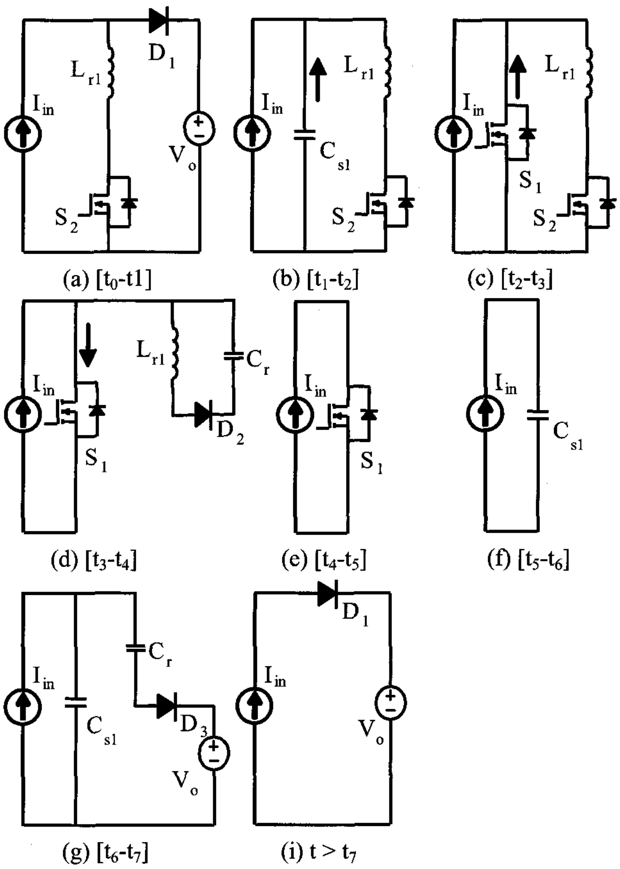


Fig. 3 Modes of operation of a ZVT-PWM boost converter with a non-resonant auxiliary circuit

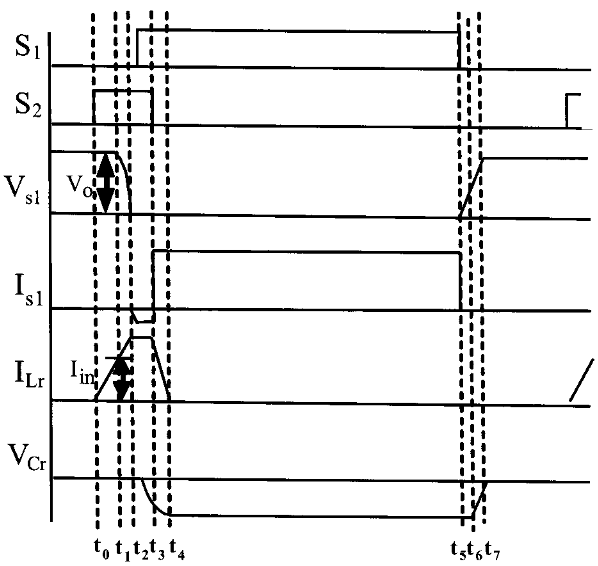


Fig. 4 Typical waveforms of a ZVT-PWM boost converter with a non-resonant auxiliary circuit

Fig. 3 shows circuit diagrams of the modes of operation that the converter shown in Fig. 2 goes through during a switching cycle. For these diagrams, the input inductor, L_{in}, is assumed large enough to be considered as a constant current source, I_{in}, and the output capacitor, C_o, is large enough to be considered as a voltage source, V_o.. Typical waveforms that illustrate the converter's operation are shown in Fig. 4.

The converter works as follows: Before the auxiliary switch S_2 is turned on to help the main switch S_1 turn on with ZVS, current flows through the main power boost diode D_1. At some time $t = t_0$, the auxiliary switch S_2 is turned on and current begins to be diverted from D_1 to the auxiliary circuit. Since there is an inductor in series with the switch, it is turned on with zero-current switching (ZCS) as the inductor slows down the rate of current rise in the switch. At $t = t_1$, there is no current flowing in D_1 and capacitor C_{s1} begins to discharge as the voltage across it is now not clamped to the output voltage. C_{s1} is totally discharged at some time $t = t_2$ and the body diode of S_1 conducts current. S_1 can be turned on with ZVS as the voltage across C_{s1} is almost zero.

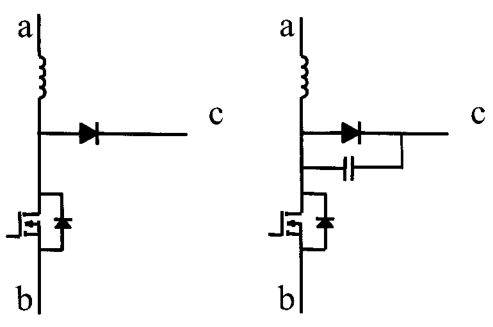


Fig. 5 Other non-resonant auxiliary circuits

Once S_1 has been turned on, S_2 can be turned off at some time $t = t_3$. When this happens, the current through L_r is diverted to D_2 and charges capacitor C_r and the current in S_1 stops flowing through the body diode and instead flows through the switch. When the current through L_r becomes zero at some time $t = t_4$, the converter then operates like a conventional PFC boost converter. S_1 is turned off at $t = t_5$ and capacitor C_{s1} is charged until D_3 begins to conduct at $t = t_6$. C_r is eventually discharged through D_3 and current then flows through D_1 at $t = t_7$ until S_1 is turned on again to start a new switching cycle.

The following facts, which are true for all ZVT-PWM converters with non-resonant auxiliary circuits, should be noted:

(i) The current flowing through the auxiliary switch is interrupted when the switch is turned off. Although the switch has a hard turn-off that somewhat offsets the gain in efficiency that is derived by having the auxiliary circuit in the circuit, these turn-off losses are still less than the turn-on losses of the main power switch in a conventional PWM converter.

(ii) The operation of the auxiliary circuit in the converter does not affect the voltage or current stress of the main power switch or the main power boost diode.

Other non-resonant auxiliary circuits that can be used in ZVT-PWM converters were proposed in [2], [4], [8], [9]; some of these are shown in Fig. 5. Regardless of how these circuits may look, the fundamental circuit properties of all non-resonant circuits are the same. The only real difference is in the way that energy is transferred out of the auxiliary circuit after the auxiliary switch is turned off.

2.2 ZVT-PWM Converter with Resonant Auxiliary Circuit

Consider the converter shown in Fig. 6, which is an example of a ZVT-PWM converter with a resonant auxiliary circuit [5], [6]. The auxiliary circuit consists

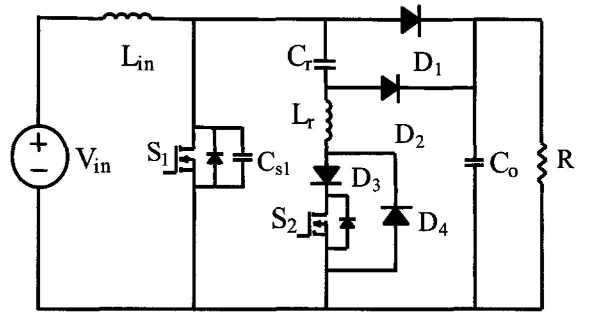


Fig. 6 ZVT-PWM boost converter with a resonant auxiliary circuit

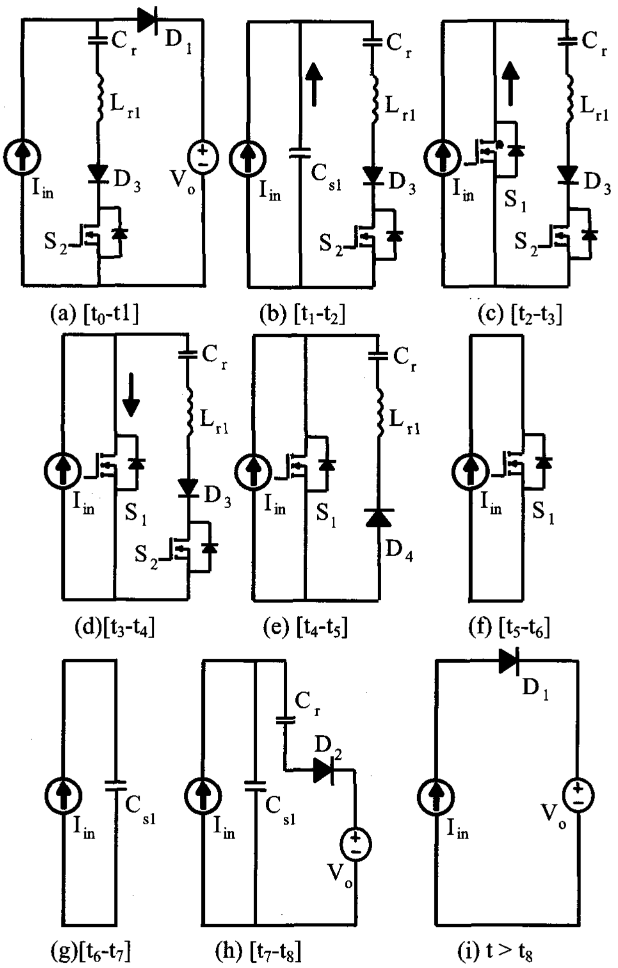


Fig. 7 Modes of operation of a ZVT-PWM boost converter with a resonant auxiliary circuit

of a switch, S_2, an inductor, L_r, a capacitor, C_r, and three diodes, D_2, D_3 and D_4. The purpose of D_3 is to keep current from flowing through the body diode of S_2 so that current can flow through D_4, which is a faster device. The circuit is a resonant circuit because there is a capacitor in series with the auxiliary circuit inductor.

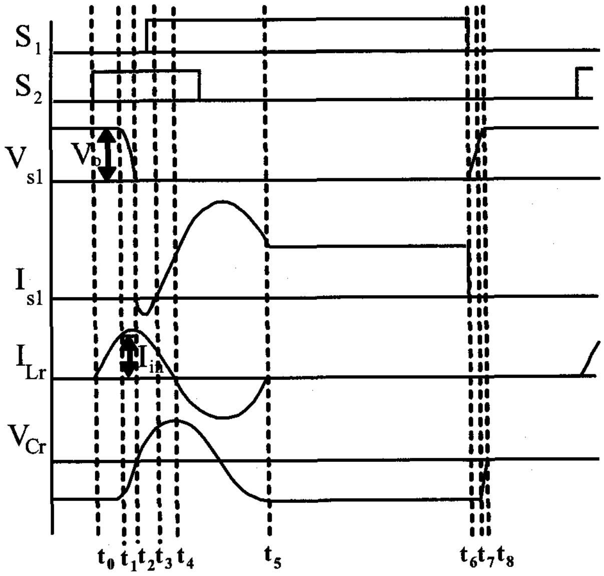


Fig. 8 Typical waveforms of a ZVT-PWM boost converter with a resonant auxiliary circuit

Fig. 7 shows the circuit diagrams of the modes of operation that the converter shown in Fig. 6 goes through during a switching cycle, while Fig. 8 shows typical waveforms that illustrate the converter's operation. The converter works as follows: The auxiliary switch S_2 is turned on with ZCS at $t = t_0$ and current begins to be diverted from D_1 to the auxiliary circuit. At $t = t_1$, capacitor C_{s1} begins to discharge as there is no current flowing in D_1 and is totally discharged at some time $t = t_2$ when the body diode of S_1 conducts current. S_1 can then be turned on with ZVS.

Initially, during the time interval from t_0 to t_2 when current is flowing through S_2, the current through S_2 rises, but then begins to drop as capacitor C_r is being charged - especially as C_{s1} is being discharged and the net voltage across L_{r1} is negative. At $t = t_3$, auxiliary circuit current I_{Lr2} becomes less than the input current I_{in} and, thus, the current through S_1 changes direction and stops flowing through the body diode. I_{Lr2} continues decreasing until it becomes zero at $t = t_4$ then reverses direction and flows through D_4 and S_1, so that C_r can discharge; switch S_2 can be turned off softly while this is happening. At $t = t_5$, current stops flowing in the auxiliary circuit as the voltage across C_r has become negative and there is no path for C_r to discharge. The operation of the converter becomes identical to that of the converter shown in Fig. 2 until the start of the next switching cycle.

The following facts, which are true for all ZVT-PWM converters with resonant auxiliary circuits, should be noted:

(i) The series inductor-capacitor components in the auxiliary circuit force the auxiliary switch current to drop to zero naturally so that there is no current flowing through the auxiliary switch when the switch is turned off. The switch is turned off softly while current is flowing through diode D_4, which is anti-parallel to it.

(ii) The operation of the auxiliary circuit in the converter results in an increase in the peak current stress of the main power switch S_1 due to the auxiliary circuit current that flows through D_4 when it is in its negative resonant half-cycle. This circulating current increases both the peak current stress of the main switch and conduction losses.

Other resonant auxiliary circuits that can be used in ZVT-PWM converters were proposed in [3], [7], and [10]; some of these are shown in Fig. 9. Regardless of how these circuits may look, the fundamental circuit properties of all resonant circuits are the same. The only real difference is in the way that energy is transferred out of the auxiliary circuit to the load. In general, the more sophisticated the auxiliary circuit, the more efficiently this process will occur.

3. Dual Auxiliary Circuits in ZVT-PWM Converters

In recent years, dual auxiliary circuits that combine the advantages of resonant and non-resonant converters while reducing the drawbacks of each have been proposed (i.e. [11-13]). The auxiliary switch in these circuits has the soft turn-off of switches in resonant auxiliary circuits, but without the increase in main switch peak current stress and conduction losses as is the case with non-resonant circuits.

An example of a boost converter with a dual auxiliary circuit is shown in Fig. 10 [13]. This auxiliary circuit can be considered to be dual since it has two parallel branches: a non-resonant branch consisting of components: L_{r1}, L_{r2}, D_3, D_4 and a resonant branch consisting of components: L_{r2}, C_r D_4. In general, a dual auxiliary circuit can be formed by combining any one non-resonant auxiliary circuit with any one resonant auxiliary circuit then eliminating all redundant components; a procedure for doing so was presented in [13]. In the dual circuit shown in Fig. 10, the circuit has been formed by combining the non-resonant auxiliary circuit presented in Section II.A with the resonant circuit presented in Section II.B then eliminating all redundant components.

The equivalent circuit for each mode is shown in Fig. 11 and the converter waveforms are shown in Fig. 12. The converter works as follows: At t_0, the auxiliary switch S_2 is turned on with ZCS. The current through L_{r1}, L_{r2} and C_r increases as current is being diverted away from the boost diode, D_1. The mode ends at $t = t_1$ when the current flowing through D_1 is zero. At t_1, the capacitor across the main switch, C_s, begins to be discharged through the auxiliary circuit. Current I_{Lr1}, and voltage V_{Cs} continue to increase. I_{Lr2} reaches its maximum value and begins to decrease when V_{Cs} drops below V_{Cr}. C_s is still being discharged until it is totally discharged at $t = t_2$, when the main switch body-diode begins to conduct.

At t_2, the body-diode of the main switch begins to conduct as I_{Lr2} is larger than I_{in}; this allows the main

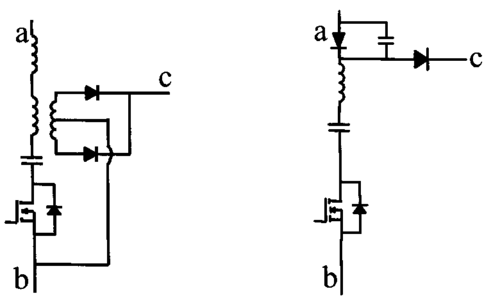


Fig. 9 Other resonant auxiliary circuits

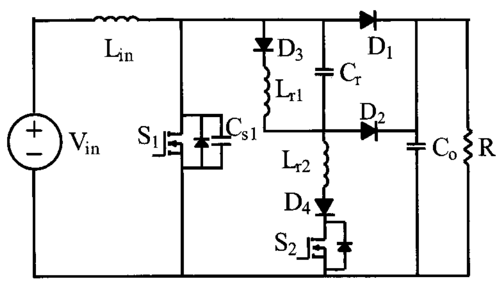


Fig. 10 ZVT-PWM boost converter with a dual auxiliary circuit

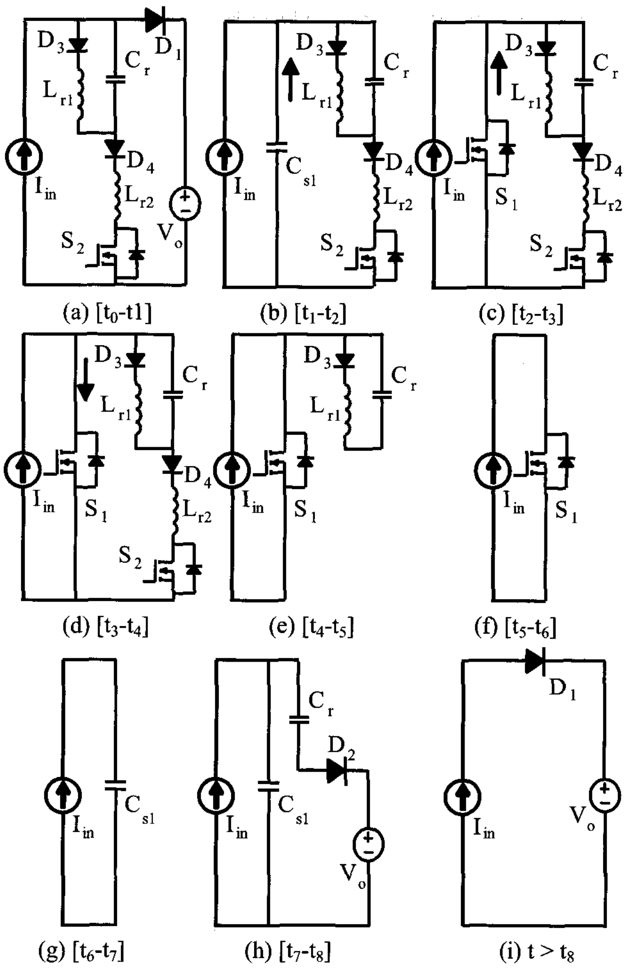


Fig. 11 Modes of operation of a ZVT-PWM boost converter with a dual auxiliary circuit

switch S_1 to be turned on with ZVS. Current I_{Lr1} and voltage V_{Cr} continue to increase. Some time during this mode, a resonant process involving the resonant branch of the auxiliary circuit begins and currents I_{Cr} and I_{Lr2} start to decrease. It continues to do so until t = t_3, when the main switch S_1 can be turned on with ZVS. At t_3, current stops flowing through the body-diode of main switch S_1 and starts flowing through the switch. The resonant process that began earlier continues as current I_{Lr1} and voltage V_{Cr} continue to increase and currents I_{Cr} and I_{Lr2} continue to decrease.

At t = t_4, I_{Lr2} becomes zero and $I_{Lr1} = I_{Cr}$ as diode D_4 blocks any negative resonant current that would otherwise flow. The auxiliary switch can be turned off with ZCS as there is no current flowing through it. The current through the main switch is equal to i_{in} and the energy from

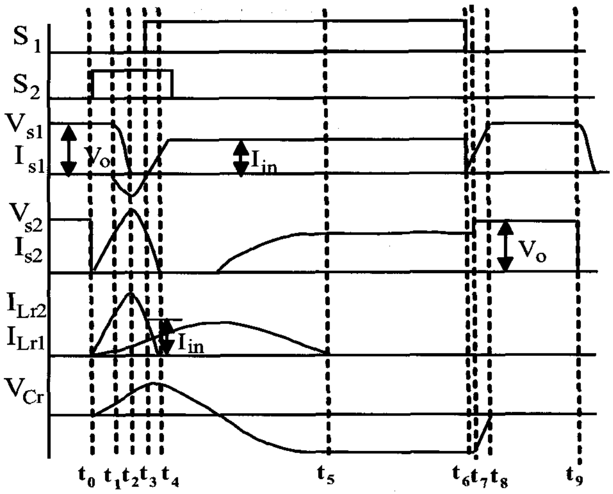


Fig. 12 Typical waveforms of a ZVT-PWM boost converter with a dual auxiliary circuit

inductor L_{r1} is transferred to C_r until t=t_5 when the current through L_{r1} becomes zero and diode D_3 prevents the current from reversing direction. The operation of the converter from time t_5 onwards (Fig. 11(f)-(i)), when current no longer flows in the auxiliary circuit, is exactly the same as that of the ZVT-PWM converter with the non-resonant auxiliary circuit discussed in Section II.A (Fig. 3(f)-(i)).

It can be seen from Fig. 11(e) that the switch in the dual auxiliary circuit, like the switch in any dual auxiliary circuit, is turned off softly while current is diverted away from the switch by the resonant branch, but without any circulating current fed back into the main power switch as it is contained in the auxiliary circuit.

4. An Off-Tuned Dual Auxiliary Circuit

Presently, dual auxiliary circuits are the most efficient

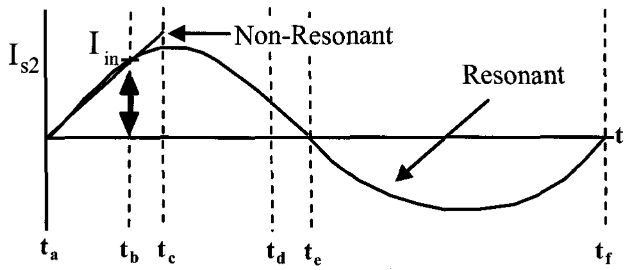


Fig. 13 Auxiliary switch current waveforms of a ZVT-PWM boost converter

type of auxiliary circuits in ZVT-PWM converters because they have lower switching losses than non-resonant auxiliary circuits and lower conduction losses than resonant auxiliary circuits. One question that can be asked, however, is whether it is possible to further improve the efficiency of dual auxiliary circuits - what would it take to maximize the efficiency of auxiliary circuits in ZVT-PWM converters?

To answer this question, consider the auxiliary switch current waveforms shown in Fig. 13. If the auxiliary switch S_2 is turned on at some time t_a to discharge the capacitance across the main power switch S_1, then it is turned off at time t_c. If the switch is in a non-resonant auxiliary circuit, t_c is when the auxiliary switch current I_{s2} is greater than the input current I_{in} after t_b; if it is a dual auxiliary circuit, t_c is at time t_e ; if it is in a resonant auxiliary circuit, t_c is some time between t_e and t_f. In the case of a resonant auxiliary circuit, current would continue to flow through the anti-parallel diode across the switch until t_f.

Let us say that the auxiliary switch is turned off at time t_c in Fig. 13. If this is done, it can be seen that the switch will be turned off with some current flowing through it, but this current will still be significantly less than it would be if the switch were turned off at t_c than it would be if it were in a non-resonant circuit. Moreover, any increase in conduction losses would be fairly small. Turning the switch off at t_c would also result in the switch conducting even less current than it would if it were in a dual auxiliary circuit and significantly less current that it would if it were in a resonant auxiliary circuit. Interrupting the resonant cycle of the auxiliary switch current would reduce the current circulating in the auxiliary circuit.

Although the turn-off losses in the auxiliary switch are greater than those of a switch in a dual or resonant

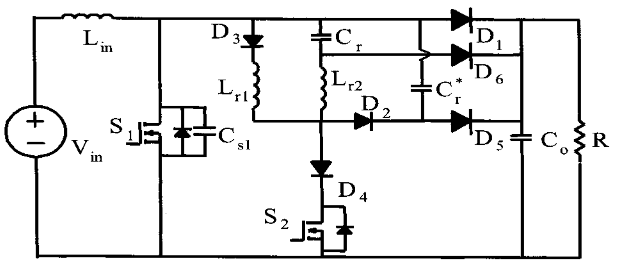


Fig. 14 A ZVT-PWM boost converter with an off-tuned dual auxiliary circuit

auxiliary circuit, these losses are more than offset by the reduction in conduction losses.

In terms of circuit implementation, an auxiliary circuit can be made to operate in this way if the resonant branch of the dual circuit is "off-tuned" so that the current through the auxiliary switch is reduced, but not completely eliminated, before it is turned off. This is in contrast to the "appropriate" tuning of the resonant branch in a dual auxiliary circuit so that the auxiliary switch turns off with zero current. Fig. 14 shows an example a ZVT-PWM boost converter with an off-tuned variation of the dual auxiliary circuit in Fig. 10.

Just like a dual auxiliary circuit, the circuit in Fig. 14 has a non-resonant branch and a resonant branch. The non-resonant branch consists of components L_{r1}, D_3 and D_4, and the resonant branch consists of components L_{r2}, C_r, D_4. Components D_2 and C_r* are added to provide a path where the remaining auxiliary switch current can be diverted when the switch is turned off. This is needed as the switch does not turn off softly. Energy from L_{r1} and L_{r2} is transferred to C_r*. Diodes D_6 and D_5 allow the voltages across capacitors C_r and C_r*, respectively, to return to zero every cycle by transferring the energy in these capacitors to the output each cycle.

Fig. 15 shows the circuit diagrams of the modes of operation that the converter shown in Fig. 14 goes through during a switching cycle. The converter's modes of operation are as follows:

Mode 1 (t_0-t_1): At t_0, the auxiliary switch S_2 is turned on and current begins to be diverted away from the boost diode, D_1. S_2 turns on with ZCS due to the presence of inductors in both circuit branches. The equations that define this mode are given in equs. (1) to (3):

$$v_{cr} + L_{r2}\frac{di_2}{dt} = V_o \, (1) \quad L_{r1}\frac{di_1}{dt} = V_o \, (2) \quad i_2 = C_r\frac{dv_{cr}}{dt} \quad (3)$$

The solutions to the above equations are given below by equs. (4) to (7).The resonant frequency in this mode is given by (8).

$$v_{c_r} = V_o\left(1-\cos(\omega_0 t)\right) \qquad (4) \qquad\qquad v_{c_s}(t) = V_o \qquad (5)$$

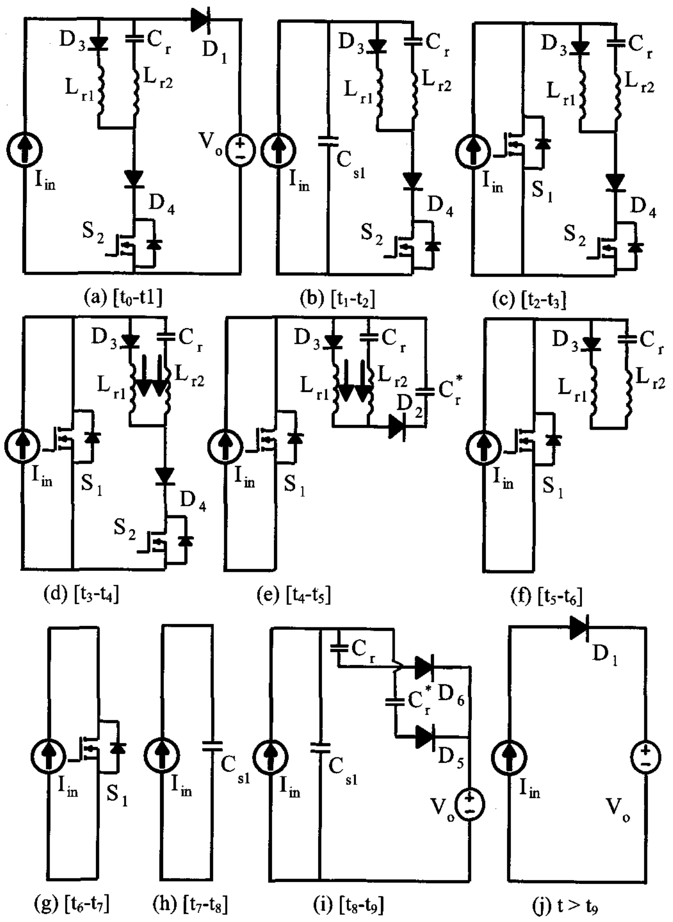


Fig. 15 Modes of operation of a ZVT-PWM boost converter with an off-tuned dual auxiliary circuit

$$i_1 = \frac{V_o}{L_{r_1}} t \tag{6}$$

$$i_2 = C_r \omega_0 V_o \sin(\omega_0 t) \tag{7}$$

where

$$\omega_0 = \frac{1}{\sqrt{L_{r_2} C_r}} \tag{8}$$

Mode 2 (t_1-t_2): At t = t_1, the current flowing through D_1 is zero and the capacitor of the main switch C_{s1} begins to be discharged through the auxiliary circuit. The current through L_{r1} continues to rise during this interval. The current through L_{r2} rises until the voltages across capacitors C_{s1} and C_r become equal, and then starts decreasing. The equations that define this mode are given in equs. (9) to (12):

$$v_{c_s} = L_{r1} \frac{di_1}{dt} \tag{9}$$

$$v_{c_s} = v_{c_r} + L_{r2} \frac{di_2}{dt} \tag{10}$$

$$i_2 = C_r \frac{dv_{c_r}}{dt} \tag{11}$$

$$i_1 + i_2 = I_{in} - C_s \frac{dv_{c_s}}{dt} \tag{12}$$

Equation (13) defines the voltage across the capacitor C_r. The other parameters (i_1, i_2 and v_{C_S}) are defined based on equs. (14) to (16):

$$v_{c_r} = A_1 \cos(\omega_{d_1} t) + B_1 \sin(\omega_{d_1} t) + A_2 \cos(\omega_{d_2} t) + B_2 \sin(\omega_{d_2} t) \tag{13}$$

$$i_2 = C_r \frac{dv_{c_r}}{dt} \tag{14}$$

$$v_{c_s} = v_{c_r} + L_{r2} C_r \frac{d^2 v_{c_r}}{dt^2} \tag{15}$$

$$i_1 = -(C_r + C_s)\frac{dv_{c_r}}{dt} - L_{r2} C_r C_s \frac{d^3 v_{c_r}}{dt^3} \tag{16}$$

where

$$\omega_{d_1} = \sqrt{\frac{\omega_1^2 + \sqrt{\omega_1^4 - 4\omega_2^4}}{2}} \quad (17) \qquad \omega_{d_2} = \sqrt{\frac{\omega_1^2 - \sqrt{\omega_1^4 - 4\omega_2^4}}{2}} \quad (18)$$

and A_1, A_2, B_1, B_2, D_1, D_2, ω_1, and ω_2 are given below

$$\omega_1^2 = \left(\frac{(L_{r1} + L_{r2})C_r + L_{r1} C_S}{L_{r1} L_{r2} C_s C_r} \right) \tag{19}$$

$$\omega_2^4 = \left(\frac{1}{L_{r1} L_{r2} C_s C_r} \right) \tag{20}$$

$$A_1 = \left(\frac{(\omega_{d_2}^2 L_{r2} C_r - 1) v_{c_r}(t_1) + V_o}{(\omega_{d_2}^2 - \omega_{d_1}^2) L_{r2} C_r} \right) \tag{21}$$

$$A_2 = \left(\frac{(\omega_{d_1}^2 L_{r2} C_r - 1) v_{c_r}(t_1) + V_o}{(\omega_{d_1}^2 - \omega_{d_2}^2) L_{r2} C_r} \right) \tag{22}$$

$$B_1 = \left(\frac{\left(\omega_{d_2}^2 - \frac{1}{L_{r2} C_r} \right) I_2(t_1)}{(\omega_{d_2}^2 - \omega_{d_1}^2) \omega_{d_1} C_r} \right) \tag{23}$$

$$B_2 = \left(\frac{\left(\omega_{d_1}^2 - \frac{1}{L_{r2} C_r} \right) I_2(t_1)}{\left(\omega_{d_1}^2 - \omega_{d_2}^2 \right) \omega_{d_2} C_r} \right) \quad (24)$$

Mode 3 (t_2-t_3): C_{s1} is totally discharged at $t = t_2$ and the main switch body-diode begins to conduct as the combined current flowing through both auxiliary circuit branches is greater than the input current I_{in}. The current through L_{r1}, I_{Lr1}, is constant because the voltage across the inductor is zero during this mode. Voltage V_{Cr} continues to increase as current I_{Lr2} passes through it and I_{Lr2} continues decreasing because of the negative voltage across the inductor. While current is flowing through the body-diode of S_1, this switch can be turned on with ZVS. The equations that define this mode are given in equs. (25) to (27):

$$v_{c_r} + L_{r2} \frac{di_2}{dt} = 0 \quad (25)$$

$$L_{r1} \frac{di_1}{dt} = 0 \quad (26)$$

$$i_2 = C_r \frac{dv_{c_r}}{dt} \quad (27)$$

The solutions to the above equations are given below by equs. (28) to (30). The resonant frequency in this mode is given by (31).

$$v_{c_r} = V_{c_r}(t_2)\cos(\omega_0 t) + \frac{I_2(t_2)}{C_r \omega_0}\sin(\omega_0 t) \,(28) \quad i_1 = I_1(t_2) \,(29)$$

$$i_2 = I_2(t_2)\sin(\omega_0 t) - C_r \omega_0 V_{c_r}(t_2)\cos(\omega_0 t) \quad (30)$$

$$\omega_0 = \frac{1}{\sqrt{L_{r2} C_r}} \quad (31)$$

Mode 4 (t_3-t_4): At $t = t_3$, the combined current flowing through both branches of the auxiliary circuit reaches the input current I_{in} as the resonant process that began in Mode 3 continues. This results in current ceasing to flow through the body-diode of S_1 and beginning to flow through the switch itself. Current I_{Lr1} still remains constant because the voltage across it is zero when current is passing through the main switch. Voltage V_{Cr} continues to increase during Mode 4 as current I_{Lr2} continues to decrease. The voltage and current equations associated with this mode of operation are as follows where the resonant frequency was defined in the last mode of operation:

$$v_{c_r} = V_{c_r}(t_3)\cos(\omega_0 t) + \frac{I_2(t_3)}{C_r \omega_0}\sin(\omega_0 t) \quad (32)$$

$$i_1 = I_1(t_2) \quad (33)$$

$$i_2 = I_2(t_3)\sin(\omega_0 t) + C_r \omega_0 V_{c_r}(t_3)\cos(\omega_0 t) \quad (34)$$

Mode 5 (t_4-t_5): At $t = t_4$, the auxiliary switch S_2 is turned off and the current in both auxiliary circuit branches flows through diode D_2 to charge C_r*. The equations associated with this mode are

$$v_{c_r^*} = L_{r1} \frac{di_1}{dt} \quad (35)$$

$$v_{c_r^*} = v_{c_r} + L_{r2} \frac{di_2}{dt} \quad (36)$$

$$i_2 = C_r \frac{dv_{c_r}}{dt} \quad (37)$$

$$i_1 + i_2 + C_r^* \frac{dv_{c_r^*}}{dt} = 0 \quad (38)$$

Equ. (39) defines the voltage across C_r and the equations for the other parameters can be derived from this equation as follows:

$$v_{c_r} = A_1\cos(\omega_{d_1} t) + B_1\sin(\omega_{d_1} t) + A_2\cos(\omega_{d_2} t) + B_2\sin(\omega_{d_2} t) \,(39)$$

$$i_2 = C_r \frac{dv_{c_r}}{dt} \quad (40)$$

$$v_{c_r^*} = v_{c_r} + L_{r2} C_r \frac{d^2 v_{c_r}}{dt^2} \quad (41)$$

$$i_1 = -\left(C_r + C_r^*\right)\frac{dv_{c_r}}{dt} - L_{r2} C_r C_r^* \frac{d^3 v_{c_r}}{dt^3} \quad (42)$$

where

$$\omega_{d_1} = \sqrt{\frac{\omega_1^2 + \sqrt{\omega_1^4 - 4\omega_2^4}}{2}} \tag{43}$$

$$\omega_{d_2} = \sqrt{\frac{\omega_1^2 - \sqrt{\omega_1^4 - 4\omega_2^4}}{2}} \tag{44}$$

$$\omega_1^2 = \left(\frac{(L_{r2} + L_{r1})C_r + L_{r1}C_r^*}{L_{r1}L_{r2}C_r^*C_r}\right) \tag{45}$$

$$\omega_2^4 = \left(\frac{1}{L_{r1}L_{r2}C_r^*C_r}\right) \tag{46}$$

$$A_1 = \left(\frac{\left(\omega_{d_2}^2 L_{r2}C_r - 1\right)V_{c_r}(t_4)}{\left(\omega_{d_2}^2 - \omega_{d_1}^2\right)L_{r2}C_r}\right) \tag{47}$$

$$A_2 = \left(\frac{\left(\omega_{d_1}^2 L_{r2}C_r - 1\right)V_{c_r}(t_4)}{\left(\omega_{d_1}^2 - \omega_{d_2}^2\right)L_{r2}C_r}\right) \tag{48}$$

$$B_1 = \left(\frac{\left(\omega_{d_2}^2 - \frac{1}{L_{r2}C_r}\right)I_2(t_4)}{\left(\omega_{d_2}^2 - \omega_{d_1}^2\right)\omega_{d_1}C_r}\right) - \left(\frac{\frac{I_1(t_2) + I_2(t_4)}{L_{r2}C_r^*}}{\left(\omega_{d_2}^2 - \omega_{d_1}^2\right)\omega_{d_1}C_r}\right) \tag{49}$$

$$B_2 = \left(\frac{\left(\omega_{d_1}^2 - \frac{1}{L_{r2}C_r}\right)I_2(t_4)}{\left(\omega_{d_1}^2 - \omega_{d_2}^2\right)\omega_{d_2}C_r}\right) - \left(\frac{\frac{I_1(t_2) + I_2(t_4)}{L_{r2}C_r^*}}{\left(\omega_{d_1}^2 - \omega_{d_2}^2\right)\omega_{d_2}C_r}\right) \tag{50}$$

Mode 6 (t_5-t_6): At $t=t_5$, current stops flowing through D_2 and C_r*. This is usually because current in the resonant branch has reversed direction and has diverted the non-resonant branch current away from D_2 so that the current flowing "up" the resonant branch is equal to the current flowing "down" the non-resonant branch. A resonant circuit between L_{r1}, L_{r2} and C_r is created and current continues to flow in the auxiliary circuit until the current through L_{r1} and L_{r2} becomes zero. Diode D_3 prevents the current from reversing direction and Capacitor C_r has a negative voltage at the end of this mode. The equations that define this mode are

$$L_{r1}\frac{di_1}{dt} = v_{c_r} + L_{r2}\frac{di_2}{dt} \tag{51}$$

$$i_1 = -i_2 = -C_r\frac{dv_{c_r}}{dt} \tag{52}$$

and they can be solved to give

$$v_{c_r} = V_{c_r}(t_5)\cos(\omega_0 t) + \frac{I_2(t_5)}{C_r\omega_0}\sin(\omega_0 t) \tag{53}$$

$$i_2 = I_2(t_5)\cos(\omega_0 t) - C_r\omega_0 V_{c_r}(t_5)\sin(\omega_0 t) \tag{54}$$

where

$$\omega_0 = \frac{1}{\sqrt{(L_{r1} + L_{r2})C_r}} \tag{55}$$

It should be noted that Mode 6 may be bypassed if Mode 5 ends with the current in each auxiliary branch falling to zero by the end of the Mode, but this rarely happens. It may also be possible for the converter to temporarily slip into Mode 5 if the voltage across C_r is more "negative" than that across C_r*. If this happens, then the converter may slip back and forth between Modes 5 and 6 until current stops flowing in the auxiliary circuit.

Mode 7 (t_6-t_7): At $t=t_6$, current is no longer flowing in the auxiliary circuit. The converter operates in the same way as a standard PWM boost converter during this mode.

Mode 8 (t_7-t_8): At $t = t_7$, the main switch S_1 turns off with ZVS as capacitor C_{s1} slows down the rate of voltage increase as it begins to be charged by I_{in}.

Mode 9 (t_8-t_9): At $t = t_8$, either the sum of V_{Cs1} and V_{Cr} is equal to V_o, which causes D_6 to conduct, or the sum of V_{Cs1} and V_{Cr}* is equal to V_o, which causes D_5 to conduct. Eventually, during this mode, both D_5 and D_6 conduct as both these capacitors are discharged by the input current while C_{s1} is being charged.

Mode 10 ($t>t_9$): At $t=t_9$, C_r and C_r* are both fully discharged and I_{in} starts flowing through D_1. The converter operates like a standard PWM converter until the auxiliary switch is turned on at the start of the next switching cycle.

5. Design of an Off-Tuned Auxiliary Circuit

Simple, experimental prototypes of a PWM boost converter implemented with the non-resonant, resonant, dual and off-tuned auxiliary circuits discussed in this paper were built so that a comparative study of the performance of these converters could be made. In order to show how the off-tuned auxiliary circuit shown in Fig. 14 was designed, a design procedure is presented and demonstrated with a sample in this section of the paper. It is based on an analysis of the steady-state characteristics of the converter, which can be determined from the mode equations derived in Section IV, as shown in [7]. The procedure is iterative and the example shown represents the final iteration. The design of the components of the main power boost converter (i.e. the main boost switch) will not be discussed as it is the same as that of a standard PWM boost converter, nor will that of capacitor C_r* as it is basically a snubber capacitor that has little impact on the operation of the auxiliary circuit.

For the example, the auxiliary circuit is to be designed for a boost converter with the following parameters: L_{in} = 1 mH, S_1 - IRFP460A MOSFET, and D_1 - HFA25TB60 diode. The converter operates according to the following specifications: Input voltage V_{in} = 100 - 250V, output voltage V_o = 400V, maximum output power P_o = 500 W, switching frequency f_{sw}=100 kHz. The value of C_r* is 1.2 nF. The estimated efficiency for this final iteration is η=95%.

The auxiliary circuit should be designed to operate under the worst case operating condition, which is when the input current is at its maximum average value. This occurs at maximum load P_o = 500 W, when the input voltage is at its minimum value, V_{in} = 100 V. The maximum input current can be found from the given specifications and is

$$I_{in} = \frac{P_O}{\eta V_{in}} = \frac{500\,W}{0.95 \cdot 100\,V} = 5.26\ A \tag{56}$$

The auxiliary circuit is activated when the input current waveform is at its lowest point, just before the main switch is to be turned on. Since the input inductor is L_{in} = 1 mH and the duty cycle for a boost converter is:

$$D = \frac{V_o - V_{in}}{V_o} = \frac{400-100}{400} = 0.75 \tag{57}$$

The peak-to-peak input current ripple when V_{in} = 100 V can be determined to be

$$I_{in,p-p} = \frac{V_{in}D}{L_{in}f_{sw}} = \frac{100 \cdot 0.75}{1mH \cdot 100kHz} = 0.75A \tag{58}$$

The auxiliary circuit should designed with V_o = 400 V and I_{in} = 5.26 - (0.5)(0.75) = 4.89 A.

The next step is to determine C_r, L_{r1}, and L_{r2}. Based on an analysis of the auxiliary circuit, performed in previous iterations not shown here, it was determined that selecting either C_r or L_{r2} first would be most useful in limiting the range of values for the other parameters as they are both in the resonant branch, which dominates the initial modes of operation. A value of C_r = 10 nF was determined to be suitable and this narrowed the range of possible sets of L_{r1} and L_{r2} component values to the ones shown in the graphs of steady-state characteristic curves in Fig. 16. The graphs have been plotted using the modal equations in Section IV using the procedure described in [7] and are as follows:

(i) *ZVS time window:* In order for the main power switch S_1 to turn on with ZVS, there must be some window of time during which it can do so. This window can be defined to be the difference between t_a, which is the earliest time when the auxiliary switch can be turned on after the output capacitance of the main switch has been completely discharged, and t_b, which is the latest time that the auxiliary switch can be turned on before this capacitance begins to recharge. This window is at its narrowest at the maximum input current that the converter encounters; if S_1 can be turned on with ZVS under this condition, then it can also be done when the input current is lower. Curves of t_a and t_b vs L_{r2} for various values of L_{r1} are shown in Figs. 16(a) and 16(b).

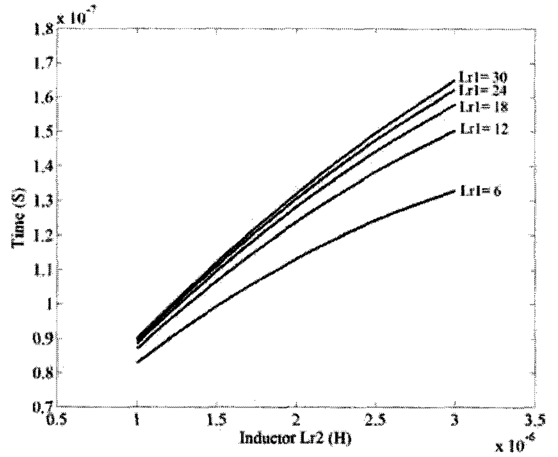
(ii) *Peak auxiliary switch current:* The peak current flowing in the auxiliary circuit should be as small as possible to reduce current stress. This current is most likely to reach its peak sometime during Modes 3 or 4 of operation. Curves of the peak auxiliary switch current $I_{S2,pk}$ vs L_{r2} for various values of L_{r1} are shown in Fig. 17(a).

(iii) *Auxiliary circuit conduction time:* The amount of time that the auxiliary circuit is in operation should be as small as possible to reduce conduction losses due to current circulating in the converter. A measure of this time can be an approximation of the length of time from Mode 1, when S_2 is turned on, to Mode 7, when current stops flowing in the auxiliary circuit, t_6, $t_{0\text{-}6}$.Curves of $t_{0\text{-}6}$ vs L_{r2} for various values of L_{r1} are shown in Fig. 17(b).

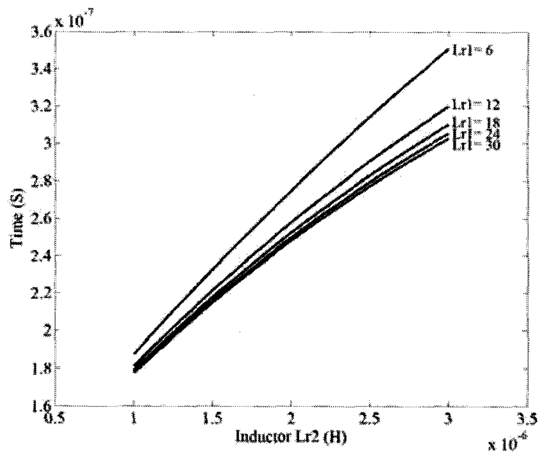
As it is impossible to satisfy all the above criteria, several compromises must be made. For example, although both minimum auxiliary peak current and conduction time are desired, these two parameters are inversely proportional so that minimizing one of these parameters maximizes the other and vice versa. The same relationship is true for the worst-case ZVS time window and the peak switch current - the longer the window, the higher the peak must be and vice versa. Based on the graphs in Fig. 16 and the above-mentioned criteria, L_{r1} = 18 μH and L_{r2} = 2 μH can be used.

6. Experimental Results

The operating conditions of the converters with the non-resonant, resonant, dual and off-tuned auxiliary circuits were input voltage V_{in} = 100 V -250 V, V_o = 400 V, maximum power $P_{o,max}$ = 500 W, switching frequency f_{sw} = 100 kHz. The following components were common to all converters: main switch S_1 - IRFP460, auxiliary switch

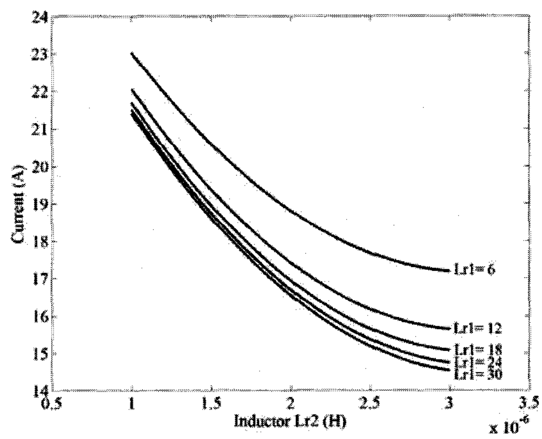


(a)

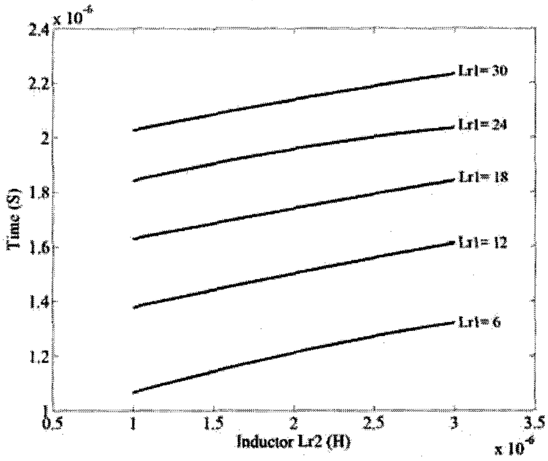


(b)

Fig. 16 Steady-state characteristic curves: (a) S_1 turn-on time t_a vs L_{r2} (b) S_1 turn-on time t_b vs L_{r2}



(a)



(b)

Fig. 17 (a) Peak current through L_{r1} and L_{r2}, $I_{Lr1,pk}$ and $I_{Lr2,pk}$ vs L_{r2} (b) Conduction time t_{Lr1} and t_{Lr2} vs L_{r2}

S_2 - IRF840, boost diode D_1 - HFA25TB60, input inductor L_{in} - 1 mH, and output capacitor C_o - 470μF. All auxiliary circuit diodes were MUR420 devices. The inductor and capacitor values for the non-resonant auxiliary circuit were L_{r1} = 13 μH and C_r = 1.2 nF. The inductor and capacitor values for the resonant auxiliary circuit were L_{r1} = 5.8 μH and C_r = 1.2 nF. The inductor and capacitor values for the dual auxiliary circuit were L_{r1} = 30μH, L_{r2} = 7.5μH, and C_r = 4.4 nF. The inductor and capacitor values for the off-tuned auxiliary circuit were L_{r1} = 18μH, L_{r2} = 2.1μH, C_r = 10.5 nF, and C_r^* = 1.2 nF .

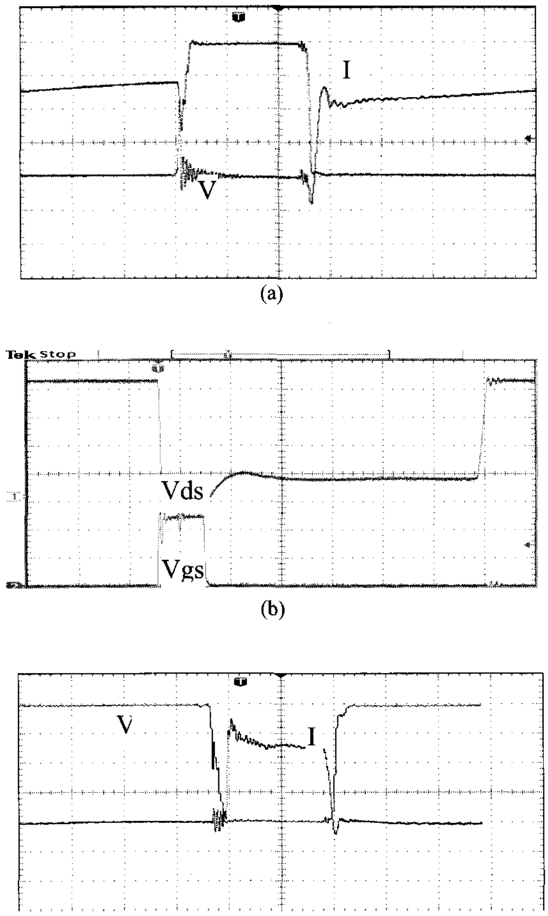
Fig. 18(a) shows typical waveforms of the drain to source voltage V_{ds1} and current I_{s1} of switch S_1. It can be seen that the switch voltage drops to zero and the switch can turn on with ZVS. Fig. 18(b) shows typical waveforms of the drain to source V_{ds2} and the gate to source voltage V_{gs2} of the auxiliary switch S_2. It can be seen that when the switch is turned off, current that was flowing through the switch is transferred to capacitor C_r^* and the voltage across the switch rises slowly as this capacitor is being charged. Fig. 18(c) shows the boost diode waveforms.

Fig. 19 shows the efficiency of the boost converters with the four different auxiliary circuits. It can be seen from Fig. 19 that the off-tuned dual circuit is generally the most efficient circuit. This is because this circuit has the advantages of the non-resonant and resonant circuits, but not the disadvantages. It also operates with less current circulating in it than the dual circuit. The following, more general conclusions can also be made from Fig. 19:

(i) The off-tuned auxiliary circuit (Fig. 14) is an off-tuned version of the dual auxiliary circuit (Fig. 10), which is itself derived from the non-resonant circuit (Fig. 2) and the resonant circuit (Fig. 6). The off-tuned circuit is the most efficient of this set of four circuits. It can, therefore, be stated as a circuit property that if any non-resonant circuit is combined with any resonant circuit to form a dual circuit that is then off-tuned, then the off-tuned circuit will likely be the most efficient of that set of four circuits.

(ii) The improvement in efficiency of the off-tuned circuit compared to the dual circuit is greater when the converter operates under low line, heavy load conditions when the converter is operating with maximum current. Under operating conditions when the converter is operating with little current, the current circulating in the dual circuit will be small so that the conduction losses will be fairly small and the dual circuit may be more efficient.

(iii) It should also be noted that the off-tuned circuit presented in this paper may be less efficient than the circuits belonging to some other, more sophisticated set of resonant, non-resonant, and dual circuits. There are many possible non-resonant and resonant auxiliary circuits that can be combined to form any number of possible dual circuits. The off-tuned circuit presented in this paper is, therefore, not the only



(c)

Fig. 18 Experimental waveforms (a) Main switch voltage V_{ds1} and current I_{s1}, scale (V_{ds1}: 100 V/div, I_{s1}: 2 A/div, 1 μs/div) (b) Auxiliary switch voltage V_{ds2} and gate to source voltage V_{gs2}, scale (V_{ds1}: 100 V/div, V_{gs1}: 10 V/div, 1 μs/div) (c) Main boost diode D_1 voltage V_{D1} and current I_{D1}: (V:100V/div, I:2A/div, 1μs /div V)

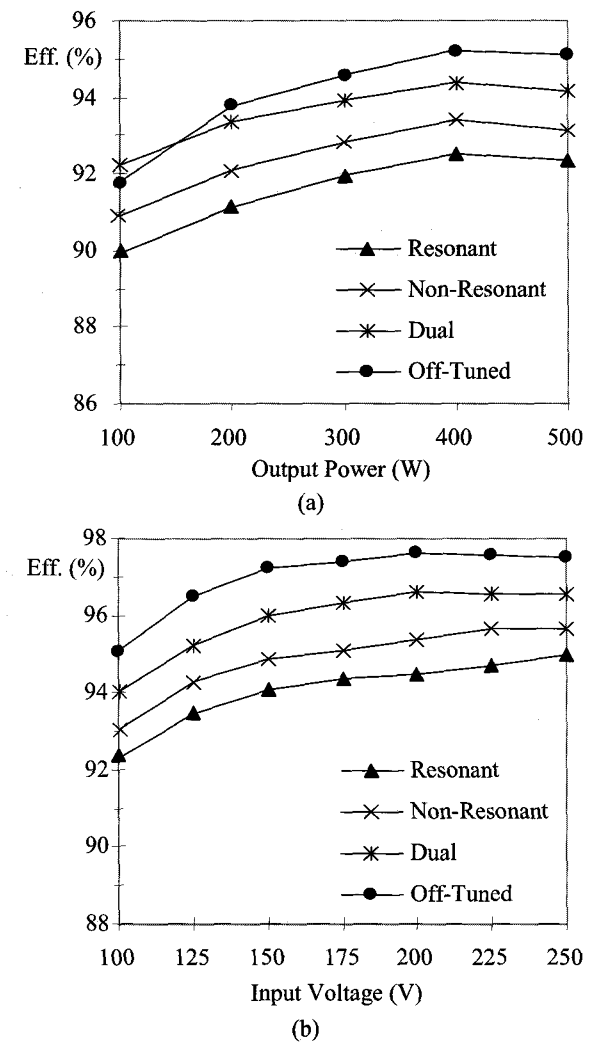


Fig. 19 Converter efficiency (a) Efficiency vs. output power, V_{in} = 100 V. (b) Efficiency vs. input voltage, P_o=500 W

possible circuit of its type and another off-tuned circuit can be derived from a different combination of non-resonant and resonant auxiliary circuits. Regardless of the set of resonant, non-resonant, and dual circuits, the off-tuned circuit derived from the set will likely be the most efficient circuit of the set.

(iv) A corollary of this property would be that any of the dozens of previously proposed non-resonant auxiliary circuits can be made even more efficient if implemented with a resonant branch and then off-tuned, thus decreasing auxiliary circuit switching losses without significantly increasing auxiliary circuit conduction losses. This is especially true for non-resonant circuits as there have been considerably more non-resonant than resonant circuits proposed and off-tuned circuits are considerably more efficient.

(v) The maximum improvement in efficiency of the off-tuned circuit when compared to the dual circuit is shown in Fig. 19. This represents the maximum gain in efficiency that can be achieved with ZVT-PWM converter structures as almost all previously proposed auxiliary circuits are non-resonant, resonant, or dual. It may be possible to achieve higher converter efficiencies, but it would take an approach that is completely different than the ZVT-PWM converter approach that has been studied for many years by power electronics experts. The efficiencies of off-tuned auxiliary circuits are probably the maximum that can be achieved with the ZVT-PWM approach in single-switch PWM converters.

(vi) As a general circuit property, the more components that an auxiliary circuit has, the more efficient it will be, but the more it will cost. It is up to a circuit designer to determine the cost benefits of one type of converter over another for his or her particular application as efficiency may be the most important factor in one application, overriding cost considerations, while cost may be the primary factor in another.

7. Conclusion

Most auxiliary circuits in single switch ZVT-PWM converters are either non-resonant, resonant, or dual. The auxiliary switch in any non-resonant auxiliary circuit turns off with considerable current flowing through it; thus, it has switching losses that partially offset any gains in efficiency due to the reduction of turn-on losses in the main converter switch. The auxiliary switch in any resonant circuit can be made to turn off softly, but at the expense of an increase in conduction losses due to a considerable amount of circulating current flowing in the auxiliary circuit. Moreover, the main switch has a higher peak current stress than that found in conventional PWM converters as it must conduct the circulating current in the auxiliary circuit in addition to the input current. Dual auxiliary circuits combine the advantages of non-resonant and resonant auxiliary circuits so that the auxiliary switch can turn off softly as in resonant auxiliary circuits, but without the main switch peak current stress and with less circulating current. At the present time, dual circuits are the most efficient type of auxiliary circuits.

In this paper, the fundamental circuit principle of "off-tuning" was presented as a way of maximizing the efficiency of auxiliary circuits. The circulating current in dual auxiliary circuits can be reduced even further by "off-tuning" the resonant branch so that there are some auxiliary switch turn-off losses, but less than those found in non-resonant circuits. The paper reviewed the operation of auxiliary circuits in ZVT-PWM converters, and then discussed the properties and characteristics of the new off-tuned type of auxiliary circuits. There are many possible off-tuned auxiliary circuits as there are presently many previously proposed non-resonant and resonant circuits.

Experimental results obtained from 500W, 100 kHz prototype converters confirmed the feasibility of a ZVT-PWM boost converter operating with an experimental off-tuned auxiliary circuit and a comparison was made between the experimental circuit and the original non-resonant, resonant, and dual circuits from which it was derived. Based on this comparison, several general circuit properties were determined. It was concluded that an off-tuned circuit will be the most efficient circuit of the set of non-resonant, resonant, and dual circuits from which it was derived, but it also has the most components. It is up to a circuit designer to determine the cost benefits of one type of converter over another for his or her particular application.

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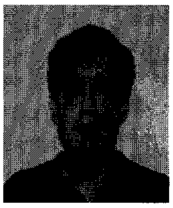

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