

Letters

Direct ZVS Start-Up of a Current-Fed Resonant Inverter

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Abstract—Zero voltage switching (ZVS) is critical for reliable operation of standard current-fed parallel resonant inverters. Under steady-state conditions, ZVS can be achieved using common techniques such as a phase lock loop, a voltage controlled oscillator, and other integral controllers. However, during transient processes, achieving ZVS is not trivial for such controllers and consequently switch failure can occur. This paper proposes a dynamic ZVS method to solve the start-up problems by using a forced dc current. Start-up conditions are analyzed and complete dynamic ZVS control is achieved. If the ramp-up delay of practical dc power supplies is utilized, the start-up process can be controlled to be overshoot-free at no extra cost. The validity of this method is proven using both PSpice simulations and experimental results.

Index Terms—Current-fed inverter, resonant converter, soft switching, zero voltage switching (ZVS).

I. INTRODUCTION

WITH ever increasing concerns about electromagnetic compatibility (EMC) issues, more attention is being paid to resonant converters as they provide better sinusoidal waveforms with lower harmonics. This is particularly important in applications like inductively coupled power transfer (ICPT) where a long coil or track loop is exposed rather than enclosed in a box. Furthermore, resonant converters can make use of natural oscillation to achieve zero voltage switching (ZVS) and/or zero current switching (ZCS) thus eliminating switching losses. As such both higher power-packing densities and conversion efficiencies can be achieved at high switching frequencies without snubbers. Moreover, with a parallel resonant converter, only real power is supplied through the switching devices while reactive power circulates inside the resonant tank, enabling high voltage and current levels to be generated with low conduction losses using low VA rated switching devices.

However, compared with hard-switched pulse width modulation (PWM) converters, resonant converters are more difficult to control and may have a varying switching frequency [1]. Normally PWM switching can be implemented within a designer's predetermined pattern, while switching control of resonant converters must take the circuit's oscillation properties into consideration, adding further constraints [2]. At steady-state, the match between the switching frequency and the circuit oscillation of a resonant converter can be achieved using a phase

lock loop (PLL), a voltage controlled oscillator (VCO), or some other integral controllers, but these controllers cannot cope with fast transient processes such as start-up. Thus, high current or voltage stresses can exist which may cause the switching devices to fail. Consequently, these controllers are only suitable for low-voltage and current converters.

Instantaneous zero-voltage detection is a fast control method for resonant converters. Using this method, Boys *et al.* [3]–[5] successfully generated high frequency track currents for ICPT systems now in use in the materials handling industries. However, even here ZVS is a problem in the first few cycles and a special start-up procedure is required. The common method is to use an oscillator to force the circuit to start up at a low voltage, then change the controller to zero voltage detection control, and finally increase the source voltage as required.

This paper proposes a novel method of achieving dynamic ZVS start-up for a current-fed resonant inverter. The practical ramp-up delay of the dc power supply is considered, and a method of direct on-line overshoot-free start-up at no extra cost is presented.

II. NO ZERO VOLTAGE CROSSING PROBLEM AT START-UP

Fig. 1 shows a typical full-bridge current-fed resonant converter. It has a parallel resonant tank comprising an inductor L and a capacitor C . A dc inductor links the dc power supply E_d and an inverting network consisting of four semiconductor switches. These switches have to be controlled on and off at zero crossing points of the resonant voltage (v_{ac}) to ensure reliable and efficient operation of the inverter. If the switching is premature, i.e., the switch pair ($S1 + /S1-$ or $S2 + /S2-$) is turned on before v_{ac} drops to zero, v_{ac} will be directly shorted through the newly turned on switch pair and the body diodes of the other pair. This can result in dangerously high instantaneous shorting currents, which may cause switch failure. On the other hand, if the switching instant is late, i.e., the switch pair is turned on after v_{ac} crosses zero, the resonant capacitor is shorted, preventing resonance in the following half cycle.

To achieve ZVS, zero crossing points must exist in the resonant voltage. For practical current-fed resonant converters, the dc inductor L_d is much larger than the resonant inductor L , thus under normal steady-state operation the dc current is essentially constant and the switching network injects (approximately) an alternating square-wave load current into the resonant tank. However, on start-up this is not the case as the dc current ramps up gradually. Fig. 2(a) shows a start-up equivalent circuit where only one switch pair ($S1 + /S1-$ in Fig. 1)

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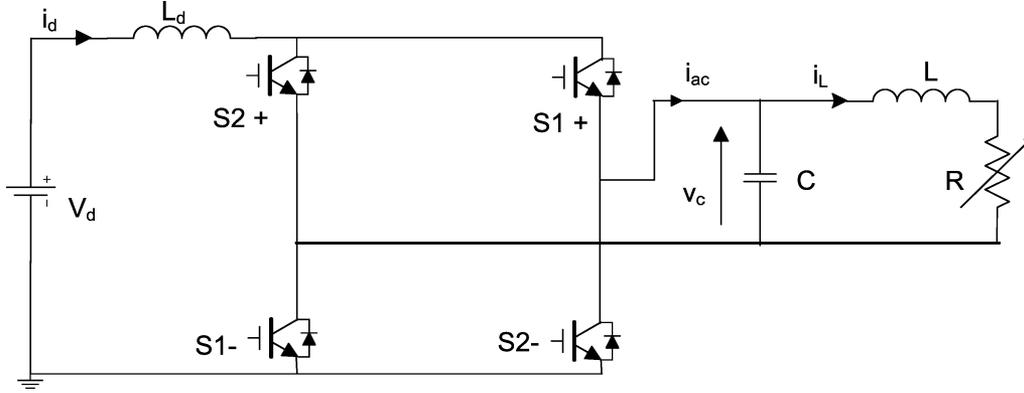


Fig. 1. Basic topology of a current-fed resonant inverter.

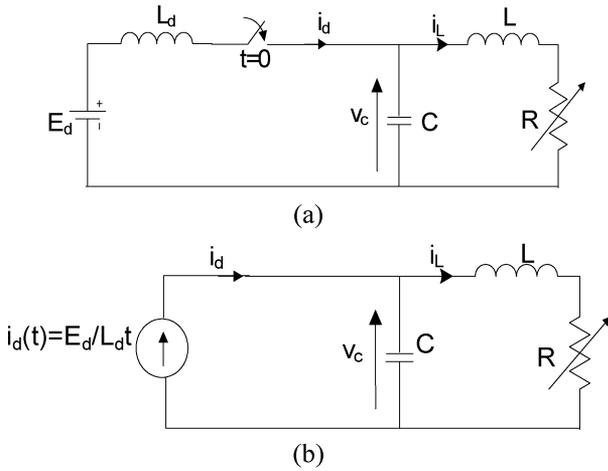


Fig. 2. Equivalent circuit and ramp-current input model. (a) Equivalent circuit and (b) ramp-current input model.

is turned on to start the system. Its state-space equation can be written as

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_L \\ v_c \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_d} \\ 0 & -\frac{R}{L} & \frac{1}{L} \\ \frac{1}{C} & -\frac{1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} \\ 0 \\ 0 \end{bmatrix} E_d. \quad (1)$$

As all the parameters are known, a numerical solution for the resonant voltage $v_c(t)$ can be obtained using available software packages such as MATLAB. But reaching a general conclusion for all situations is not easy. Considering the existence of the large dc inductance and noting that v_c is small at start-up, the injection current actually ramps up almost linearly with a slope of E_d/L_d . This can be modeled as a ramp-up current input into the resonant tank as shown in Fig. 2(b). Thus, a second-order differential equation can be written as

$$LC \frac{d^2 v_c}{dt^2} + RC \frac{dv_c}{dt} + v_c = \frac{E_d}{L_d} Rt + \frac{L}{L_d} E_d. \quad (2)$$

Using the initial conditions $v_c|_{t=0} = 0$ and $dv_c/dt|_{t=0} = 0$ yields

$$v_c(t) = \frac{E_d}{L_d \sin \theta} (L - R^2 C) e^{-\frac{t}{T}} \sin(\omega_f t - \theta) + \frac{E_d}{L_d} Rt + \frac{E_d}{L_d} (L - R^2 C) \quad (3)$$

where ω_f is the natural free-ringing frequency

$$\omega_f = \frac{1}{\omega_0} \sqrt{1 - \left(\frac{1}{2Q}\right)^2} \quad (4)$$

$\omega_0 = 1/\sqrt{LC}$ is the undamped natural frequency, $Q = \omega_0 L/R$ is the circuit quality factor, $t = 2L/R$ is the time constant, and θ is an initial phase angle which can be expressed as

$$\theta = \arctan \frac{\omega_f T (L - R^2 C)}{R(RC - T) - L_d}. \quad (5)$$

Under ideal oscillatory conditions where the equivalent load resistor R is zero, the time constant T infinite, and the initial phase angle $\theta = -90^\circ$, the resonant voltage can be expressed as

$$v_c(t) = \frac{L}{L_d} E_d (1 - \cos \omega_f t). \quad (6)$$

From (6), it is clear that even under ideal conditions where no damping exists, $v_c(t)$ is always greater than or equal to zero. Practical circuit losses or loads damp the oscillation so that zero voltage crossing points do not exist in the real circuit.

III. SOLVING THE START-UP PROBLEM

The inverter start-up problem can be solved if energy is injected into the resonant tank prior to turn-on. Here, either the resonant capacitor needs to have an initial voltage, or the resonant inductor needs an initial current, and system oscillation will then naturally result with zero voltage crossings. To do this, however, requires additional charging circuitry. An alternative option is to give the dc inductor an initial current. If the switches in both legs of Fig. 1 are controlled to be on for a short time labeled " t_1 ," the dc inductor current will ramp up to a certain value $I_d(0)$. If one leg is then switched off, the injection current in Fig. 2(b) will have an initial value $I_d(0)$. Provided $I_d(0)$ is much greater than the current increase ΔI_d in the first half cycle of the oscillation, the starting process is approximately equivalent to a step-current input response. Thus (2) becomes

$$LC \frac{d^2 v_c}{dt^2} + RC \frac{dv_c}{dt} + v_c = I_d(0)R. \quad (7)$$

And the complete solution of v_c becomes

$$v_c(t) = \frac{I_d(0)R}{\sin\theta} e^{-\frac{t}{T}} \sin(\omega_f t - \theta) + I_d(0)R \quad (8)$$

where the initial phase angle is

$$\theta = \arctan \frac{\omega_f RC}{1 - \frac{RC}{T}}. \quad (9)$$

Under ideal oscillation conditions with an equivalent load resistor of zero, time constant T , infinity, and initial phase angle $\theta = 0$, the resonant voltage can be expressed as

$$v_c(t) = \frac{I_d(0)}{\omega_f C} \sin(\omega_f t). \quad (10)$$

Comparing (10) with (6), it can be seen that under ideal undamped conditions, the ramp-up current injection and the step-input current injection have quite different oscillation properties. The former oscillates above zero with a dc offset E_d , while the latter oscillates around zero with the necessary zero voltage instants.

IV. ZERO VOLTAGE CROSSING CONDITION ANALYSIS

There are several factors that make zero voltage difficult to achieve. The first obvious factor is that the injection current is a step input plus a ramp-up input rather than a pure step input. However, if the initial current $I_{d(0)}$ is much larger than the current increase ΔI_d in the first half-switching cycle, then this effect will be very small.

Another factor worthy of special concern is the effect of the load. For a given system at a certain frequency, a heavier load means a lower Q . In order to achieve zero voltage crossing, a minimum requirement from (4) is that the quality factor Q be larger than 0.5 (note that the condition for zero phase angle resonance is $Q > 1$), otherwise, the circuit does not oscillate and ZVS is impossible. Furthermore, (8) shows that the complete voltage solution includes two parts: a decaying natural oscillatory component and a forced dc component. Even with $Q > 0.5$, the dc component may cause the nonexistence of zero crossing. The minimum voltage can be found to occur at

$$\omega_f t_{\min} = \arctan(\omega t) + \pi + \theta \quad (11)$$

and the corresponding minimum voltage at this point can be expressed as

$$v_{c\min} = -I_d(0)RQe^{-\frac{t_{\min}}{T}} + I_d(0)R. \quad (12)$$

Thus, to guarantee $v_{c\min}$ is less than zero, the following condition should be met:

$$e^{-\frac{t_{\min}}{T}} > \frac{1}{Q}. \quad (13)$$

Equation (13) indicates that zero voltage crossing is guaranteed during start-up, providing the time constant T is large

enough to keep the percentage of the voltage decay smaller than $1 - 1/Q$ before reaching its minimum value.

Considering the relationship $\omega_0 t = 2Q$, and the fact that the minimum voltage time t_{\min} occurs approximately at $(3\pi/2)/\omega_f \approx (3\pi/2)/\omega_0$, then the condition shown in (13) can be rewritten as

$$Q \ln Q > \frac{3\pi}{4}. \quad (14)$$

It is easy to solve the above equation numerically resulting in the following requirement for Q :

$$Q > 2.54. \quad (15)$$

This is not a difficult condition to meet as a design normally would have $Q > 3$ to keep the resonant current and frequency approximately constant as the load varies [5]. In applications of magnetically coupled loads such as ICPT, the resonant track current builds slowly at start-up so that the equivalent dynamic load of the pick-ups is very small. Therefore ZVS start-up should not be a problem even under heavy loads.

V. SIMULATION AND EXPERIMENTAL RESULTS

Fig. 3(a) shows a typical PSpice simulation for a resonant inverter with the data shown in Table I. Here the dc supply E_d is assumed to be a step input while the switches in both legs S1 and S2 are controlled to be on for a period of 200 μ s (which is much larger than half the switching period of about 50 μ s) to boost an initial dc current. Following this, S2 is switched off while S1 remains on, and the resonant voltage magnitude oscillates around zero allowing normal zero voltage detection control schemes to be employed. Fig. 3(a) shows that ZVS is completely achieved but there are voltage and current overshoots.

For normal dc power supplies, at start-up the output voltage is not a pure step input but ramps up slowly due to switch-on delays. In Fig. 3(b), the parameters in Table I are used but E_d is replaced with a ramp-up time of 2 ms. It can be seen that if the converter is started at $t_0 = 0.5$ ms when E_d is much less than its maximum value, the start-up overshoot can be contained or eliminated.

Practical ramping times for E_d can be very long. The measured delay of a typical regulated dc power supply with a manual switch is about 100 to 150 ms. Fig. 4 shows typical experimental results of the resonant voltage and dc current waveforms at start-up and at steady-state. It can be seen that in addition to dynamic ZVS, complete overshoot-free operation is achieved.

With this technique, the controller design can be very simple. The major points of concern are the selection of t_0 to set the initial E_d , and the pre-energizing period t_1 to determine the initial dc current $I_{d(0)}$. None of these is critical because of the slow changes in E_d . Normal timing control or comparative threshold control can be employed for implementation.

VI. CONCLUSION

A complete dynamic analysis of the first half cycle of a current-fed parallel resonant inverter has shown that zero voltage crossing points do not naturally exist, making ZVS impossible under a normal oscillatory startup process. A dynamic ZVS start-up method using a forced dc current was proposed and verified using PSpice simulations and experimental results. The

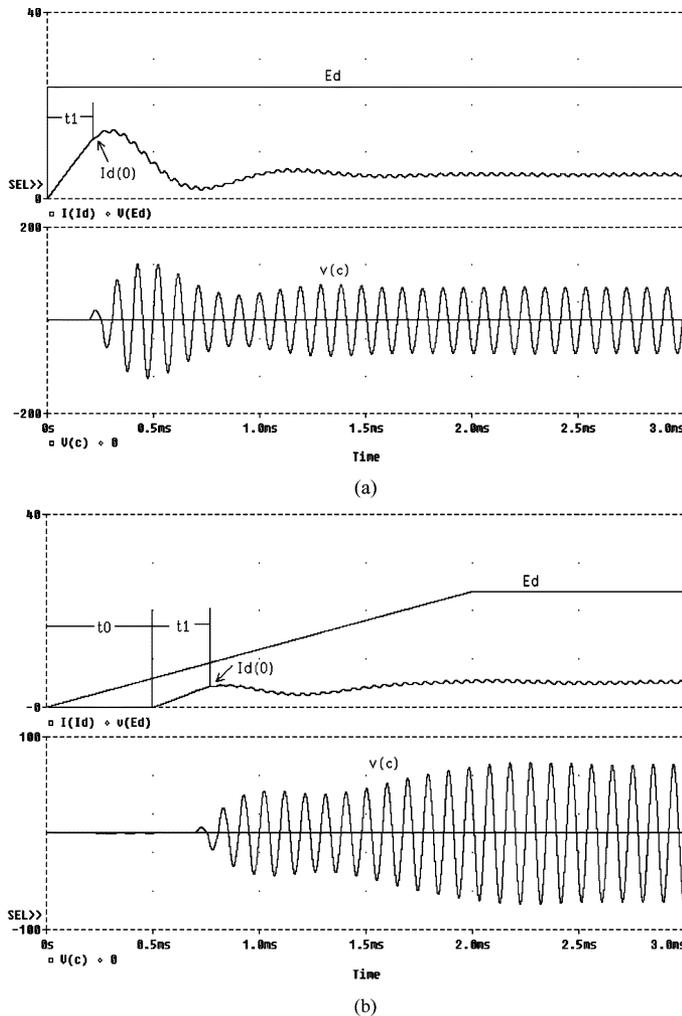


Fig. 3. PSpice simulation results of ZVS start-up: (a) step-input dc supply and (b) ramp dc power supply.

TABLE I
CONVERTER DATA

Inductor L	50 μ H
Capacitor C	4.5 μ F
dc inductor L_d	200 μ H
dc power supply E_d	24V
Undamped natural frequency f_0	10kHz
Load resistor R	0.5 Ω
Quality factor Q	6.28

conditions for ZVS were discussed, and it was found that the maximum equivalent load for ZVS at start-up corresponds to a quality factor Q of about 2.54. Furthermore, the ramp-up delay of a practical dc power supply can be advantageously utilized to achieve a completely direct, on-line, overshoot-free start-up by turning on the inverter at a lower dc voltage level. Compared with traditional start-up methods, this approach improves

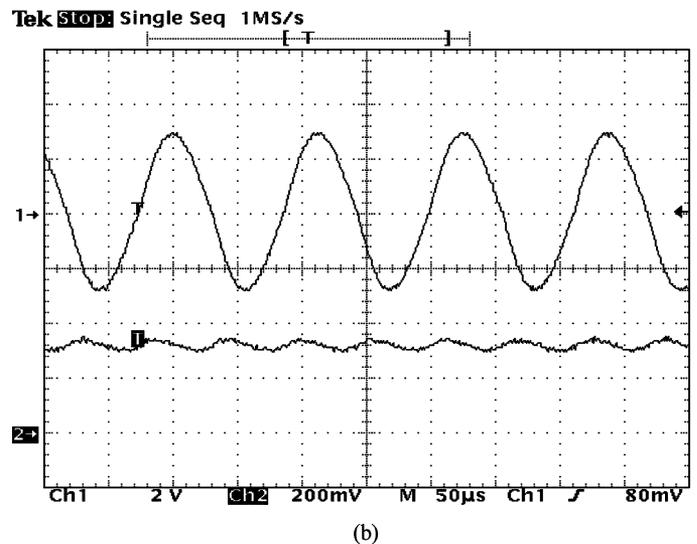
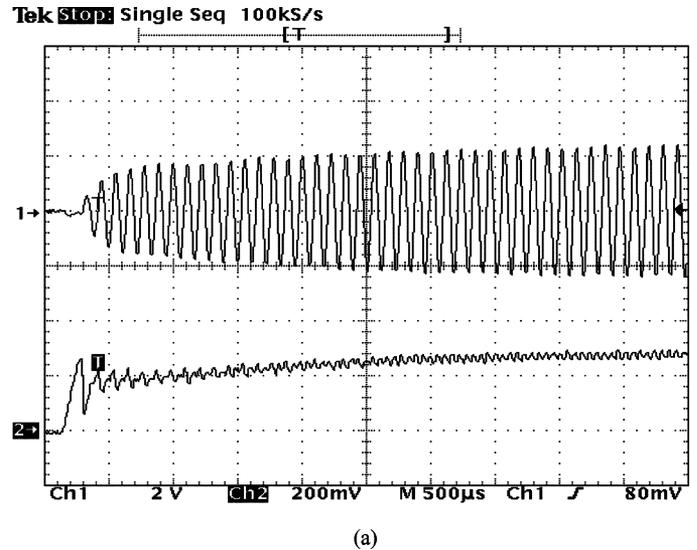


Fig. 4. Experimental results: (a) start-up resonant voltage v_c (trace 1-upper) and dc current I_d (trace 2) and (b) steady-state resonant voltage v_c (trace 1-upper) and I_d current id (trace 2).

system reliability, is very simple to implement, and requires no additional hardware.

REFERENCES

- [1] S. S. Ang, *Power-Switching Converters*. New York: Marcel Dekker, 1995, ch. 3.
- [2] M. K. Kazimierzczuk and D. Czarkowski, *Resonant Power Converters*. New York: Wiley, 1995, ch. 1, 2.
- [3] A. W. Green and J. T. Boys, "An inductively coupled high frequency power system for material handling applications," in *Proc. Int. Power Eng. Conf.*, 1993, pp. 821–826.
- [4] J. T. Boys, G. A. Covic, and A. W. Green, "Stability and control of inductively coupled power transfer system," *Proc. Inst. Elect. Eng.*, vol. 147, no. 1, pp. 37–43, Jan. 2000.
- [5] J. T. Boys and A. W. Green, "Inductively coupled power transmission—concept, design and application," *Trans. Inst. Prof. Eng. New Zealand*, vol. 22, pp. 1–9, 1995.