A More Accurate ZVS Criterion for Resonant Converters

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***Abstract*—Zero voltage switching (ZVS) is essential at the high-frequency operation of resonant converter and the appropriate ZVS condition needs to be formulated to achieve the soft-switching condition of power MOSFET devices. Conventionally, energy-balance is commonly used ZVS criteria for non-resonant converter, which has been directly applied to the resonant converter without verification. In this paper, the analysis has shown that the conventional energy based ZVS criterion is not so accurate as in the non-resonant case when it comes to the resonant converter. A more accurate ZVS condition using effective inductance energy is proposed in this paper. The analysis is verified by both LTspice simulation and experiment.**

***Index Terms*—Energy-balance, resonant converters, soft-switching, ZVS condition.**

I. Introduction

Nowadays, the power converter is pushed into operation at high frequency to reduce the size of the passive component [1]. Since the switching frequency is limited by loss dissipation during the turn on and off of switches, soft switching is essential in the high-frequency converter to avoid switching losses, reduce electromagnetic interference (EMI) and protect the power devices. Therefore, the resonant converter is widely used for soft switching purposes, and its topology is actively investigated as [2]. Meanwhile, the energy relation is the most common zero-voltage switching (ZVS) criterion that was first adopted in [3] for non-resonant converters. By this criterion, it is known that ZVS is achieved when the total energy in the output capacitor of MOSFET is totally released during the dead time by energy stored in the inductor.

However, most ZVS studies for resonant converters have focused mainly on topology, control, and design. Energy-based criterion are just directly applied to resonant converters without verification [4], [5], [6], [7]. The important question regarding the accuracy of ZVS criterion remains unanswered. To date, no study has specifically investigated on ZVS criterion for the resonant converter.

In the case of resonant converter, the resonant tank has not only the inductor but also the capacitor, which means one more energy storage component exists in the circuit. Therefore, both capacitor and inductor should be considered at the same time in the energy balance process. Moreover, during the ZVS transition, the power dissipation due to the load resistance cannot be ignored.

This study deeply discusses ZVS criterion for the resonant converter. It is found in this paper that the conventional ZVS criterion for the non-resonant cannot be directly used. The new ZVS criterion is proposed including the stored energy in a resonant inductor, capacitor tank, and the dissipation power of load resistance. The accuracy of the proposed ZVS criterion is verified by both LTspice simulation and experiment.

The paper is organized as follows: in Section II, the proposed ZVS condition is presented. The simulation verification is presented in Section III. The experiment result is shown in Section IV. The conclusions are drawn in Section V.

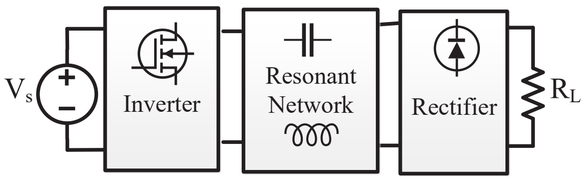


Fig. 1. Typical resonant converter configuration.

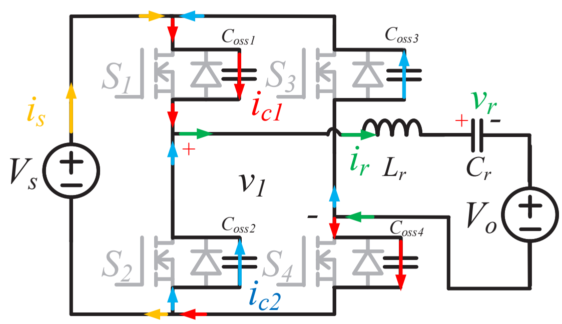
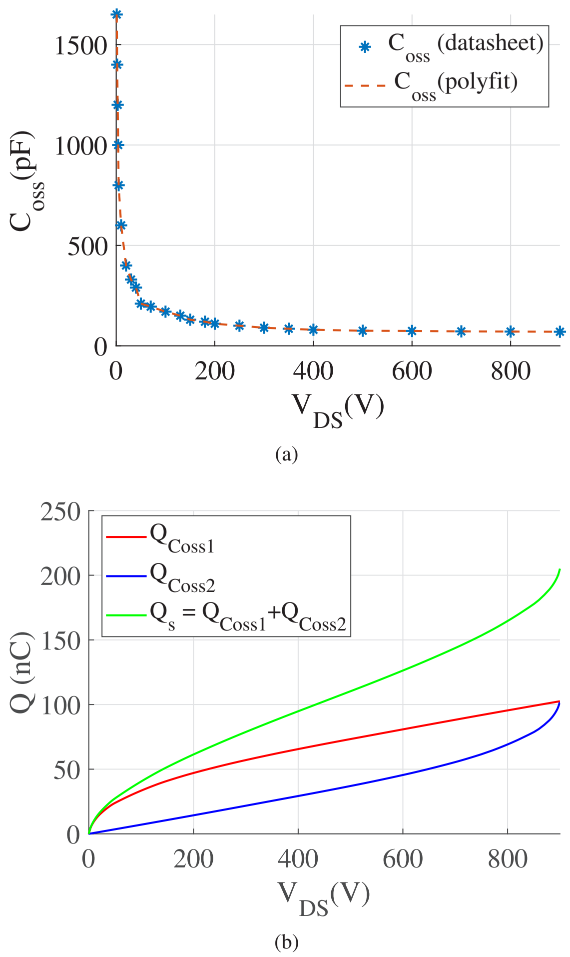


Fig. 2. ZVS equivalent circuit during the dead time ($t_0 \sim t_1$).

II. Proposed ZVS condition

The typical resonant converter system is shown in Fig. 1. Since full-bridge configurations are widely used for inverters and the series resonant network is most common among the resonant network, those configurations are used for analysis in this paper. It should be noted that it is possible to apply the similar procedure to other resonant converters. For the ZVS analysis purpose, the load resistance and diode rectifier are simplified as the output voltage source as shown in Fig. 2.

The operation principle of the resonant converter is presented in [2]. Applying fundamental harmonic approximation,



(a)
(b)

Fig. 3. Nonlinear output capacitance characteristics of the MOSFETs (a) C_{oss} (b) Q_{Coss} for C3M0065090D (CREE).

the first harmonic of the voltage between bridge legs and the current of the resonant tank can be calculated as

$$v_1(t) = \frac{4V_s}{\pi} \cos(\omega_s t) \quad (1)$$

$$i_r(t) = \frac{4V_s}{\pi Z} \cos(\omega_s t + \theta) \quad (2)$$

where ω_s is the frequency angular, θ is the phase difference between the voltage of the inverter and tank current, and Z is the input impedance of the series-resonant network.

Considering the full-bridge with 50% duty, switches S_1 and S_4 are turned on and off at the same time. During the dead time, the output capacitors of switches S_1 and S_2 is charged and discharged, respectively. But, it is well known that the parasitic output capacitance, C_{oss}, of MOSFET is nonlinear with drain-source voltage, V_{DS} [8] as shown in Fig. **??**, where SiC MOSFET (C3M0065090D, CREE) is used as the power switch. The total displacement charge in the circuit during the dead time is the sum of charge stored in the output capacitor of S_1 and charge released in the output capacitor of S_2. Therefore, total equivalent charge Q_s as shown in Fig. **??** (not equal to $2Q_{Coss}$) should be used in the ZVS calculation.

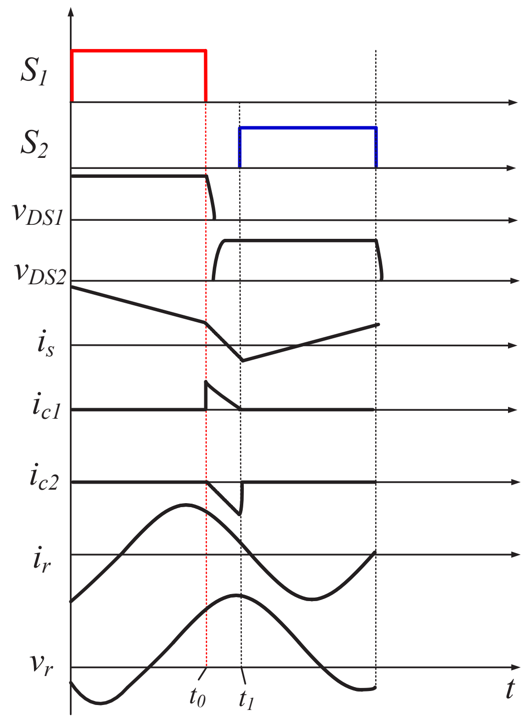


Fig. 4. Key operation waveform.

It should be noted that Q_s is the function of drain-source voltage.

According to the equivalent circuit during the dead time as shown in Fig. 2. The value of source current i_s, and the resonant tank current i_r, can be calculated as

$$i_s = i_{c1} - i_{c2} \quad (3)$$

$$i_r = i_{c1} + i_{c2}. \quad (4)$$

The source current, i_s, is positive at t_0, and then becomes negative when switch capacitor current i_{c_2} is greater than capacitor current i_{c_1} as shown in Fig. 4. Therefore, the supplied and absorbed energy at the source is zero during the ZVS transition. Considering the energy balance equation of the circuit during the dead time as

$$E_{initial} = E_{final} + E_{dissipated} \quad (5)$$

where $E_{initial}$ is the initial energy at $t = t_0$, E_{final} is the final energy at $t = t_1$, and $E_{dissipated}$ is the dissipated energy. The initial energy includes the stored energy in the four output capacitors of MOSFETs, the stored energy in the inductor L_r, and the stored energy in the resonant capacitor C_r. Therefore, the formula of the initial energy can be given by

$$E_{initial} = Q_s(V_s)V_s + \frac{1}{2}L_r i_r^2(t_0) + \frac{1}{2}C_r v_r^2(t_0) \quad (6)$$

Meanwhile, the dissipated energy at the output voltage source can be calculated as

$$E_{dissipated} = Q_s(V_s)V_0. \quad (7)$$

and the final energy of ZVS transition is given by

$$E_{final} = Q_s(V_s)V_s + \frac{1}{2}L_r i_r^2(t_1) + \frac{1}{2}C_r v_r^2(t_1). \quad (8)$$

Then the energy balance equation becomes as

$$\frac{1}{2}L_r i_r^2(t_0) + \frac{1}{2}C_r i_r^2(t_0) = Q_s(V_s)V_0 + \frac{1}{2}L_r i_r^2(t_1) + \frac{1}{2}C_r v_r^2(t_1). \quad (9)$$

Therefore, the minimum energy stored in the resonant tank to achieve ZVS condition under above resonant condition is given by

$$\frac{1}{2}L_e i_r^2(t_0) \geq Q_s(V_s)V_o \quad (10)$$

$$L_e = \frac{1}{\omega_s}\left(\omega_s L_r - \frac{1}{\omega_s C_r}\right) \quad (11)$$

where L_e is the effective inductance of the resonant tank. The value of L_e is always positive, because the switching frequency needs to be above the resonant frequency of the resonant network to achieve the ZVS condition, where the impedance of the tank becomes inductive. The effective inductance is the function of the angular frequency and value of the passive component in the resonant tank, and it is much smaller than the actual value of the inductor in the conventional ZVS formula. When the switching frequency is equal to the resonant frequency, the effective inductance is equal to zero, and the ZVS feature is lost. In addition, the new ZVS formula (10) contains the load side dissipation. Therefore, this formula fully considers all the energy changes during the dead time. It is clear that the stored energy in the resonant inductor, L_r is smaller than is originally expected by the conventional ZVS formula.

III. Simulation Verification

To verify the analysis, the simulation is conducted in LTspice where nonlinear capacitor model in [8] is adopted for MOSFET characteristics shown in Fig. 3. The resonant inductance and capacitance are 2.2 mH and 4.7 nF. The switching frequency, f_s, is set to slightly higher than the resonant frequency of the resonant tank, $f_0 = \frac{1}{\sqrt{L_r C_r}}$, $f_s = 1.03 f_0$. The ZVS condition is tested with the load resistances 150 Ω and 50 Ω. The dc voltage source, V_s, is varied from 50 V to 900 V, which means that the Q_{oss} of MOSFET is also changed due to the change of the V_s.

The calculation has shown that the required value of the resonant inductor current to achieve the ZVS condition is estimated as much larger in the proposed ZVS criterion than in the conventional ZVS criterion, which is illustrated in Fig. 5. When the load resistive is equal to 150 Ω as Fig. 5a, ZVS is not achieved at all ranges of the input voltage. However, the conventional ZVS criterion (blue-dashed line) states that ZVS is achieved. On other hand, the proposed ZVS criterion (solid red line) successfully predicts the failure of ZVS as shown in Fig. 5a. When the load is equal to 50 Ω, circuit simulation shows the switch achieves ZVS in the high V_s region, but cannot achieve ZVS in the low V_s region. The ZVS condition even in that case is accurately predicted by the proposed ZVS criterion as shown in Fig. 5b.

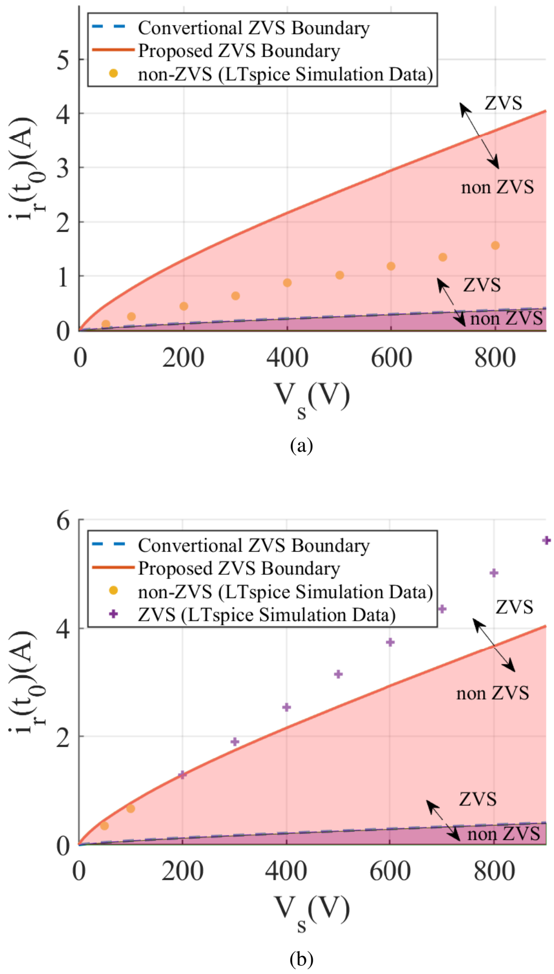


Fig. 5. Simulation results (a) $R_L = 150\ \Omega$ (b) $R_L = 50\ \Omega$.

TABLE I
Experimental parameters

Symbol	Parameters	Values	Unit
V_s	DC Input Voltage	50, 200	V
L_r	Resonant tank inductance	2.2	mH
C_r	Resonant tank capacitance	4.7	nF
R_L	Load resistance	150	Ω
f_0	Resonant frequency	50	kHz
f_s	Switching frequency	$1.03 f_0$	kHz

IV. Experimental Results

To verify the accuracy of the theoretical analysis, the experiment has been made with a full-bridge and series-resonant

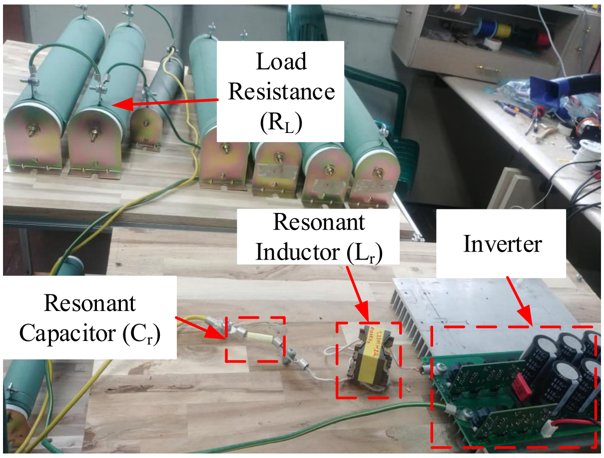


Fig. 6. Experimental setup.

network as shown in Fig. 6. The experimental parameters are shown in Table I. By (11), the value of the effective inductance, L_e, is calculated as 118 μH. Under this condition, the ZVS transition of switch S_2 is analyzed in the experiment.

Firstly, the system is tested under $V_s = 50$ V, where $C_{oss} = 130\ pF$ and $Q_s = 30\ nC$. The initial tank current at ZVS transition is 0.14 A as shown in Fig. 7a. According to (10), the minimum total stored energy in the effective inductor is 1.44 μJ. Therefore, to achieve ZVS, the initial current $i_r(t_0)$ should have been larger than 0.157 A, which states that ZVS will not be achieved. On the contrary, the conventional criterion predicts that only 0.036 A is required to achieve ZVS, and thus it is incorrectly expected that ZVS is achieved. In fact, as shown in Fig. 7a, ZVS failure occurs in S_2 as predicted by the proposed criterion.

Secondly, dc source voltage V_s is set at 200 V, where C_{oss} =100 pF and Q_s = 65 nC. In this condition, the initial tank current at ZVS transition is equal to 0.5 A as shown in Fig. 7b. By the proposed ZVS criterion the minimum total stored energy in the effective inductor should be 12.4 μJ. Therefore, the initial current $i_r(t_0)$ should be greater than 0.45 A to achieve ZVS. As the experimental result shown in Fig. 7b, the ZVS is achieved as expected by the proposed ZVS criterion.

V. CONCLUSION

This paper presents the ZVS condition of resonant converters, which points out that the conventional energy-based ZVS criterion is not accurate. A new ZVS condition that considers not only the effective stored energy in the series resonant tank but also the dissipated energy in the load is proposed. The theoretical analysis is verified with simulation and experiment. In future works, the proposed ZVS criterion will be extended to other popular resonant network such as LLC, LCC, and CLL.

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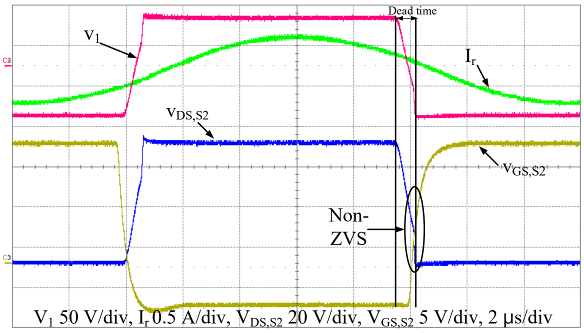
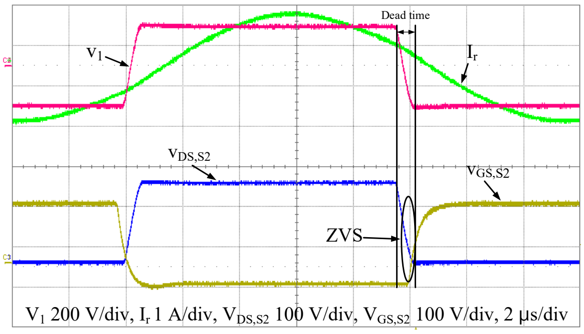


(a)



(b)

Fig. 7. ZVS transition of switch S_2 when (a) $V_s = 50$ V (b) $V_s = 200$ V.

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