Hacettepe University
Electrical and Electronics Engineering Department

ELE 789
Special Topics in Electrical and Electronics Engineering

Lecture Notes
Chapter V

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V. SOFT SWITCHING METHODS

SOFT SWITCHING METHODS IN SMPS

5.1. Comparison of Hard vs Soft Switching

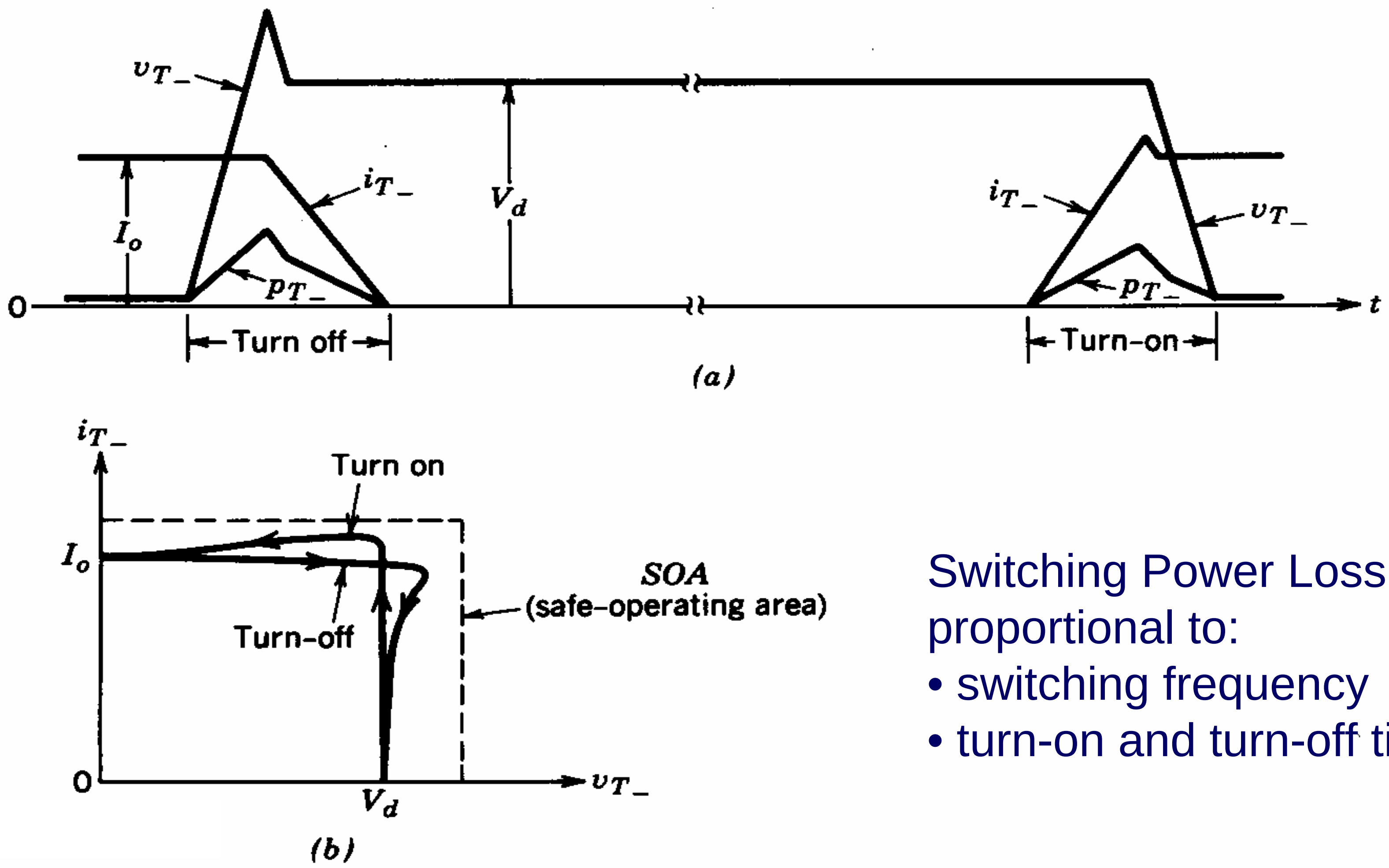
5.2. Zero-voltage, zero-current switchings

Basic Quasi-Resonant Topologies

5.3. Resonant Switch Converter Operation

Hard Switching Waveforms

5.1. Comparison of Hard vs Soft Switching

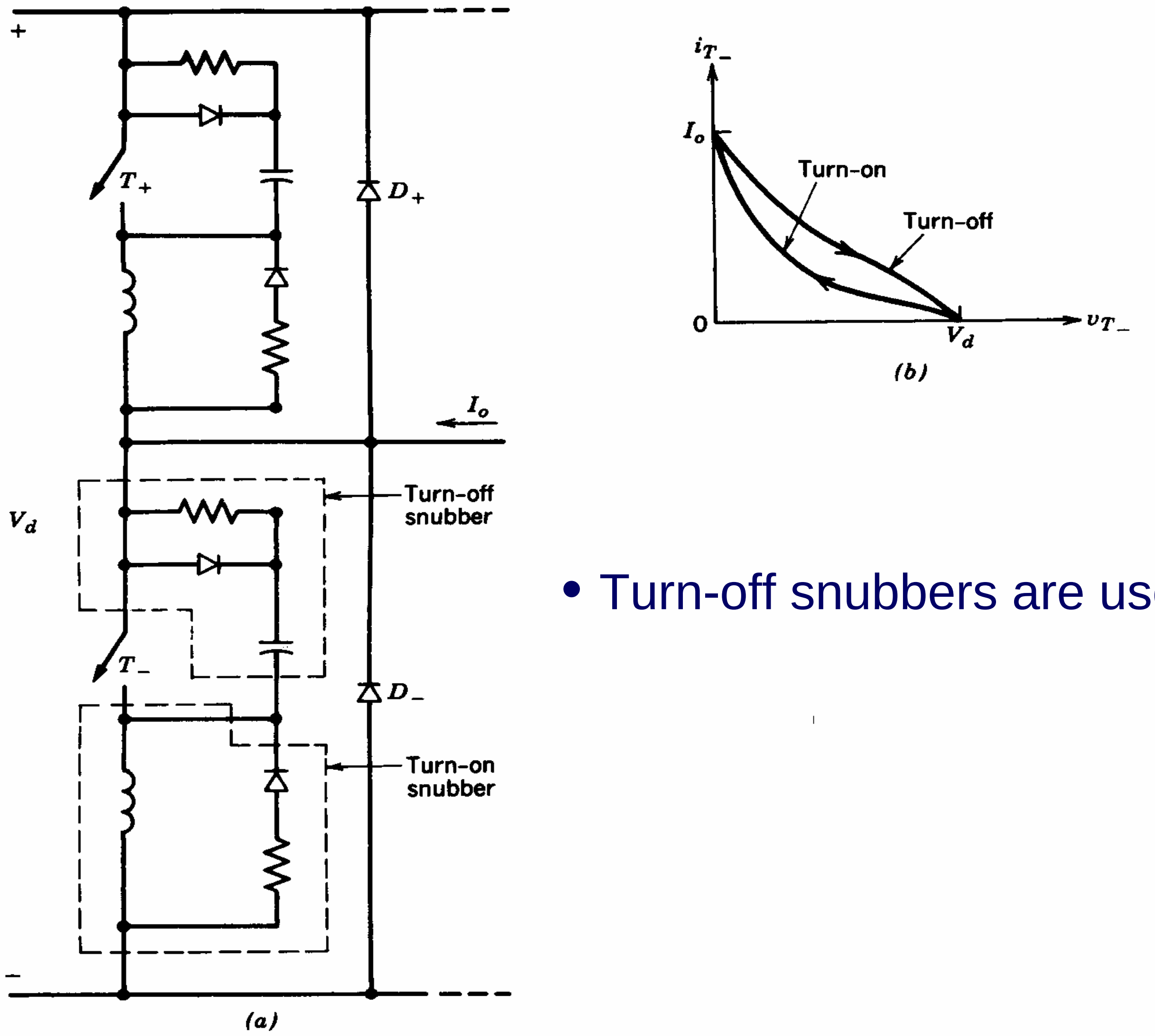


Switch-mode inductive current switchings.

Switching Power Loss is proportional to:

- switching frequency
- turn-on and turn-off times

Turn-on and Turn-off Snubbers



Dissipative snubbers: (*a*) snubber circuits; (*b*) switching loci with snubbers.

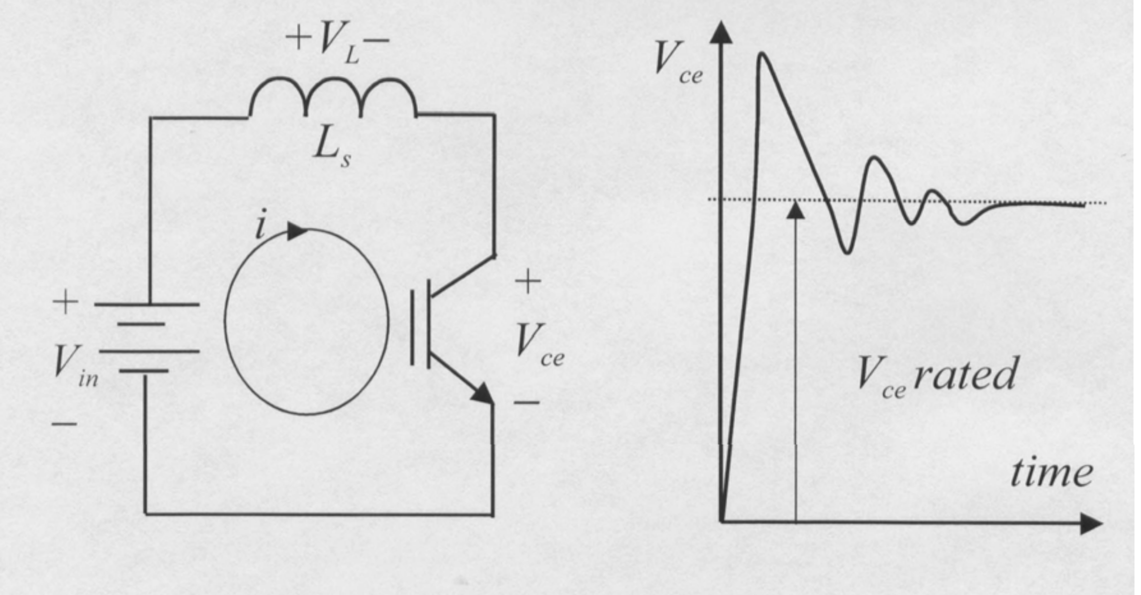
- Turn-off snubbers are used

SNUBBERS

The voltage across the switch is higher than the supply voltage for a short moment, due to stray inductances. The spike may exceed the switch rated blocking voltage, may cause overvoltage damage.

During turn-off:

$$V_{ce} = V_{in} - L_s \, di/dt$$



Simple switch at turn off

SNUBBERS

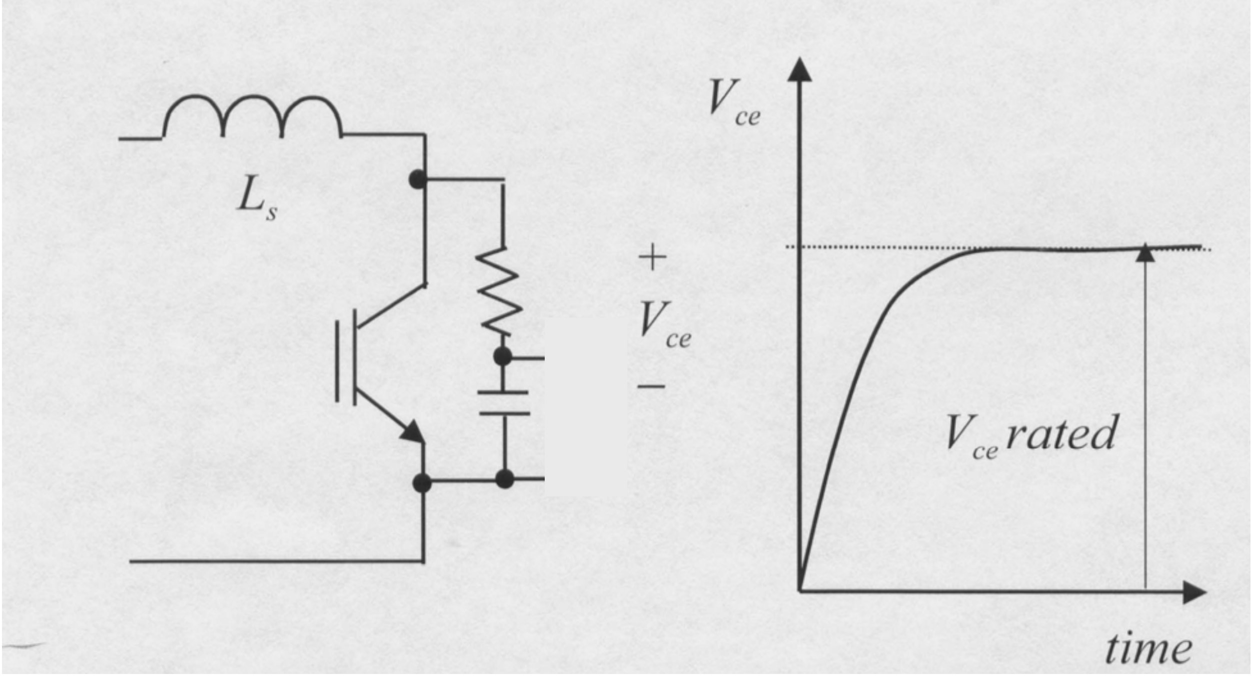
The peak voltage rating of a semiconductor used in a particular application must be greater than the peak voltage during its operation.

In practice, a device experiencing a peak off-state voltage of 500 V would be selected to have a rating between 750 V and 1000V, giving a safety factor of 1.5 to 2.

Voltage transients having high dv/dt values (due to switchings within the converter, coming from the supply side due to contactor switching, lightning etc.) are limited by means of R-C circuits referred as 'snubber circuits'.

SNUBBERS

To prevent high dv/dt , a snubber is put accross the switch. An example of RC snubber is shown below. Snubber circuit smoothens the transition, and makes the switch voltage rise more slowly. It dampens the high voltage spikes to a safe value. Most switches require snubbers, except new generation ones such as the IGBT.



SNUBBERS

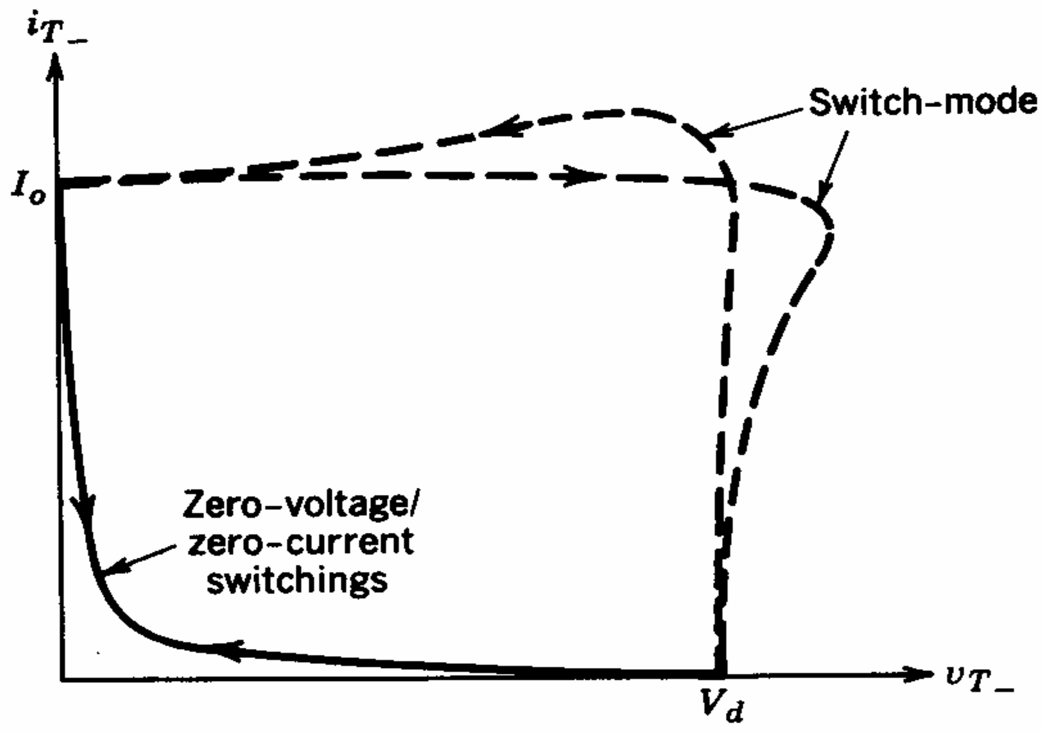
In General, Snubbers are used for

- Turn-off, to minimize large overvoltages across the device during turn-off.

-Turn-on, to minimize large over-currents through the device at turn-on (e.g. against high di/dt due to discharge of C into the thyristor)

- Stress reduction, to shape the device switching waveform, such that device voltage, and current are not simultaneously high.

Switching Trajectories



- Comparison of Hard versus soft switching

V. SOFT SWITCHING METHODS

5.2. Zero-voltage, zero-current switchings
Basic Quasi Resonant Topologies

Quasi–Resonant Topologies

A quasi–resonant topology is designed to reduce or eliminate the frequency–dependent switching losses within the power switches and rectifiers. Switching losses account for about 40% of the total loss within a PWM power supply and are proportional to the switching frequency. Eliminating these losses allows the designer to increase the operating frequency of the switching power supply and so use smaller inductors and capacitors, reducing size and weight. In addition, RFI levels are reduced due to the controlled rate of change of current or voltage.

The downside to quasi–resonant designs is that they are more complex than non–resonant topologies due to parasitic RF effects that must be considered when switching frequencies are in the 100's of kHz.

Schematically, quasi–resonant topologies are minor modifications of the standard PWM topologies. A resonant tank circuit is added to the power switch section to make either the current or the voltage "ring" through a half a sinusoid waveform. Since the sinusoid starts at zero and ends at zero, the product of the voltage and current at the starting and ending points is zero, thus has no switching loss.

There are two quasi–resonant methods: zero current switching (ZCS) or zero voltage switching (ZVS). ZCS is a fixed on–time, variable off–time method of control. ZCS starts from an initial condition where the power switch is off and no current is flowing through the resonant inductor.

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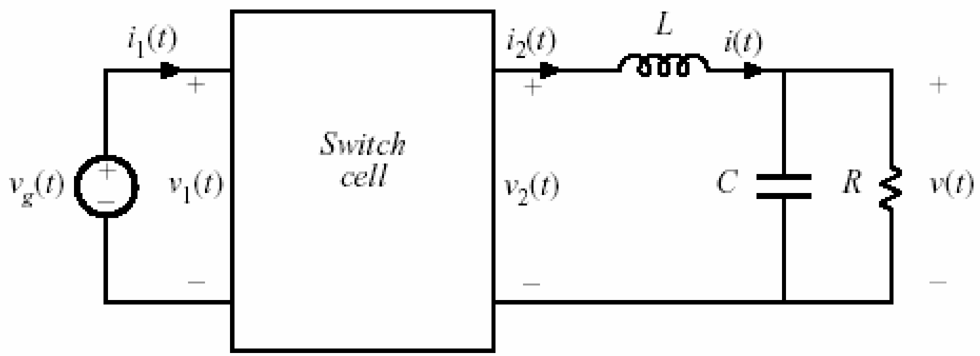
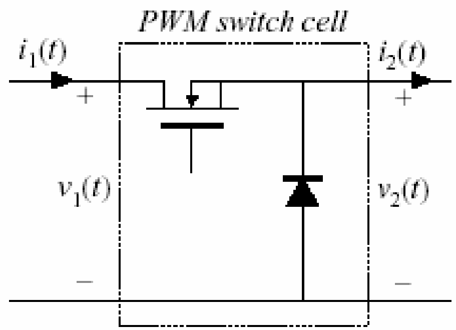
The resonant switch concept

A quite general idea:

1. PWM switch network is replaced by a resonant switch network
2. This leads to a quasi-resonant version of the original PWM converter

Example: realization of the switch cell in the buck converter





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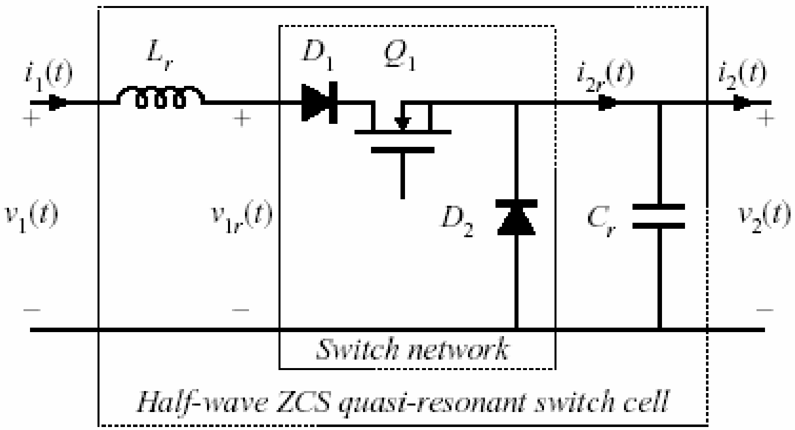
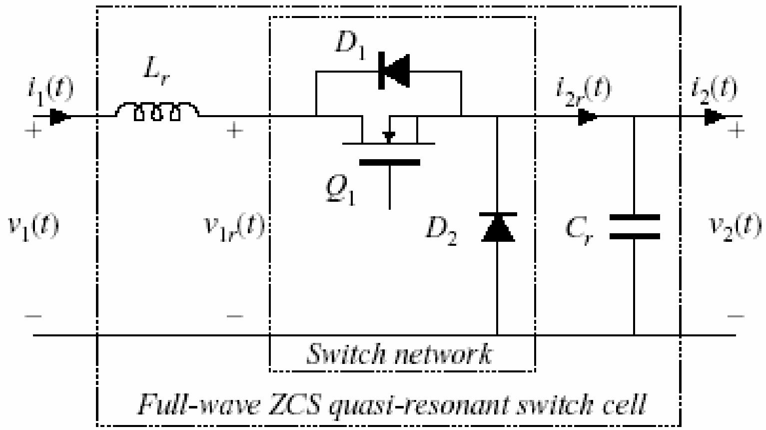
Two quasi-resonant switch cells



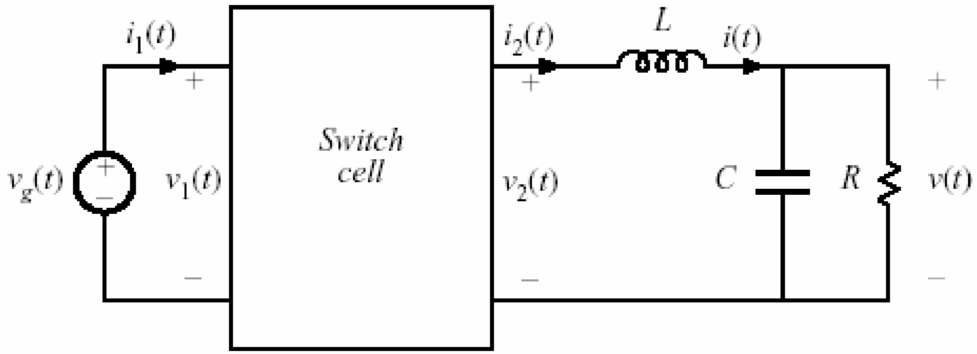
Half-wave ZCS quasi-resonant switch cell



Full-wave ZCS quasi-resonant switch cell

Insert either of the above switch cells into the buck converter, to obtain a ZCS quasi-resonant version of the buck converter. L_r and C_r are small in value, and their resonant frequency f_0 is greater than the switching frequency f_s.

$$f_0 = \frac{1}{2\pi\sqrt{L_r C_r}} = \frac{\omega_0}{2\pi}$$



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The zero-current-switching quasi-resonant switch cell

Tank inductor L_r in series with transistor: transistor switches at zero crossings of inductor current waveform

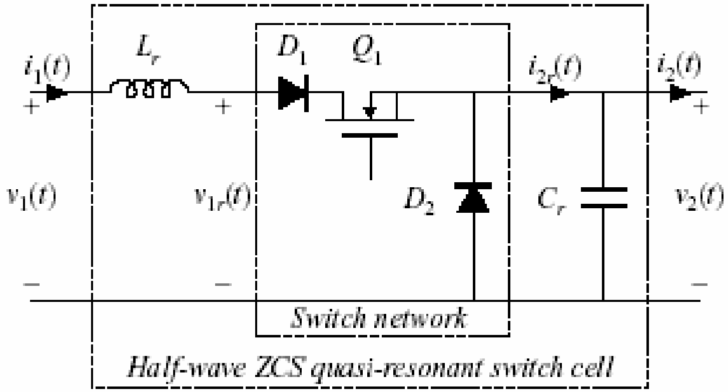
Tank capacitor C_r in parallel with diode D_2 : diode switches at zero crossings of capacitor voltage waveform

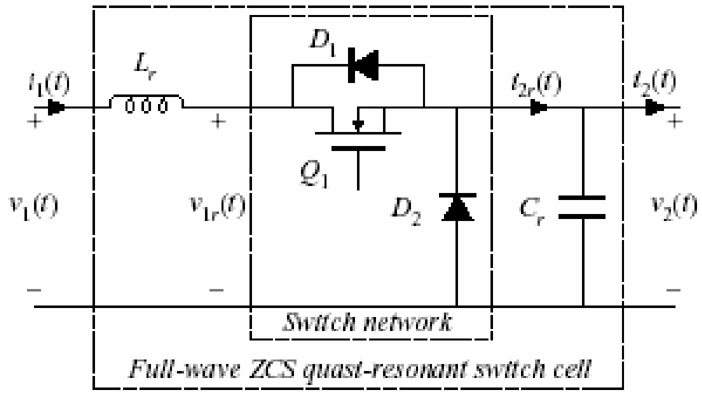
Two-quadrant switch is required:

> *Half-wave:* Q_1 and D_1 in series, transistor turns off at first zero crossing of current waveform

> *Full-wave:* Q_1 and D_1 in parallel, transistor turns off at second zero crossing of current waveform

Performances of half-wave and full-wave cells differ significantly.





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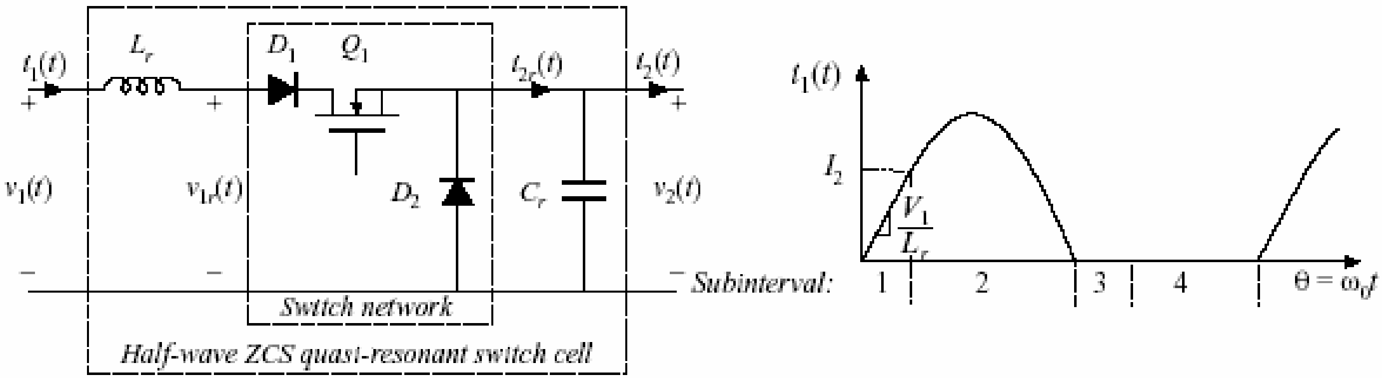
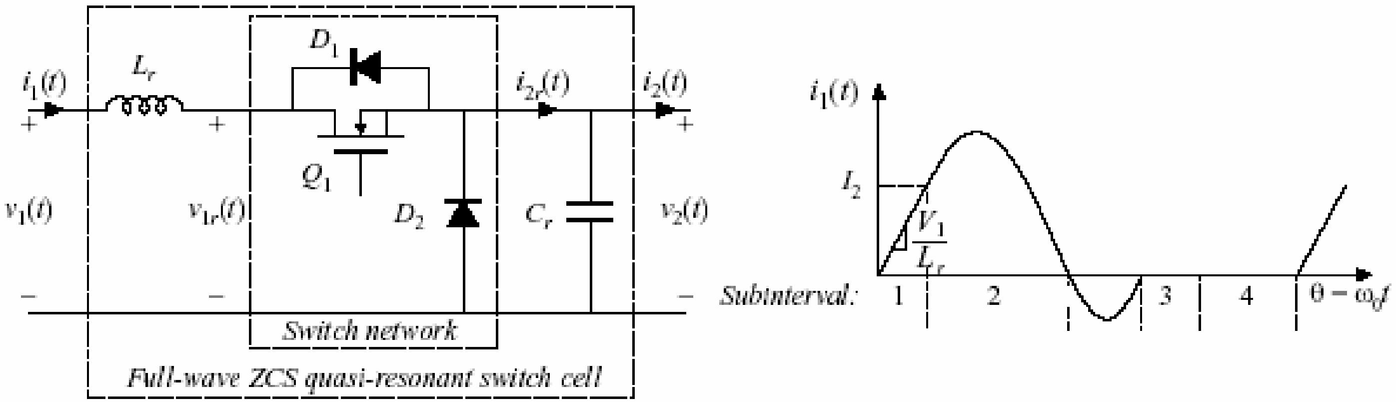
The full-wave ZCS quasi-resonant switch cell

Half wave



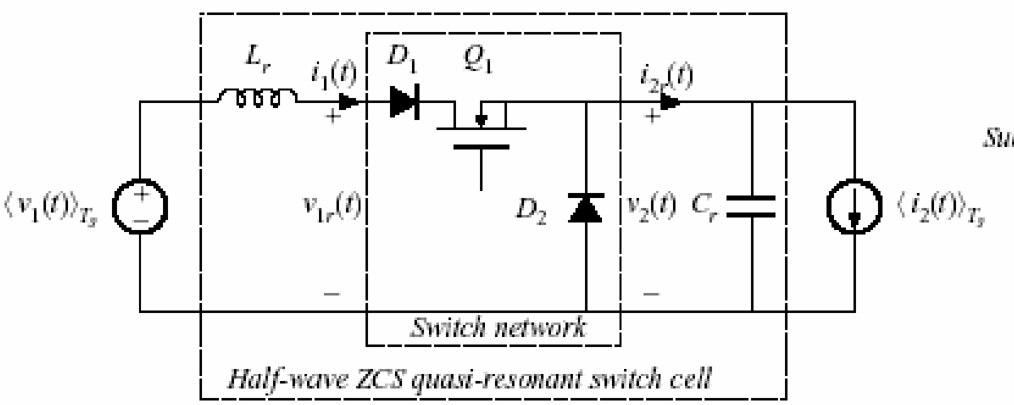
Full wave



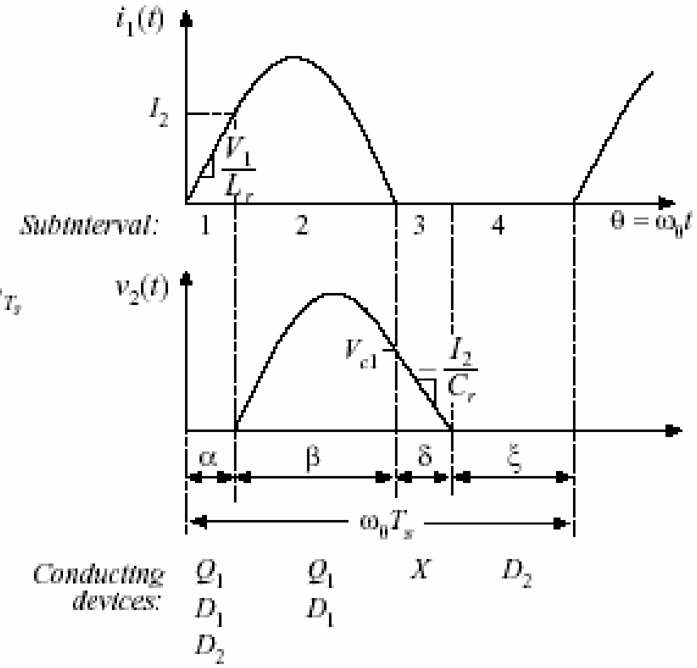
V. SOFT SWITCHING METHODS

Waveforms of the half-wave ZCS quasi-resonant switch cell

The half-wave ZCS quasi-resonant switch cell, driven by the terminal quantities $\langle v_1(t) \rangle_{Ts}$ and $\langle i_2(t) \rangle_{Ts}$.



Waveforms:



Each switching period contains four subintervals

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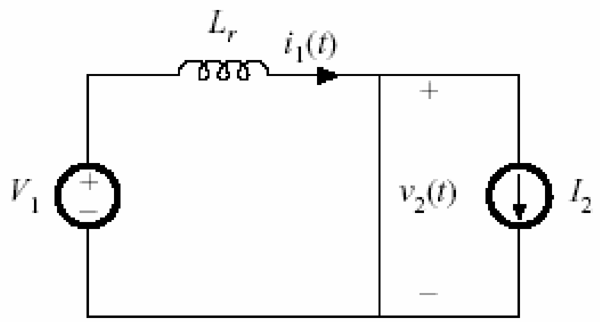
Subinterval 1

Diode D_2 is initially conducting the filter inductor current I_2. Transistor Q_1 turns on, and the tank inductor current i_1 starts to increase. So all semiconductor devices conduct during this subinterval, and the circuit reduces to:



Circuit equations:

$$\frac{di_1(t)}{dt} = \frac{V_1}{L_r} \qquad \text{with } i_1(0) = 0$$

Solution: $$i_1(t) = \frac{V_1}{L_r}\, t = \omega_0 t\, \frac{V_1}{R_0}$$

where $$R_0 = \sqrt{\frac{L_r}{C_r}}$$

This subinterval ends when diode D_2 becomes reverse-biased. This occurs at time $\omega_0 t = \alpha$, when $i_1(t) = I_2$.

$$i_1(\alpha) = \alpha\, \frac{V_1}{R_0} = I_2 \qquad \alpha = \frac{I_2 R_0}{V_1}$$

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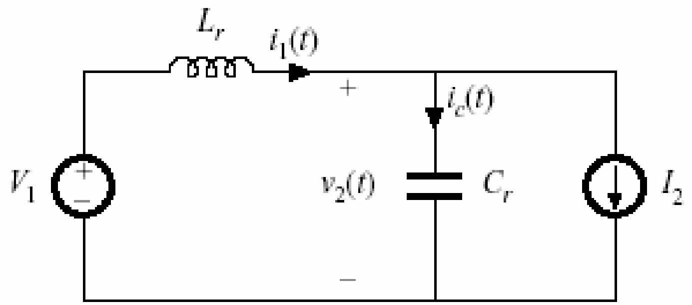
Subinterval 2

Diode D_2 is off. Transistor Q_1 conducts, and the tank inductor and tank capacitor ring sinusoidally. The circuit reduces to:



The circuit equations are

$$L_r \frac{di_1(\omega_0 t)}{dt} = V_1 - v_2(\omega_0 t) \qquad v_2(\alpha) = 0$$

$$C_r \frac{dv_2(\omega_0 t)}{dt} = i_1(\omega_0 t) - I_2 \qquad i_1(\alpha) = I_2$$

The solution is

$$i_1(\omega_0 t) = I_2 + \frac{V_1}{R_0} \sin\left(\omega_0 t - \alpha\right)$$

$$v_2(\omega_0 t) = V_1\left(1 - \cos\left(\omega_0 t - \alpha\right)\right)$$

The dc components of these waveforms are the dc solution of the circuit, while the sinusoidal components have magnitudes that depend on the initial conditions and on the characteristic impedance R_0.

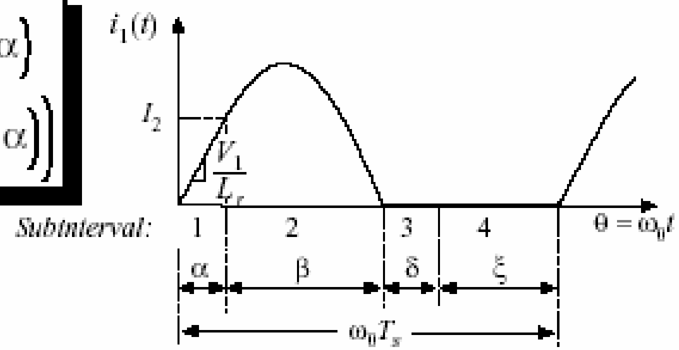
V. SOFT SWITCHING METHODS

Subinterval 2
continued

Peak inductor current:

$$I_{1pk} = I_2 + \frac{V_1}{R_0}$$

$$\boxed{\begin{aligned} i_1(\omega_0 t) &= I_2 + \frac{V_1}{R_0}\sin\left(\omega_0 t - \alpha\right) \\ v_2(\omega_0 t) &= V_1\left(1 - \cos\left(\omega_0 t - \alpha\right)\right) \end{aligned}}$$



This subinterval ends at the first zero crossing of $i_1(t)$. Define β = angular length of subinterval 2. Then

$$i_1(\alpha + \beta) = I_2 + \frac{V_1}{R_0}\sin\left(\beta\right) = 0$$

$$\sin\left(\beta\right) = -\frac{I_2 R_0}{V_1}$$

Must use care to select the correct branch of the arcsine function. Note (from the $i_1(t)$ waveform) that $\beta > \pi$.

Hence

$$\beta = \pi + \sin^{-1}\left(\frac{I_2 R_0}{V_1}\right)$$

$$-\frac{\pi}{2} < \sin^{-1}\left(x\right) \le \frac{\pi}{2}$$

$$I_2 < \frac{V_1}{R_0}$$

V. SOFT SWITCHING METHODS

Boundary of zero current switching

If the requirement

$$I_2 < \frac{V_1}{R_0}$$

is violated, then the inductor current never reaches zero. In consequence, the transistor cannot switch off at zero current.

The resonant switch operates with zero current switching only for load currents less than the above value. The characteristic impedance must be sufficiently small, so that the ringing component of the current is greater than the dc load current.

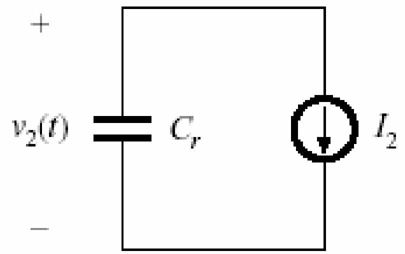
Capacitor voltage at the end of subinterval 2 is

$$v_2(\alpha + \beta) = V_{c1} = V_1\left(1 + \sqrt{1 - \left(\frac{I_2 R_0}{V_1}\right)^2}\right)$$

V. SOFT SWITCHING METHODS

Subinterval 3

All semiconductor devices are off. The circuit reduces to:



The circuit equations are

$$C_r \frac{dv_2(\omega_0 t)}{dt} = -I_2$$

$$v_2(\alpha + \beta) = V_{c1}$$

The solution is

$$v_2(\omega_0 t) = V_{c1} - I_2 R_0 \left(\omega_0 t - \alpha - \beta\right)$$

Subinterval 3 ends when the tank capacitor voltage reaches zero, and diode D_2 becomes forward-biased. Define δ = angular length of subinterval 3. Then

$$v_2(\alpha + \beta + \delta) = V_{c1} - I_2 R_0 \delta = 0$$

$$\delta = \frac{V_{c1}}{I_2 R_0} = \frac{V_1}{I_2 R_0}\left(1 - \sqrt{1 - \left(\frac{I_2 R_0}{V_1}\right)^2}\right)$$

V. SOFT SWITCHING METHODS

Subinterval 4

Subinterval 4, of angular length ξ, is identical to the diode conduction interval of the conventional PWM switch network.

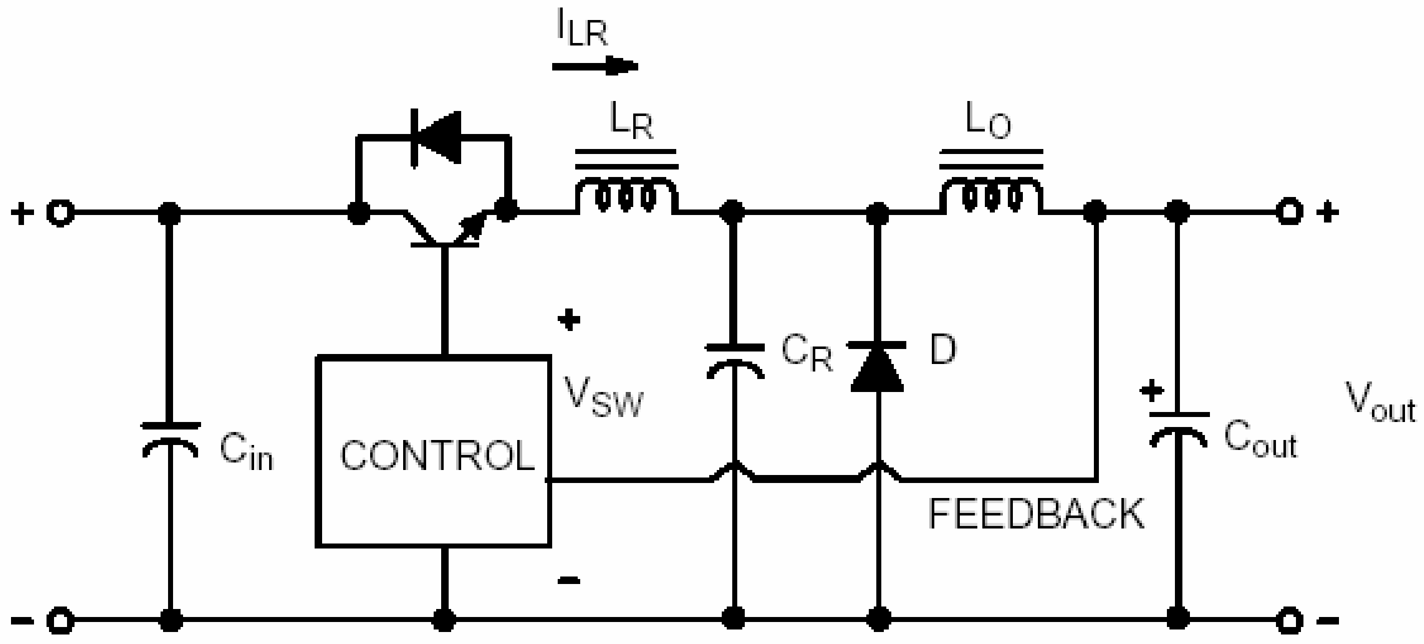
Diode D_2 conducts the filter inductor current I_2

The tank capacitor voltage $v_2(t)$ is equal to zero.

Transistor Q_1 is off, and the input current $i_1(t)$ is equal to zero.

The length of subinterval 4 can be used as a control variable. Increasing the length of this interval reduces the average output voltage.

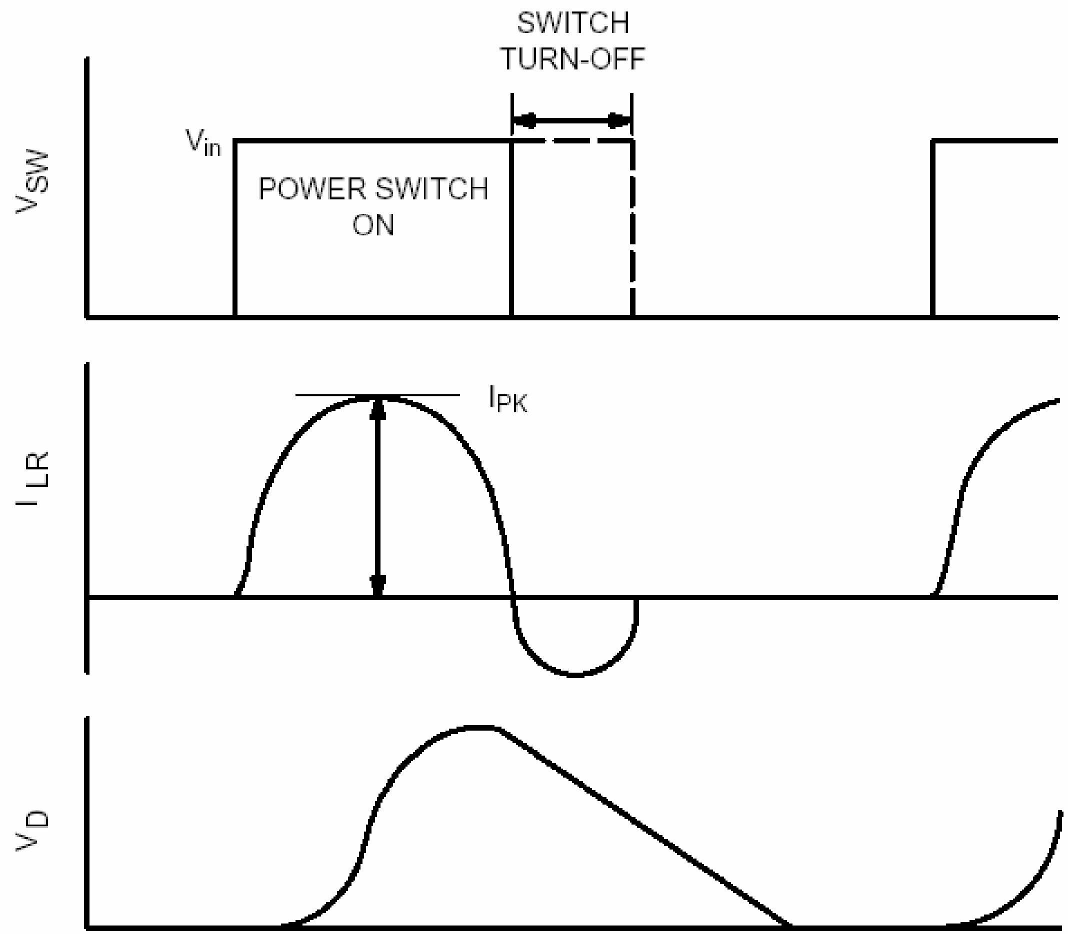
V. SOFT SWITCHING METHODS



A ZCS Quasi–Resonant Buck Converter

V. SOFT SWITCHING METHODS

Waveforms for a ZCS Quasi-Resonant Buck Converter

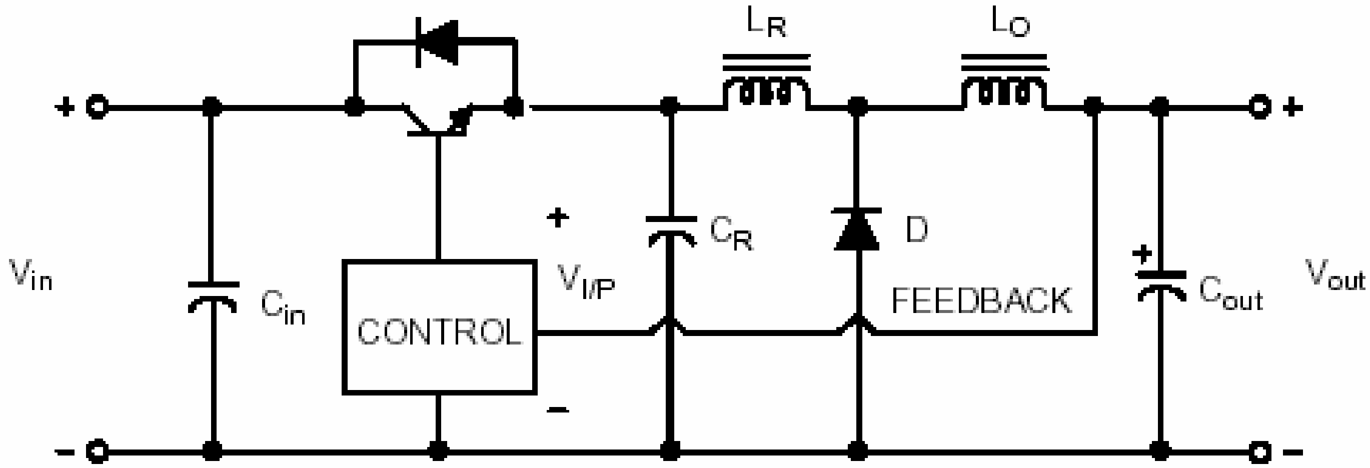


V. SOFT SWITCHING METHODS

In this design, both the power switch and the catch diode operate in a zero current switching mode. Power is passed to the output during the resonant periods. So to increase the power delivered to the load, the frequency would increase, and vice versa for decreasing loads. In typical designs the frequency can change 10:1 over the ZCS supply's operating range.

The ZVS is a fixed off–time, variable on–time method control. Here the initial condition occurs when the power switch is on, and the familiar current ramp is flowing through the filter inductor. The ZVS quasi–resonant buck converter is shown in Figure . Here, to control the power delivered to the load, the amount of "resonant off times" are varied. For light loads, the frequency is high. When the load is heavy, the frequency drops. In a typical ZVS power supply, the frequency typically varies 4:1 over the entire operating range of the supply.

There are other variations on the resonant theme that promote zero switching losses, such as full resonant PWM, full and half–bridge topologies for higher power and resonant transition topologies.



A ZVS Quasi–Resonant Buck Converter

V. SOFT SWITCHING METHODS

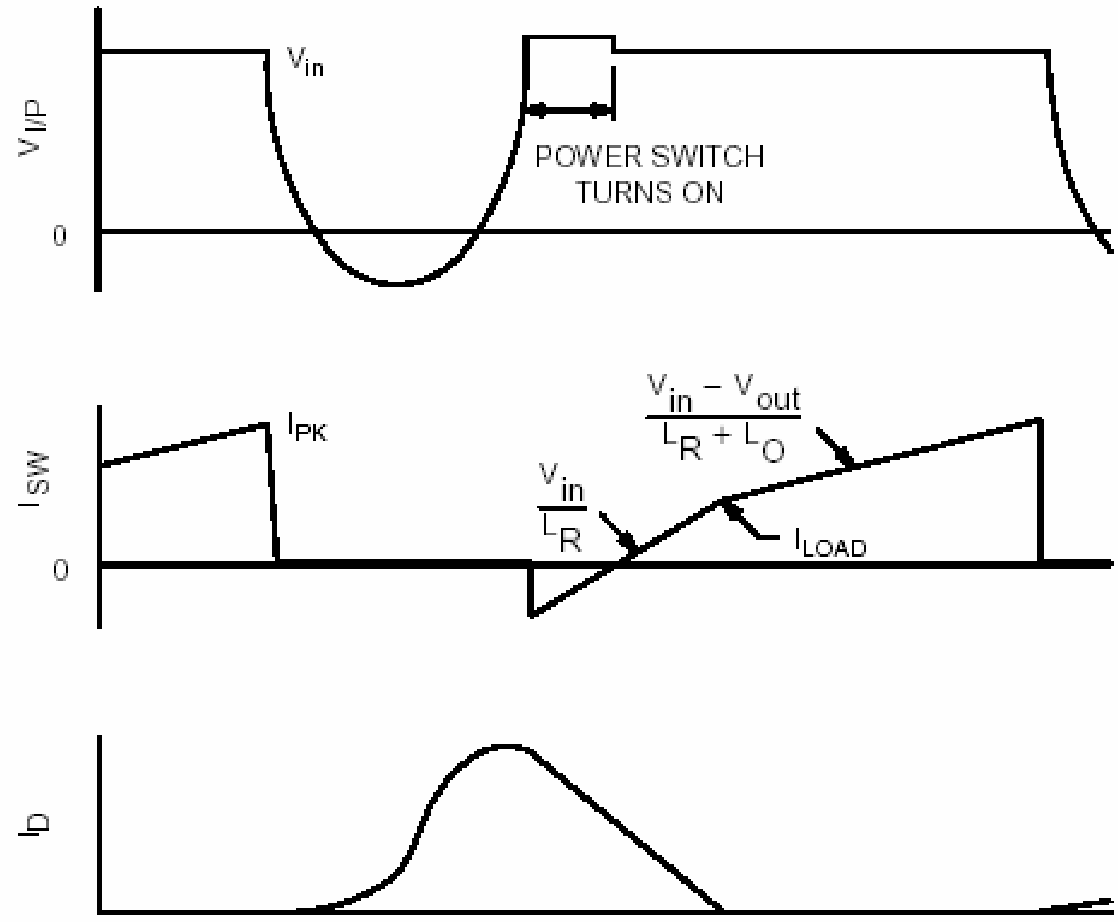
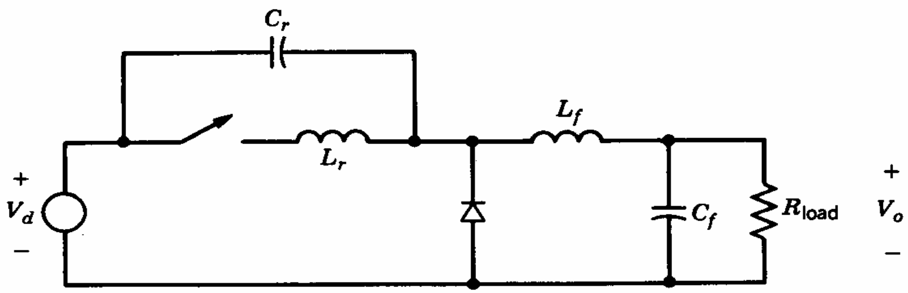
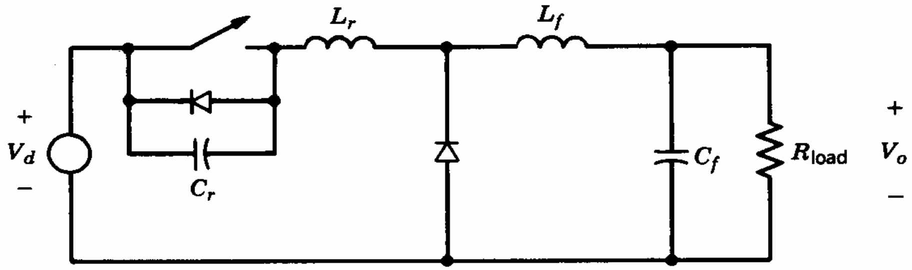


Figure Schematic and Waveforms for a ZVS Quasi-Resonant Buck Converter

5.3. Resonant Switch Converter Operation



(a)



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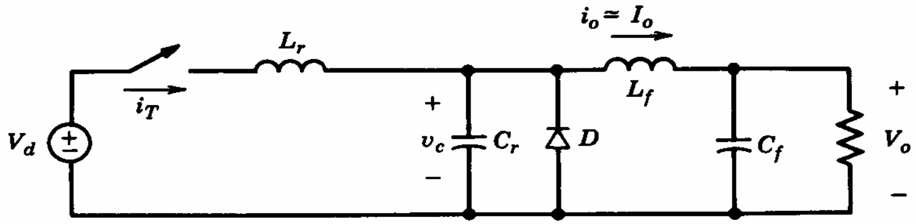
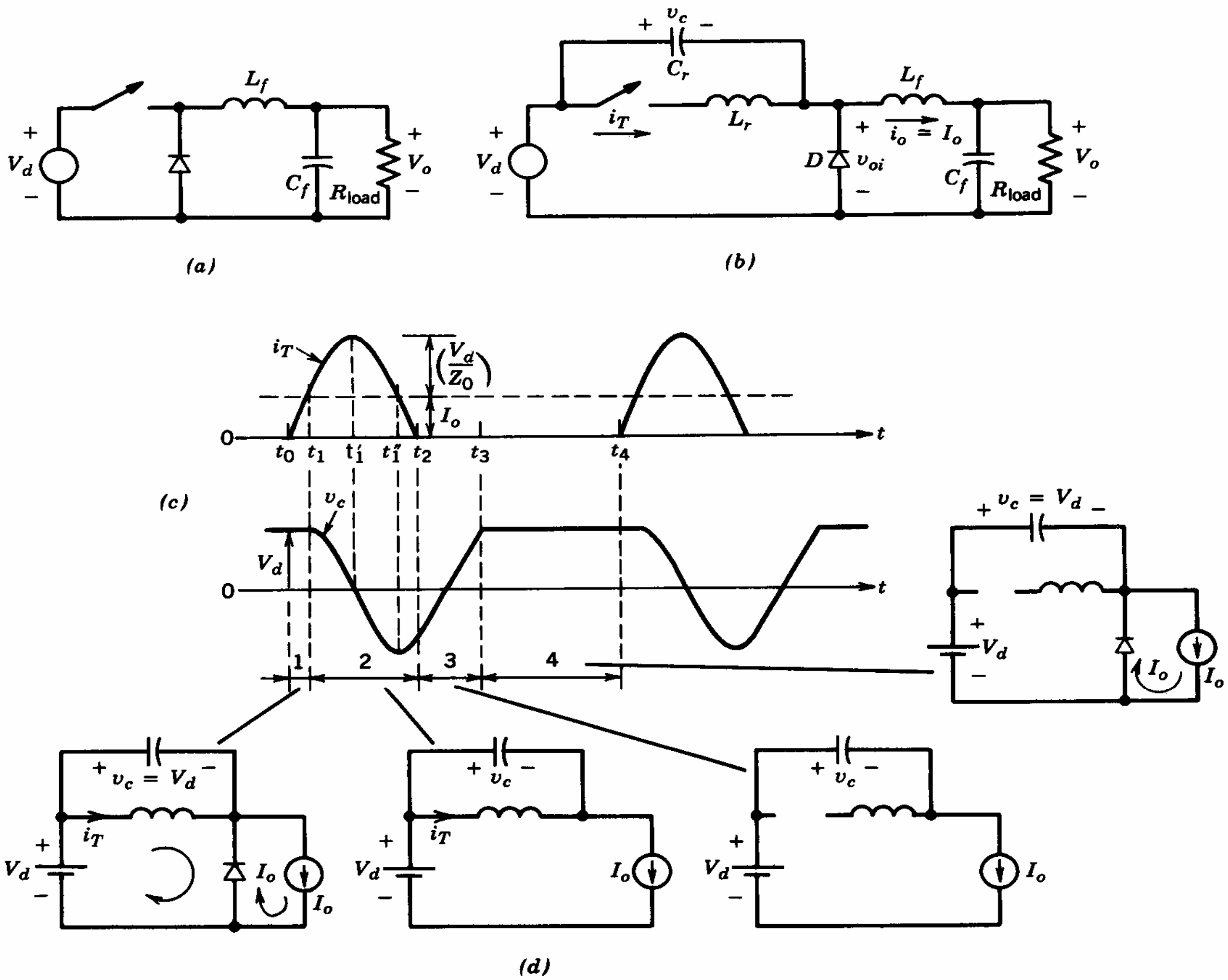


(a)

(a) ZCS Resonant Switch Converter
(b) ZVS Resonant Switch Converter

ZCS Resonant-Switch Converter



ZCS resonant-switch dc–dc converter.

- One possible implementation

ZCS Resonant-Switch Converter

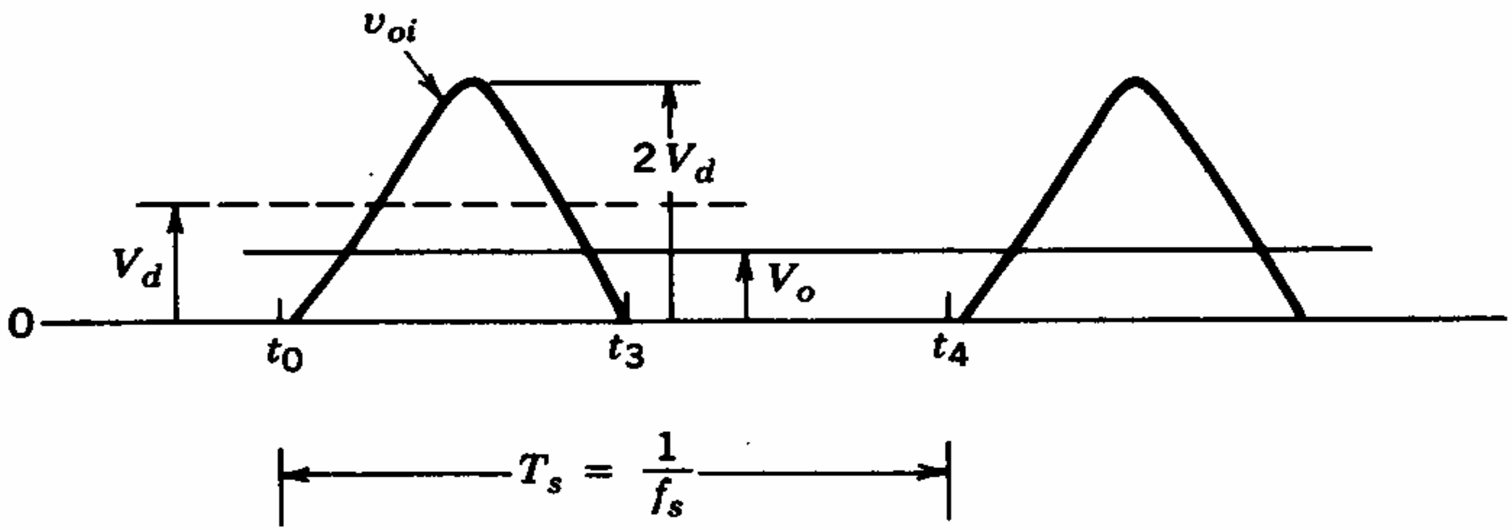
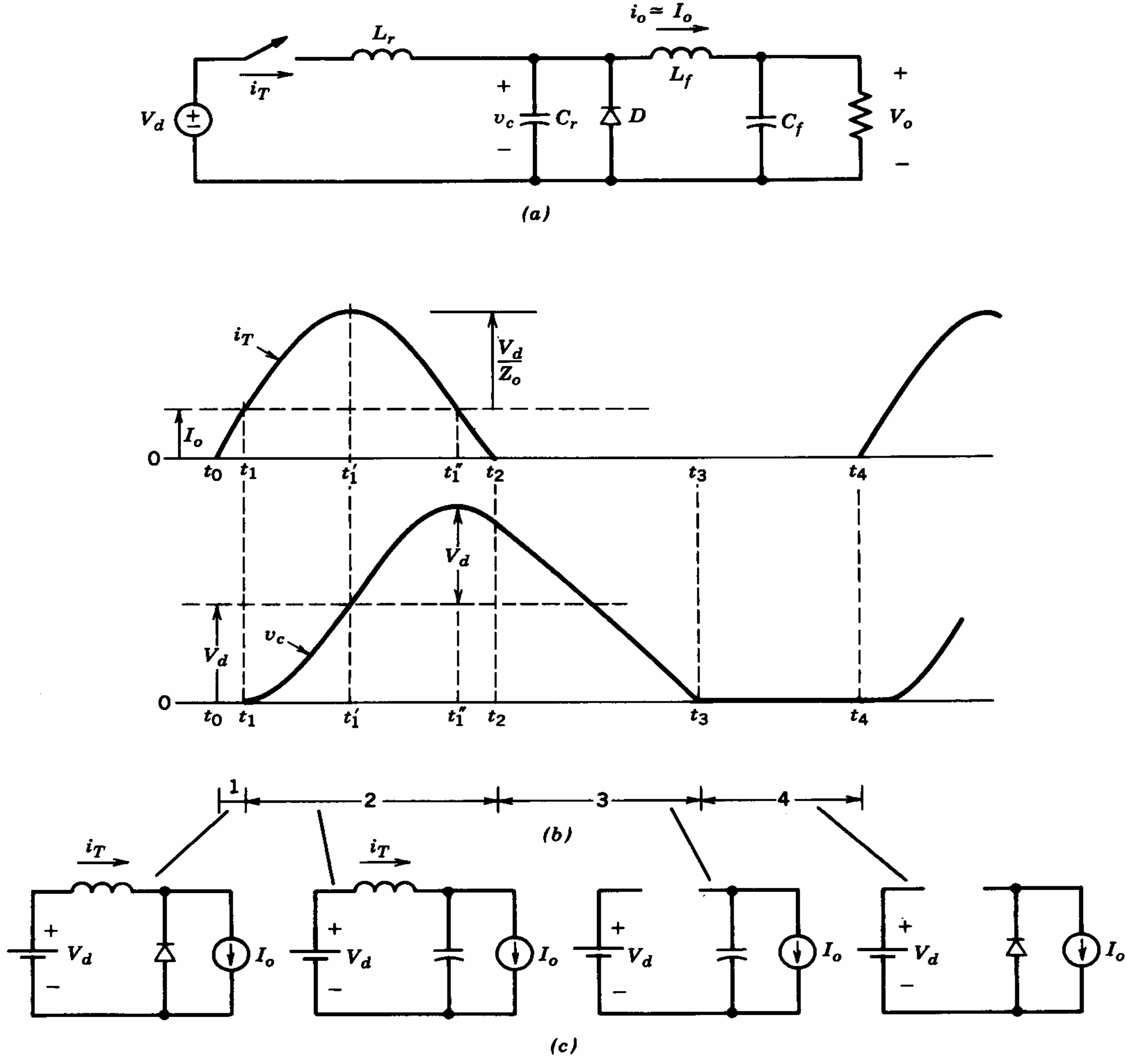


Figure v_{oi} waveform in a ZCS resonant-switch dc–dc converter.

- Waveforms; voltage is regulated by varying the switching frequency

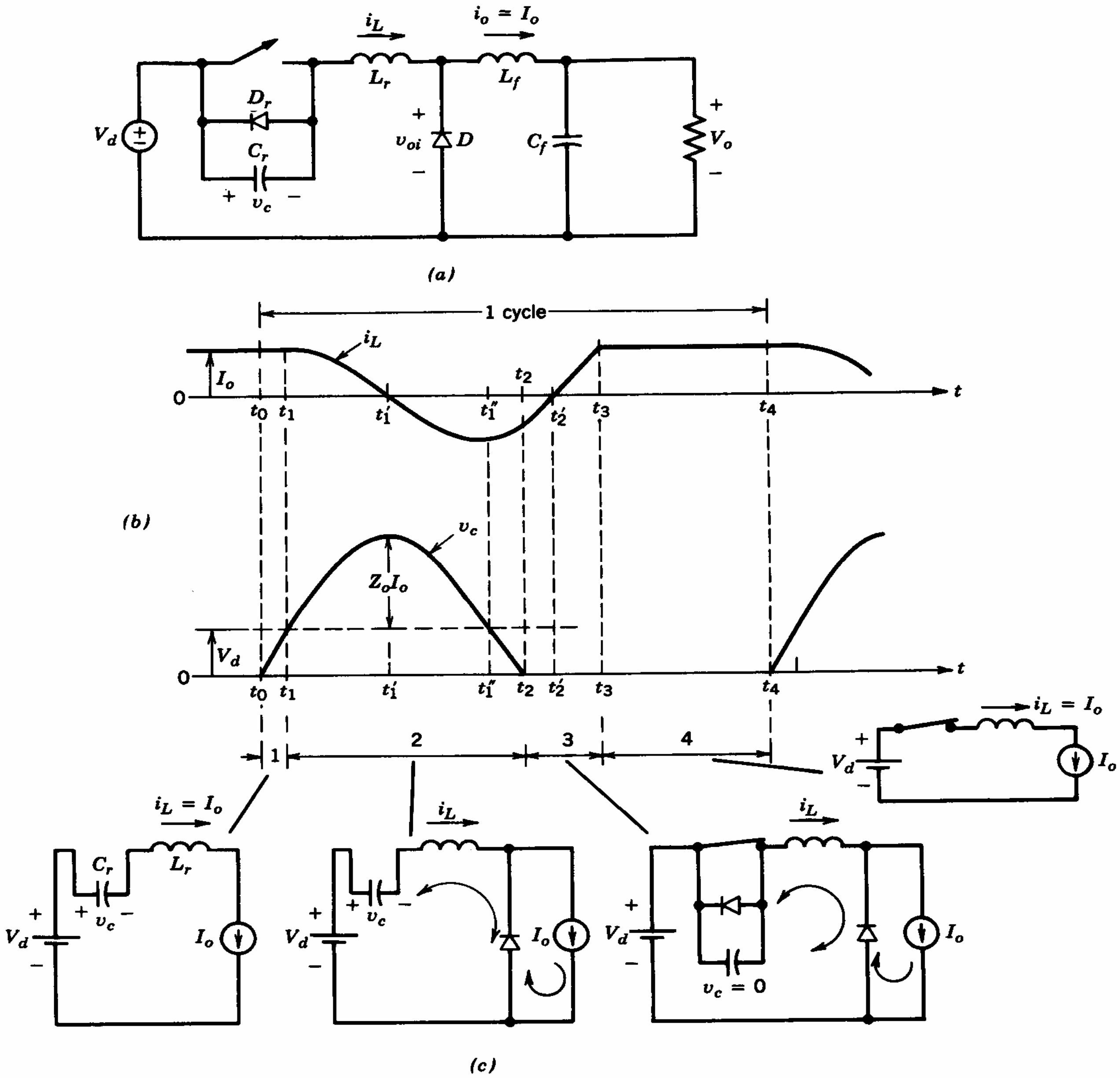
ZCS Resonant-Switch Converter

- A practical circuit



ZCS resonant-switch dc–dc converter; alternate configuration.

ZVS Resonant-Switch Converter



ZVS resonant-switch dc–dc converter.