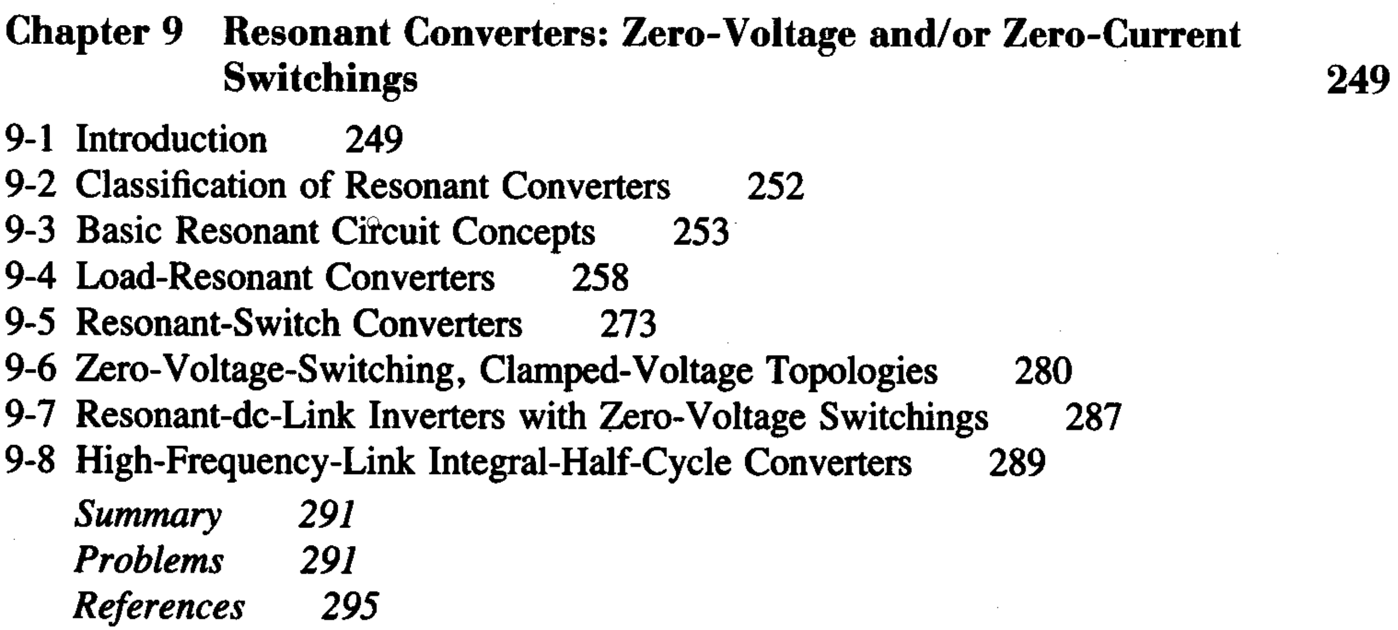
Chapter 9

Zero-Voltage or Zero-Current Switchings



- converters for soft switching

Why resonant converters

- Hard switching is based on on/off
  - Switching losses
  - Electromagnetic Interference (EMI) because of high du/dt and di/dt
- SMPS size decreses with increasing switching frequency
  - Target is to use as high f_s as possible
  - Switching losses are reduced if voltage and/or current are zero during switching

One Inverter Leg

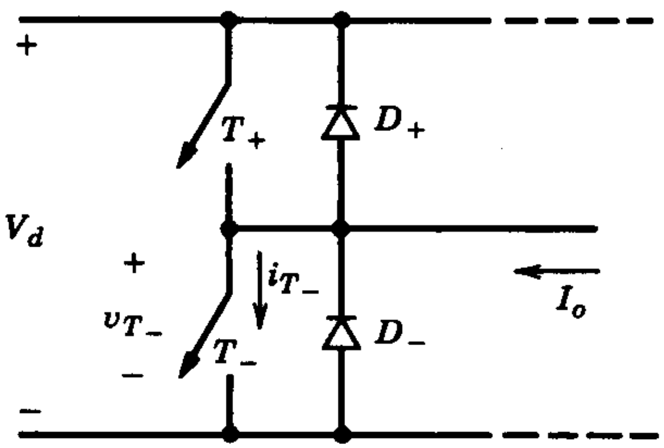


Figure 9-1 One inverter leg.

- The output current can be positive or negative

Hard Switching Waveforms

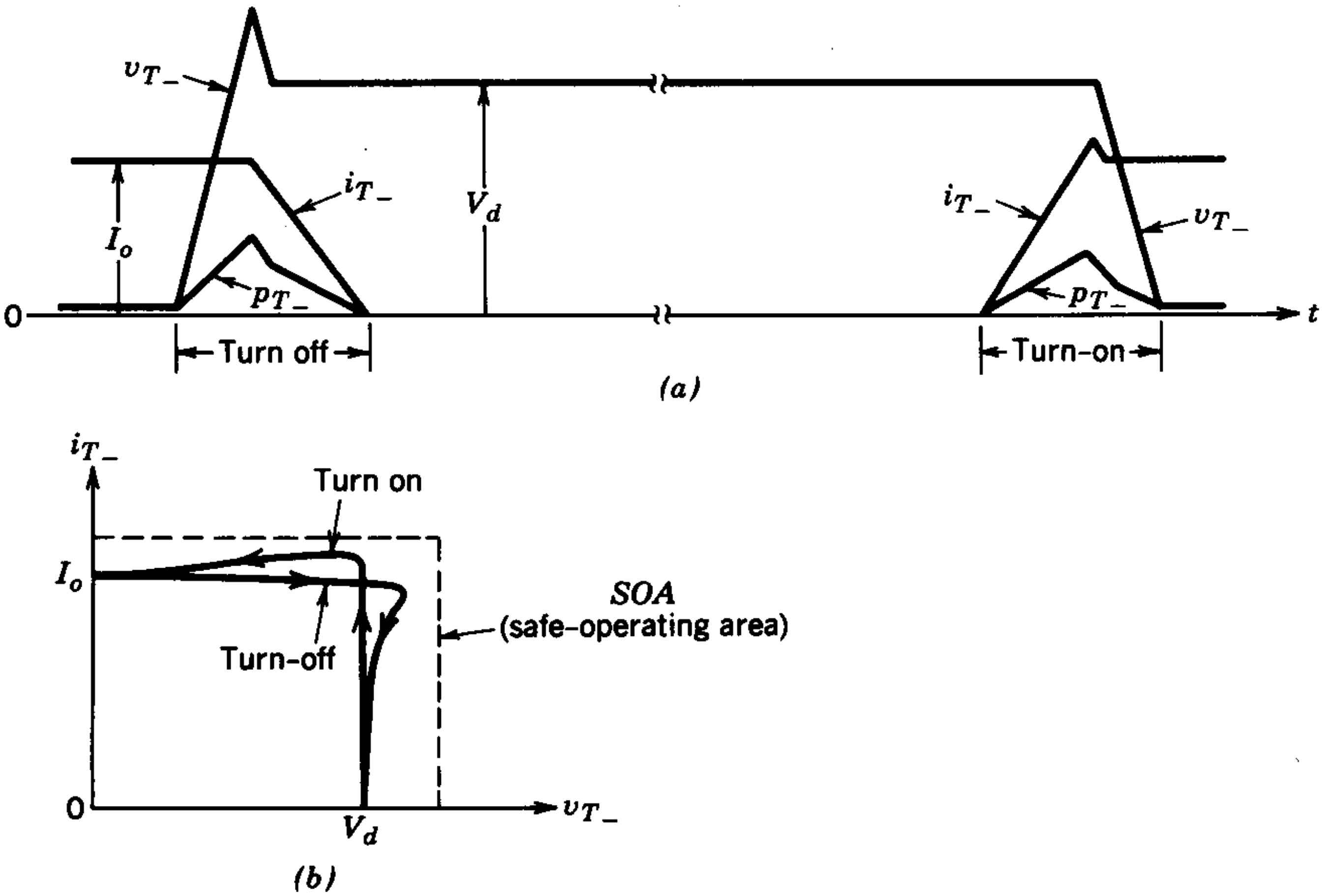


Figure 9-2 Switch-mode inductive current switchings.

- The output current can be positive or negative

Change over

- T- conducts I_o and it is turned off
  - Voltage over it increases and when it is U_d diode D+ starts to conduct
  - Because of parasitic inductances voltage exceeds U_d
- D+ conducts I_o and T- is turned on
  - Current increares and exceeds I_o because of diode reverse recovery current
  - After recovery of the diode voltage over T- drops to nearly zero

Turn-on and Turn-off Snubbers

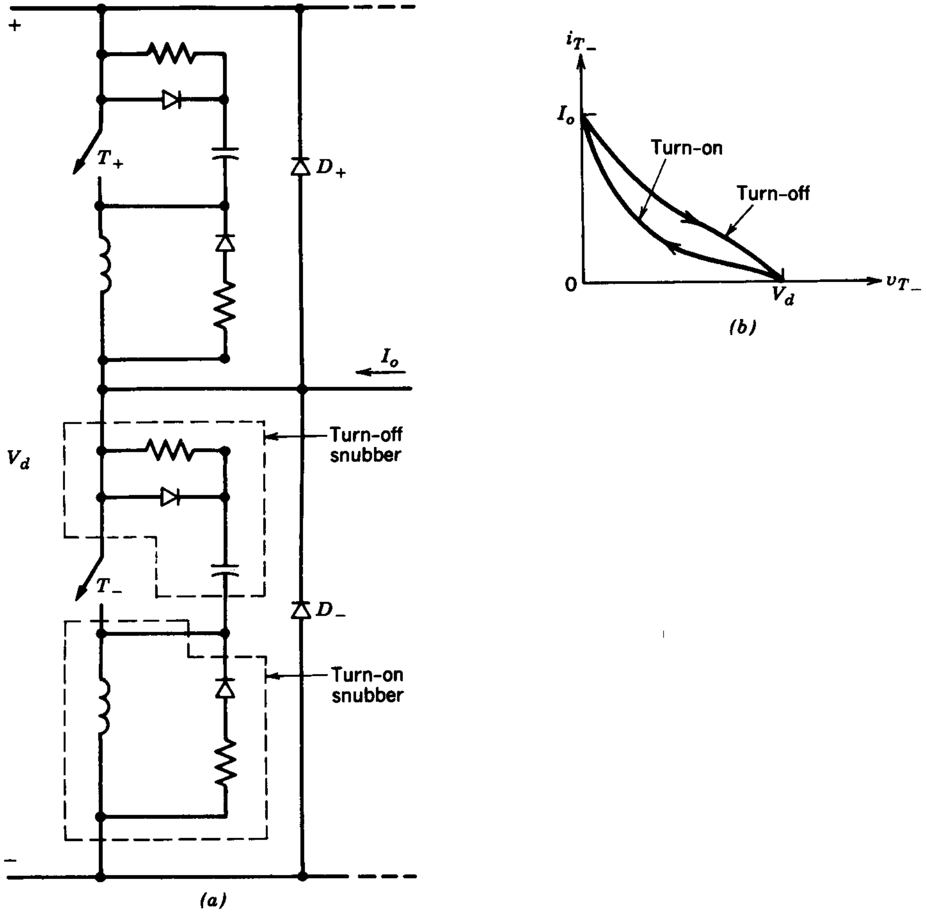


Figure 9-3 Dissipative snubbers: (*a*) snubber circuits; (*b*) switching loci with snubbers.

- Turn-off snubbers are used, turn-on very seldom

Switching Trajectories

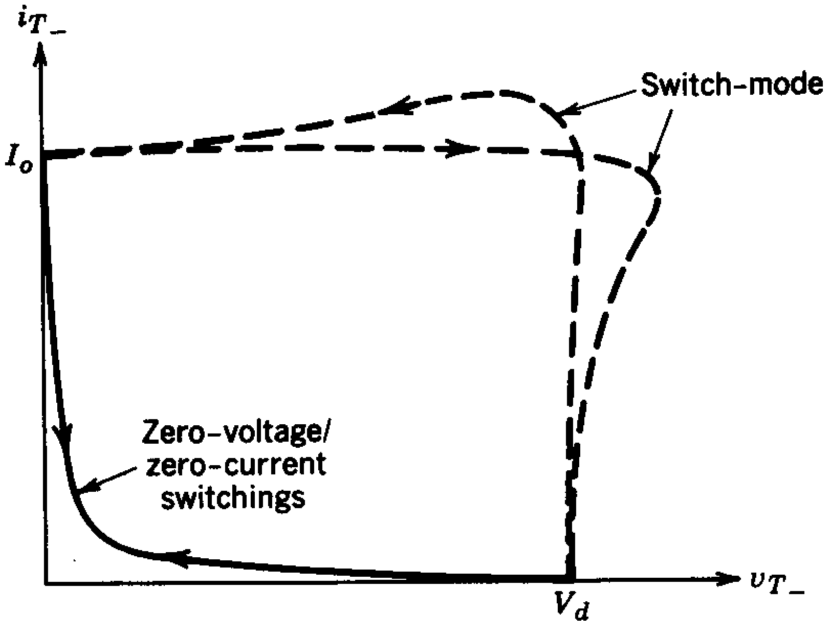


Figure 9-4 Zero-voltage-/zero-current-switching loci.

- Comparison of Hard versus soft switching

Switching losses

- Voltage and current stresses of the switches can be reduced by snubber circuits (Finnish kytkentäsuojapiiri)
  - Losses are transferred from the switch to the R of the RC-snubber
  - C discharges through R when switch is turned on
  - Total losses do not necessarily decrease, requires careful dimensioning
- In resonant circuit switching losses in theory can be even zero

Basics of resonant circuits

Series resonance

Lossless parallel resonant circuit

Undamped Series-Resonant Circuit

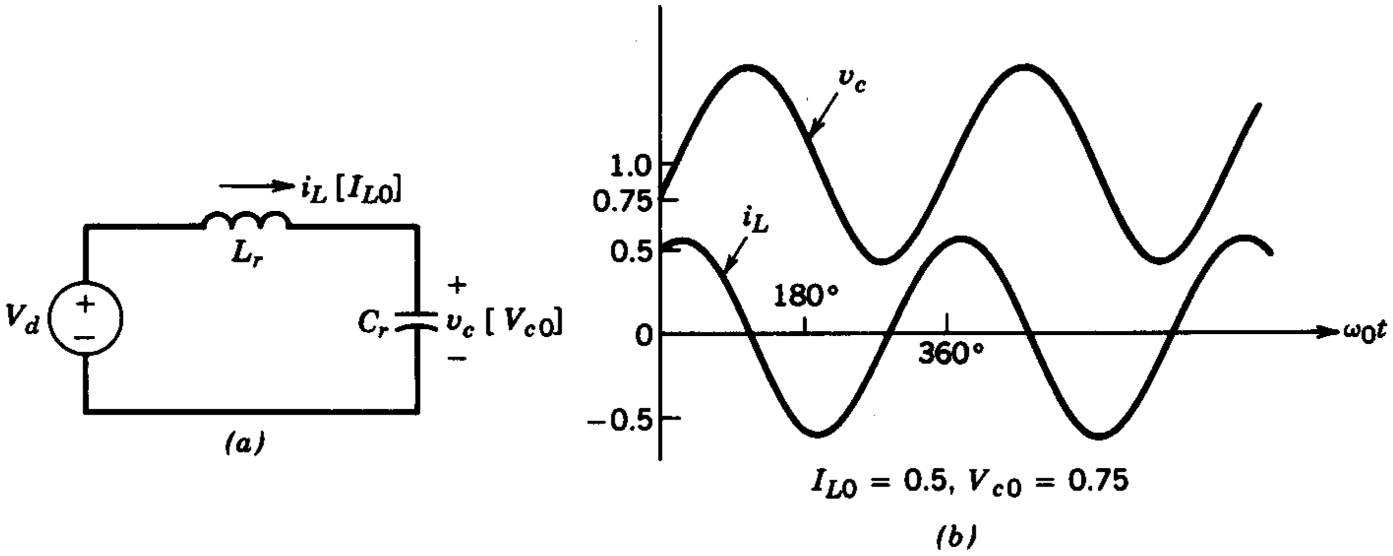


Figure 9-5 Undamped series-resonant circuit; i_L and v_c are normalized: (*a*) circuit; (*b*) waveforms with $I_{L0} = 0.5$, $V_{c0} = 0.75$.

- The waveforms shown include initial conditions

Series resonance

- Equations

$$L_r \frac{di_L}{dt} + u_C = U_d \qquad C_r \frac{du_C}{dt} = i_L$$

- Solution from time *t* = 0

$$i_L = I_{L0} \cos \omega_0 t + \frac{V_d - V_{C0}}{Z_0} \sin \omega_0 t \qquad v_C = V_d - (V_d - V_{C0}) \cos \omega_0 t + Z_0 I_{L0} \sin \omega_0 t$$

- Resonance frequency and impedance

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}} \qquad Z_0 = \sqrt{\frac{L_r}{C_r}}$$

- Often per unit values are used

$$V_{base} = V_d \qquad I_{base} = \frac{V_d}{Z_0}$$

Series-Resonant Circuit with Capacitor-Parallel Load

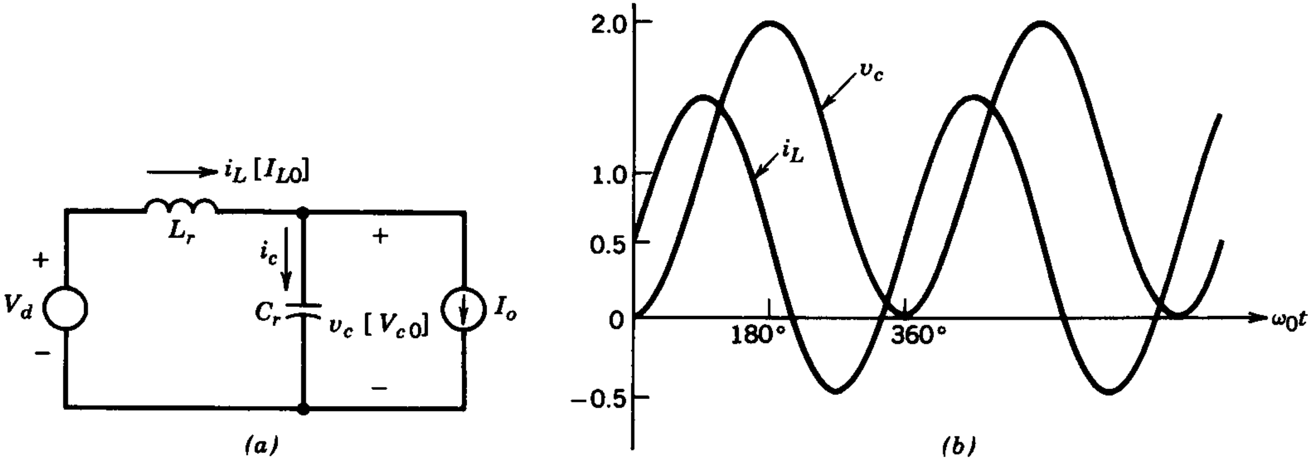


Figure 9-6 Series-resonant circuit with capacitor-parallel load (i_L and v_c are normalized): (a) circuit; (b) $V_{c0} = 0$, $I_{L0} = I_o = 0.5$.

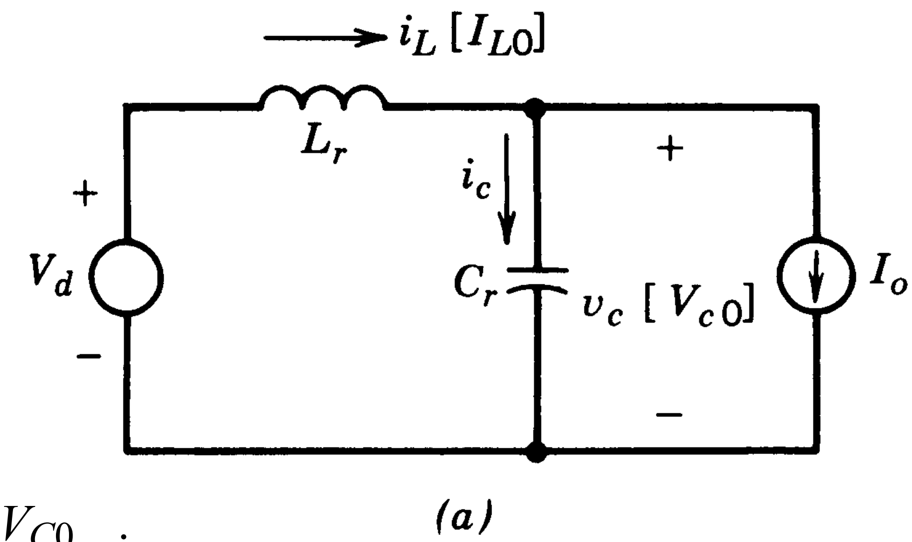
- The waveforms shown include initial conditions

Series-Resonant Circuit with Capacitor-Parallel Load

- Equations
- Derivation

$$v_C = V_d - L_r \frac{di_L}{dt} \qquad i_L - i_C = I_o$$

$$i_C = C_r \frac{dv_C}{dt} = -L_r C_r \frac{d^2 i_L}{dt^2}$$



- And using

$$\frac{d^2 i_L}{dt^2} + \omega_0^2 i_L = \omega_0^2 I_o$$

- Solution is

$$i_L = I_o + (I_{L0} - I_o) \cos \omega_0 t + \frac{V_d - V_{C0}}{Z_0} \sin \omega_0 t$$

$$v_C = V_d - (V_d - V_{C0}) \cos \omega_0 t + Z_0 (I_{L0} - I_o) \sin \omega_0 t$$

Impedance of a Series-Resonant Circuit

- Quality factor

$$Q = \frac{\omega_0 L_r}{R} = \frac{1}{\omega_0 C_r R} = \frac{Z_0}{R}$$

- The impedance is capacitive below the resonance frequency

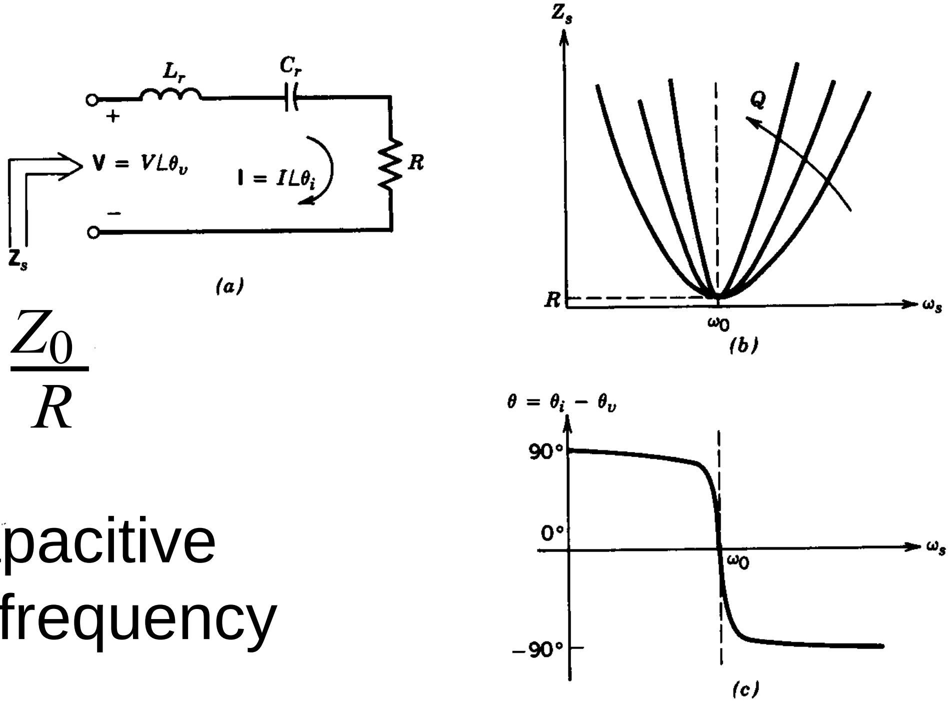


Figure 9-7 Frequency characteristics of a series-resonant circuit.

Undamped Parallel-Resonant Circuit

$$i_L + C_r \frac{dv_C}{dt} = I_d \qquad v_C = L_r \frac{di_L}{dt}$$

$$i_L = I_d + (I_{L0} - I_d) \cos \omega_0 t + \frac{V_{C0}}{Z_0} \sin \omega_0 t \qquad \omega_0 = 2\pi f_0 = \frac{1}{\sqrt{L_r C_r}}$$

$$v_C = V_{C0} \cos \omega_0 t + Z_0 (I_d - I_{L0}) \sin \omega_0 t \qquad Z_0 = \sqrt{\frac{L_r}{C_r}}$$

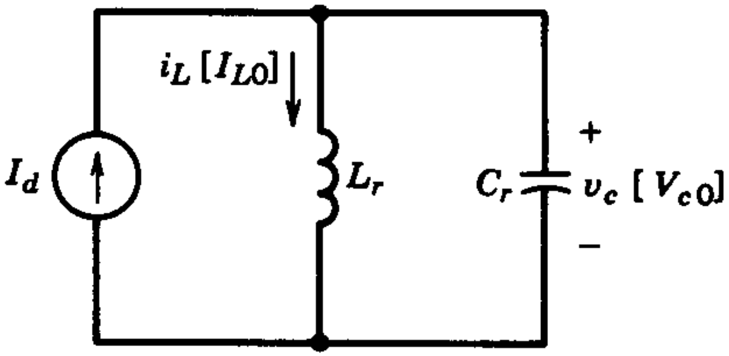


Figure 9-8 Undamped parallel-resonant circuit.

Impedance of a Parallel-Resonant Circuit

$$Q = \omega_0 R C_r = \frac{R}{\omega_0 L_r} = \frac{R}{Z_0}$$

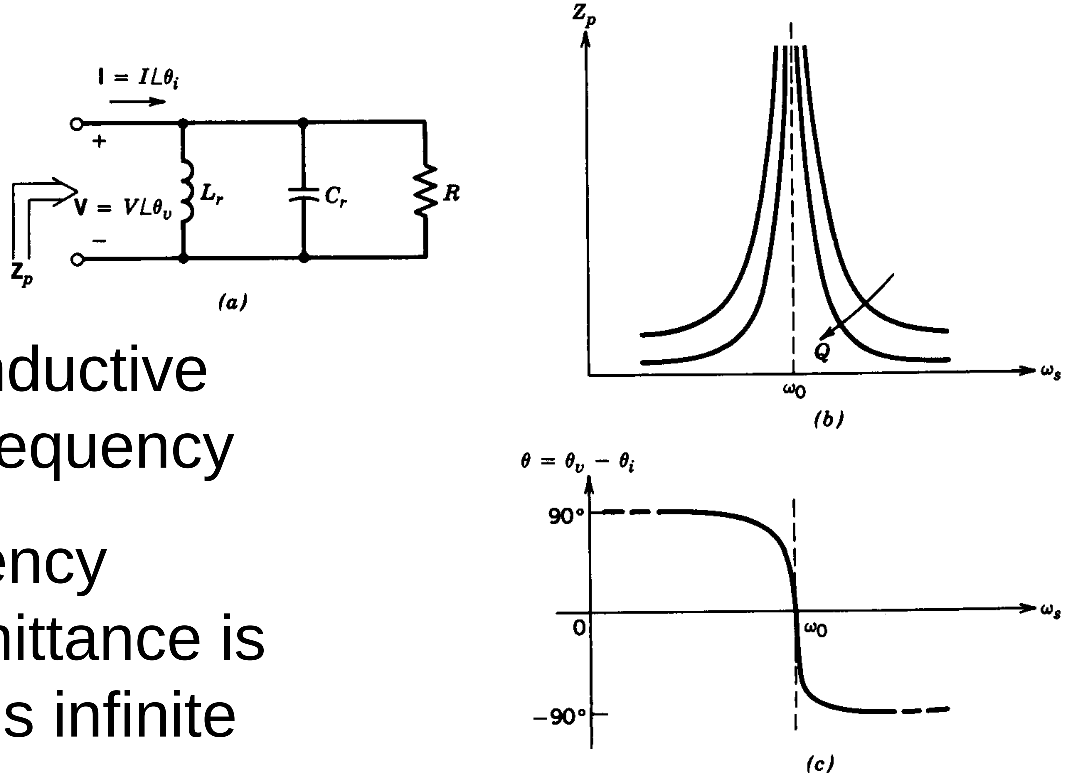


Figure 9-9 Frequency characteristics of a parallel-resonant circuit.

- The impedance is inductive below the resonant frequency
- At resonance frequency imaginary part of admittance is zero, i.e. impedance is infinite

Load resonant converters

- Series Load Resonant (SLR) Converter
  - Discontinuous area $\omega_s < \omega_0/2$
  - Continuous area $\omega_0/2 < \omega_s < \omega_0$
  - Continuous area $\omega_s > \omega_0$
  - Steady state characteristics
  - Control of SLR
- Parallel Load Resonant (PLR) Converter
  - Discontinuous area
  - Continuous area $\omega_s < \omega_0$
  - Continuous area $\omega_s > \omega_0$
  - Steady state characteristics
- Hybrid-resonant converter

Load resonant converters

- Converter has LC-resonant circuit and load current goes through it
  - Both series and parallel resonance
- Voltages and current in the resonant circuit are introducing zero voltage or current switching
- Load power is controlled by adjusting switching frequency in relation to resonance frequency
  - Impedance of the resonant circuit changes

Series Load Resonant (SLR) Converter

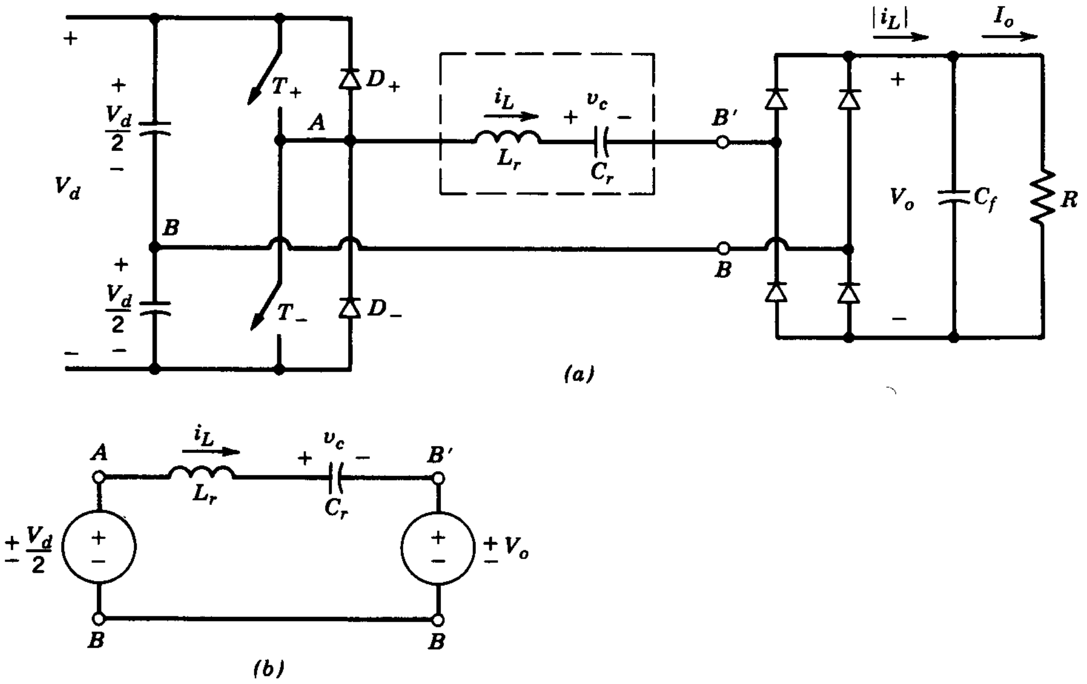


Figure 9-10 SLR dc–dc converter: (*a*) half-bridge; (*b*) equivalent circuit.

- The transformer is ignored in this equivalent circuit

Principle

- Full-bridge and transformer connection are also possible
- Current of the resonant circuit is rectified in the diode bridge
- Output voltage U_o is assumed to be constant and its polarity depends on the sign of current i_L of the resonant circuit

Polarity of voltages

- Positive current

T_+ conducts $u_{AB} = \frac{U_d}{2}$ $\quad u'_{AB} = \frac{U_d}{2} - U_o$

D_- conducts $u_{AB} = -\frac{U_d}{2}$ $\quad u'_{AB} = -\frac{U_d}{2} - U_o$

- Negative current

T_- conducts $u_{AB} = -\frac{U_d}{2}$ $\quad u'_{AB} = -\frac{U_d}{2} + U_o$

D_+ conducts $u_{AB} = \frac{U_d}{2}$ $\quad u'_{AB} = \frac{U_d}{2} + U_o$

SLR Waveforms, DCM, $\omega_s < \omega_0/2$

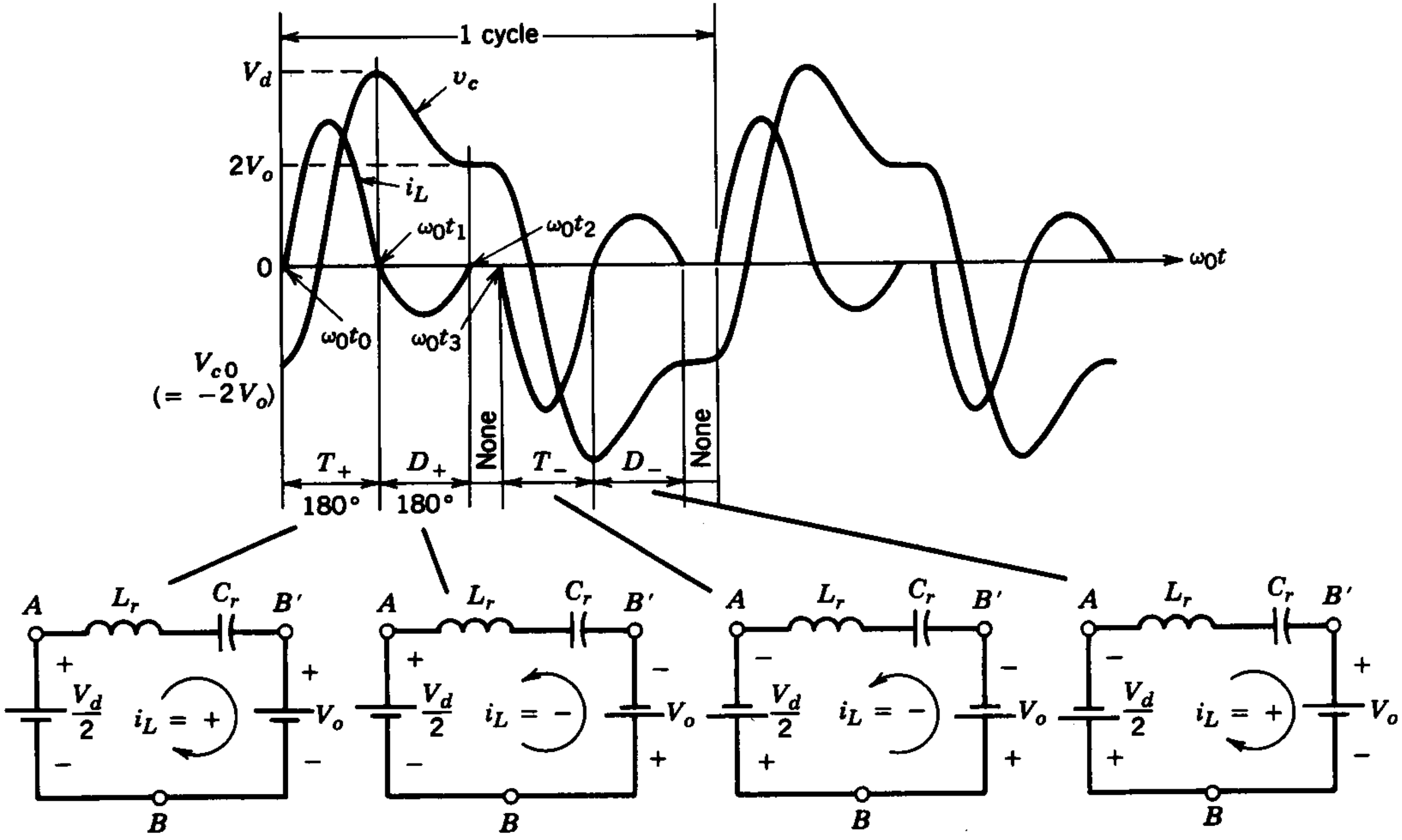


Figure 9-11 SLR dc–dc converter; discontinuous-conduction mode with $\omega_s < \frac{1}{2}\omega_0$.

Operation

- Current of T+ is zero
  - Turned on at $\omega_0 t_0$
- At $\omega_0 t_1$ current of resonant circuit turns and D+ conducts, because T- is not turned on yet ($\omega_s < \omega_0/2$)
- After 180°, at $\omega_0 t_2$ current goes to zero
  - Because of symmetry, capacitor voltage is $2U_o$
- Because $2U_o < U_d/2 + U_o$ inductor current is not increasing but it is discontinuous
- At $\omega_0 t_3$ control is given to T- and negative half cycle starts

Remarks

- Switches are turnig of naturally as current goes to zero
  - Even thyristors could be used
- Switches are turning on when current is zero but voltage not
- Peak value of current in the resonant circuit is much higher than the average of output current

SLR Waveforms, CCM, $\omega_0/2 < \omega_s < \omega_0$

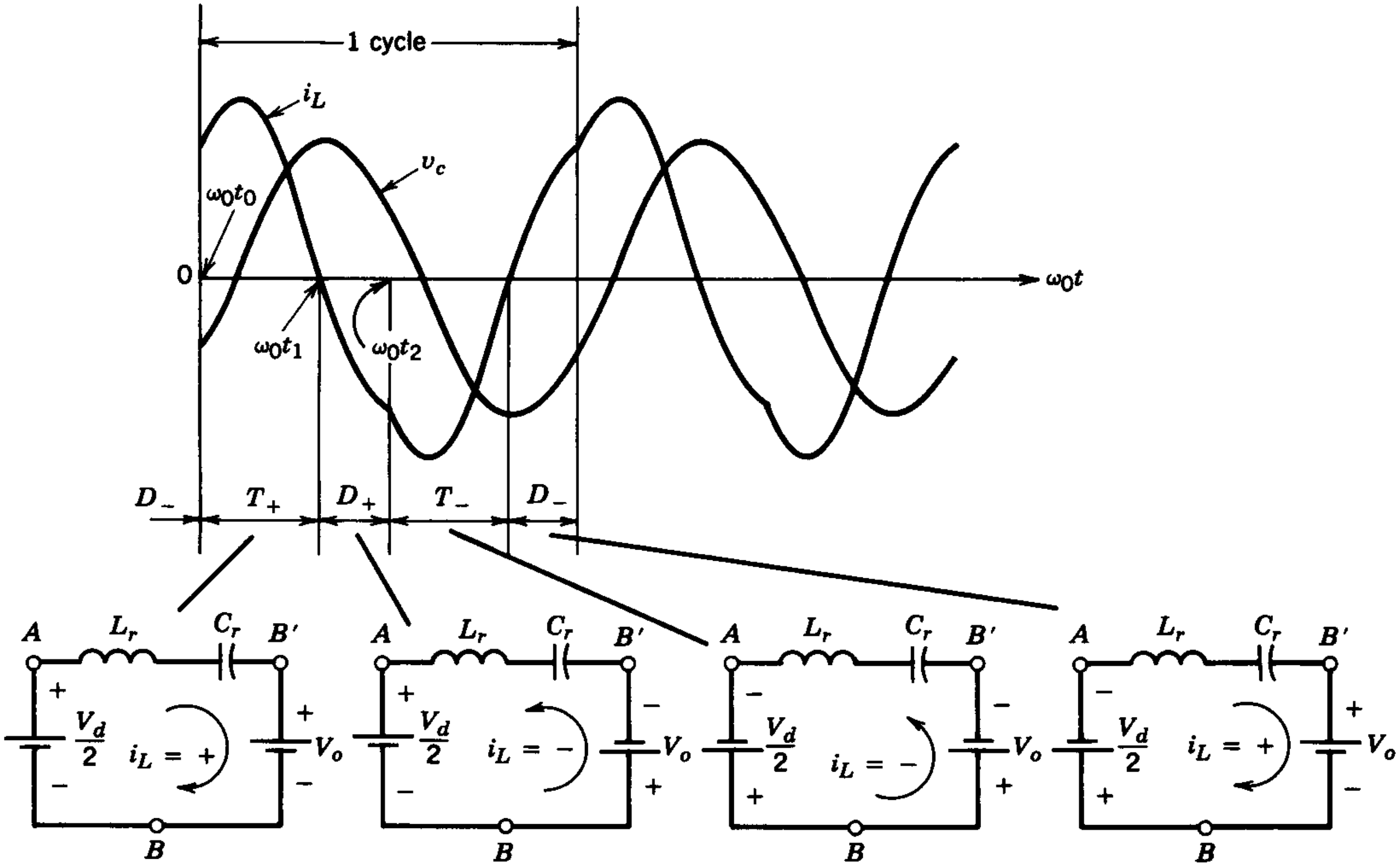


Figure 9-12 SLR dc–dc converter; continuous-conduction mode with $\frac{1}{2}\omega_0 < \omega_s < \omega_0$.

Operation

- Switch T+ current ≠ 0
  - It is turned on at $\omega_0 t_0$, voltage is U_d
  - Switch conducts less than 180°
  - At $\omega_0 t_1$ current i_L becomes negative and D+ conducts
- T- is turned on at $\omega_0 t_2$
  - This is earlier than in the previous DCM operating area $\omega_s < \omega_0/2$
  - D+ conducts less than 180°

Devices

- Turning on
  - Current and voltage are not zero => losses
- Turning off
  - Current and voltage are zero
  - Even thyristors could be used
- Reverse recovery current of the diodes must be small

SLR Waveforms, CCM, $\omega_s > \omega_0$

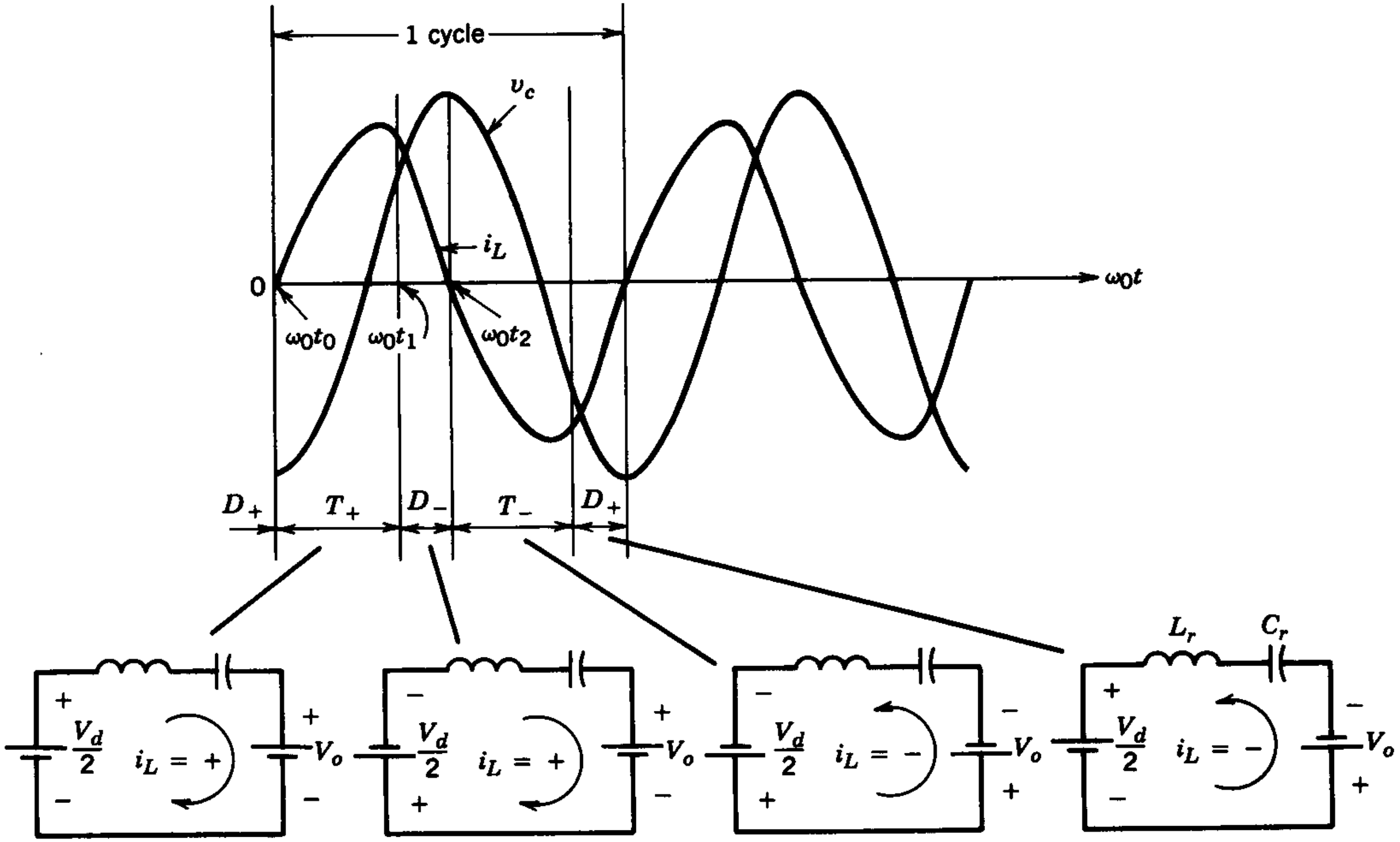


Figure 9-13 SLR dc–dc converter; continuous-conduction mode with $\omega_s > \omega_0$.

Operation

- Current of T+ is zero and it is turned on at $\omega_0 t_0$
- T+ is turned on at $\omega_0 t_1$
  - This is before the current has become zero
  - D- starts to conduct
  - Voltage over the *LC*-circuits is high and diode current goes rapidly to zero
- T- is turned on immeadiately as D- starts to conduct
  - T- can conduct as the polarity of the current changes

Switches

- Turn-on at zero current and voltage
- Turning off takes place close to the peak of the resonant current
  - Turn-off losses
- Before the switch starts to conduct the antiparall diode has conducted
  - Voltage over switch is ≈ 0
  - It is possible to use lossless snubbers, i.e. only snubber capacitor in the circuit as there is no discharge current when the switch is turned on

Lossless Snubbers in SLR Converters

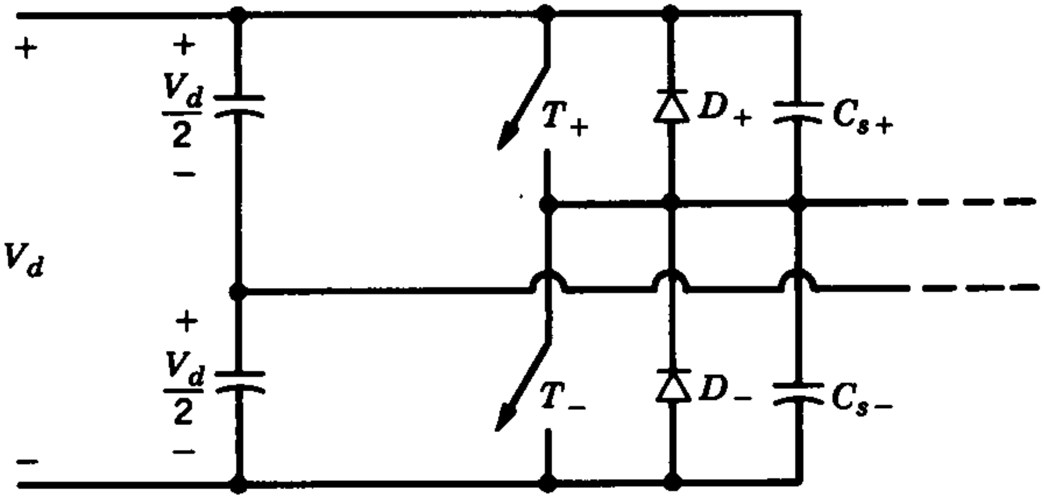


Figure 9-14 Lossless snubbers in an SLR converter at $\omega_s > \omega_0$.

- The operating frequency is above the resonance frequency

SLR Converter Characteristics

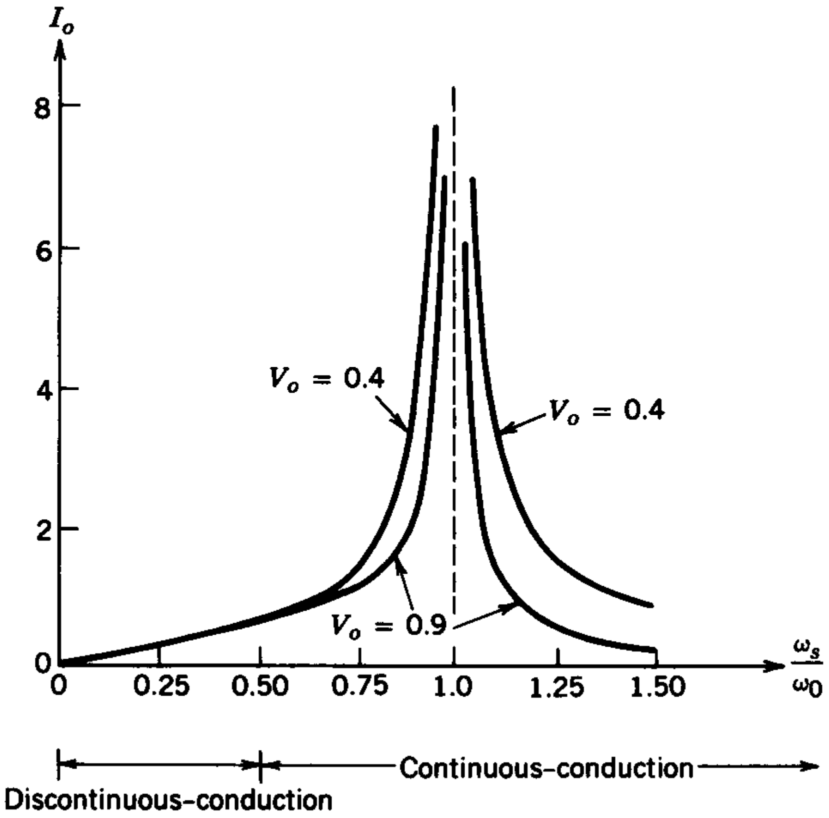


Figure 9-15 Steady-state characteristics of an SLR dc–dc converter; all parameters are normalized.

- Output Current as a function of operating frequency for various values of the output voltage

SLR Converter Control

- The operating frequency is varied to regulate the output voltage
- In full-bridge converters frequency can also be constant and voltage is controlled phase-shifting leg voltages, (*D* = 50 %)

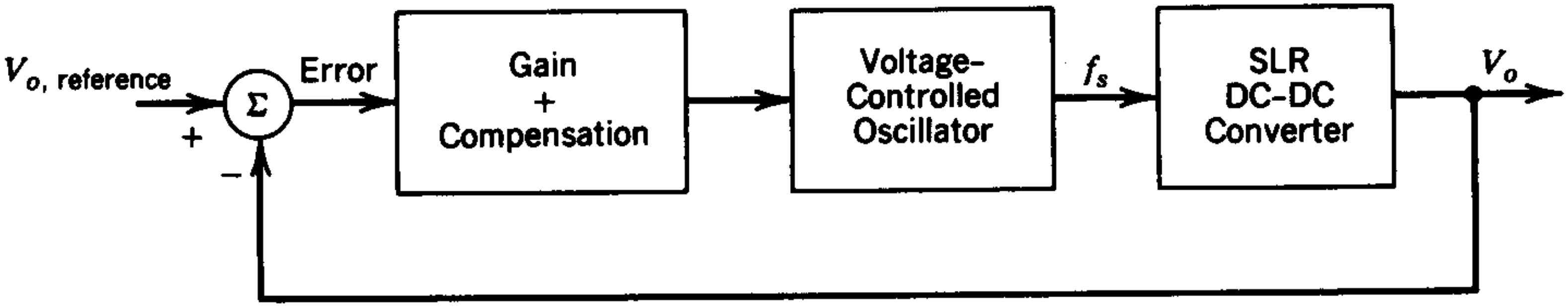


Figure 9-16 Control of SLR dc–dc converter.

Parallel Load Resonant (PLR) Converter

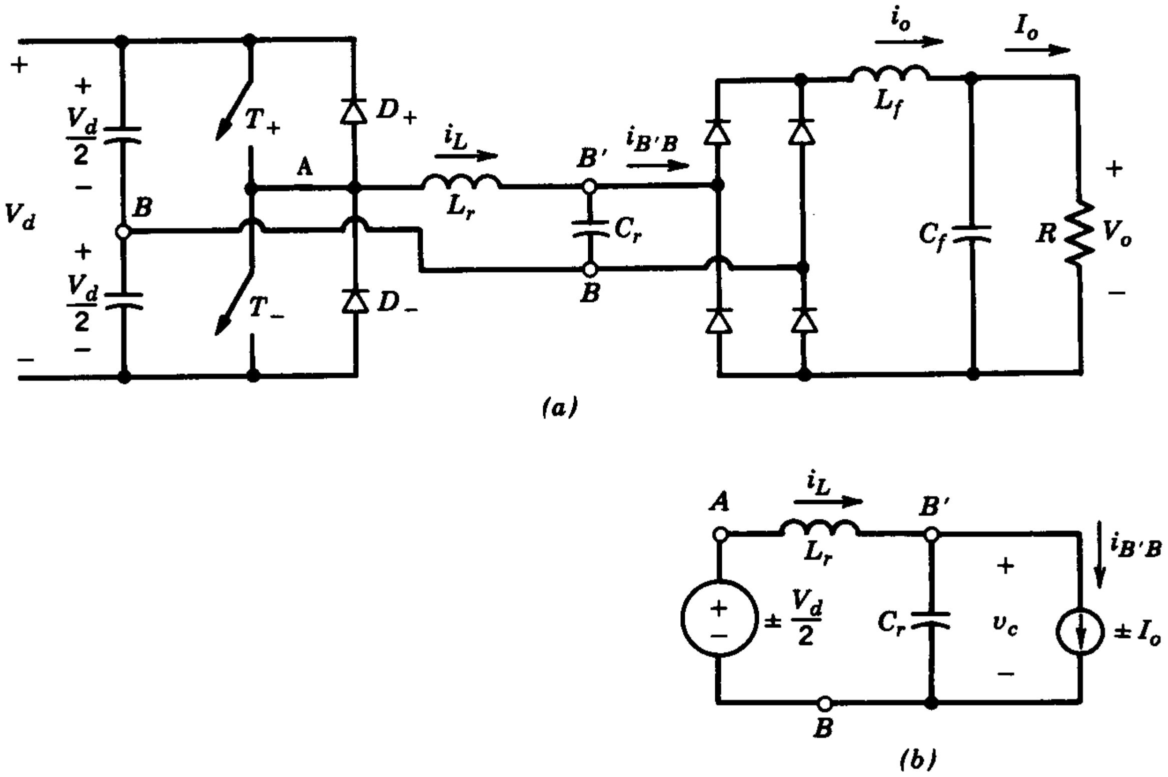


Figure 9-17 PLR dc–dc converter: (*a*) half-bridge; (*b*) equivalent circuit.

- The transformer is ignored in this equivalent circuit

Principle

- Voltage of C_r is recitified and filtered
- Output current is assumed to be constant during switching cycle
- Voltage over the resonant circuit

$$u_{AB} = \frac{U_d}{2} \qquad T_+ \text{ or } D_+ \text{ conducts}$$

$$u_{AB} = -\frac{U_d}{2} \qquad T_- \text{ or } D_- \text{ conducts}$$

- Operation depends on i_L and u_C

PLR Waveforms, DCM

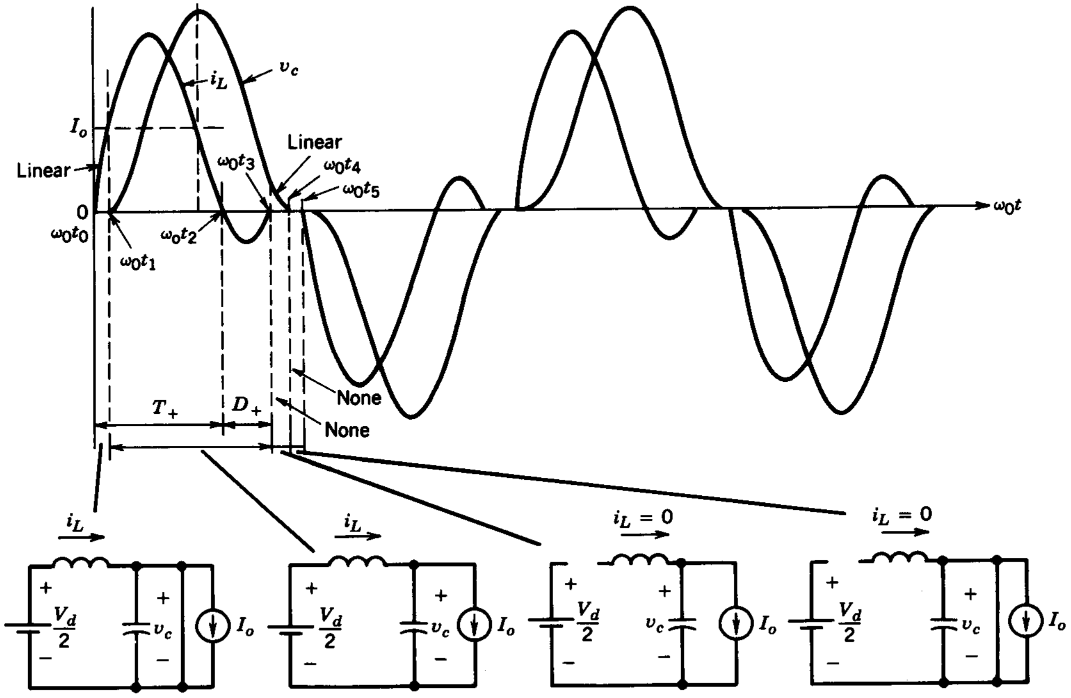


Figure 9-18 PLR dc–dc converter in a discontinuous mode.

- The current is in a discontinuous conduction mode

Operation (1/2)

- T+ is turned on at $\omega_0 t_0$, $i_L = u_C = 0$
- Constant output current flows through the diode bridge and keeps capacitor voltage as zero
  - After $\omega_0 t_1$ current difference charges resonant capacitor
- LC-circuit current i_L goes to zero at $\omega_0 t_2$ and becomes negative
  - D+ conducts as T- is not turned on

Operation (2/2)

- Gate of T+:n is removed before $\omega_0 t_3$:a
  - i_L remains zero
  - Cr discharges in time $\omega_0(t_3 - t_4)$ with I_o
  - After this we are in the beginning
- Output voltage average is adjusted with time $t_5 - t_4$
- No turn-on or turn-off losses in diodes

PLR Waveforms, CCM, $\omega_s < \omega_0$

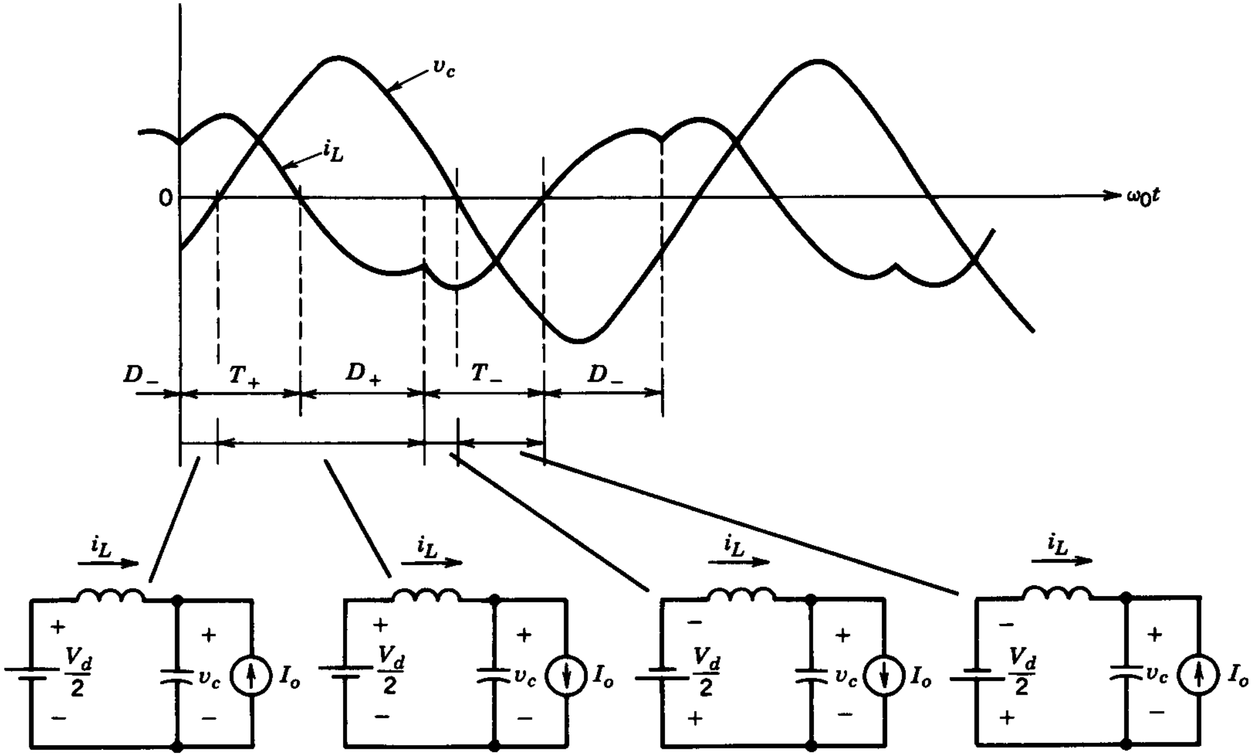


Figure 9-19 PLR dc–dc converter in a continuous mode with $\omega_s < \omega_0$.

- The operating frequency is below the resonance frequency

PLR Converter Waveforms, CCM, $\omega_s > \omega_0$

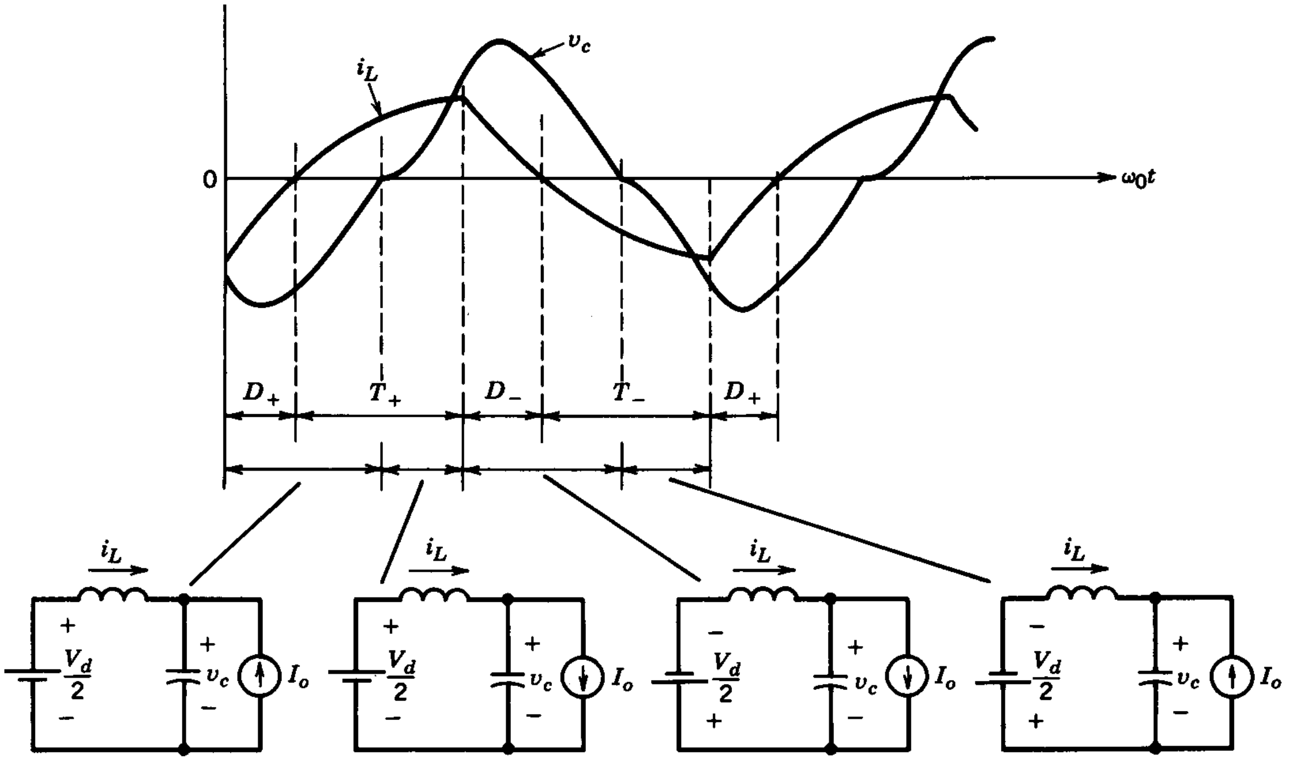


Figure 9-20 PLR dc–dc converter in a continuous mode with $\omega_s > \omega_0$.

- The operating frequency is above the resonance frequency

PLR, CCM

- No trun-on losses
- Turn-off with current
  - Losses
  - Losses can be reduced with lossless snubber as in SLR

PLR Converter Characteristics

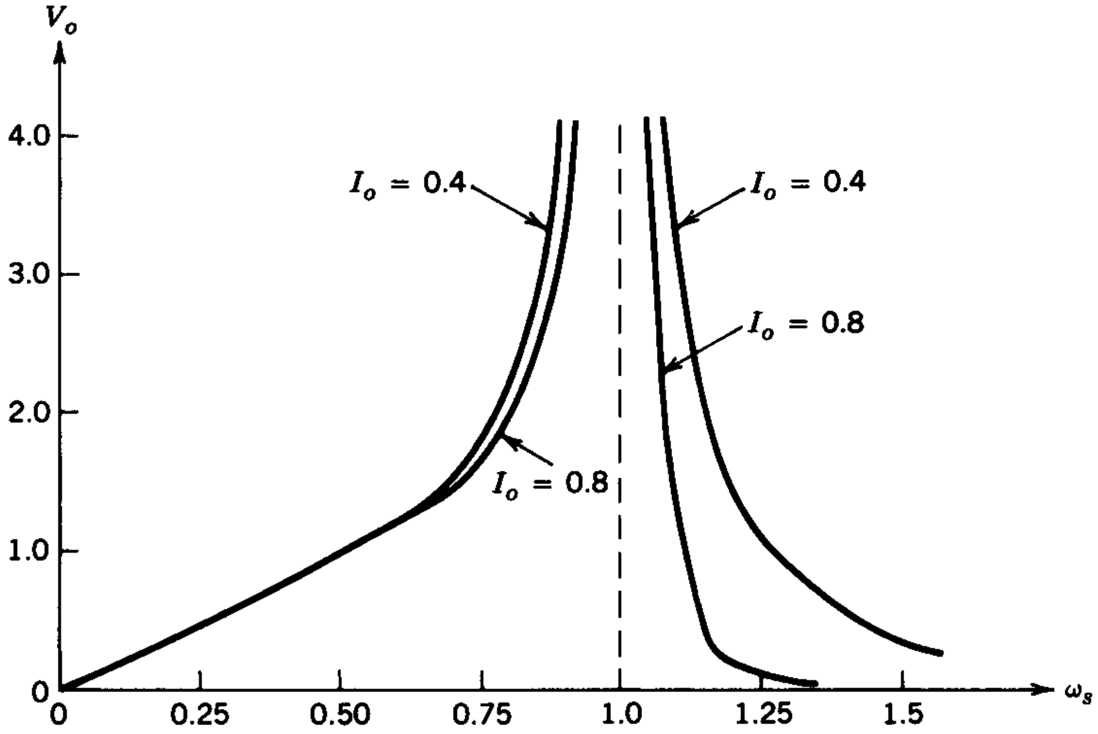


Figure 9-21 Steady-state characteristics of a PLR dc–dc converter. All quantities are normalized.

- Output voltage as a function of operating frequency for various values of the output current

PLR Characteristics

- DCM
  - Output voltage doesn’t depend on current
    - Many parallel outputs are possible
  - Output voltage depends linearly from switching frequency
- Output voltage can be higher than input
- Maximum current and voltage much higher than I_o and U_d

PLR versus SLR

- PLR
  - Acts as voltage sourc
    - Fits for multiple output SMPS
  - No built in overload protection
  - Both step up and step down operation

Hybrid-Resonant DC-DC Converter

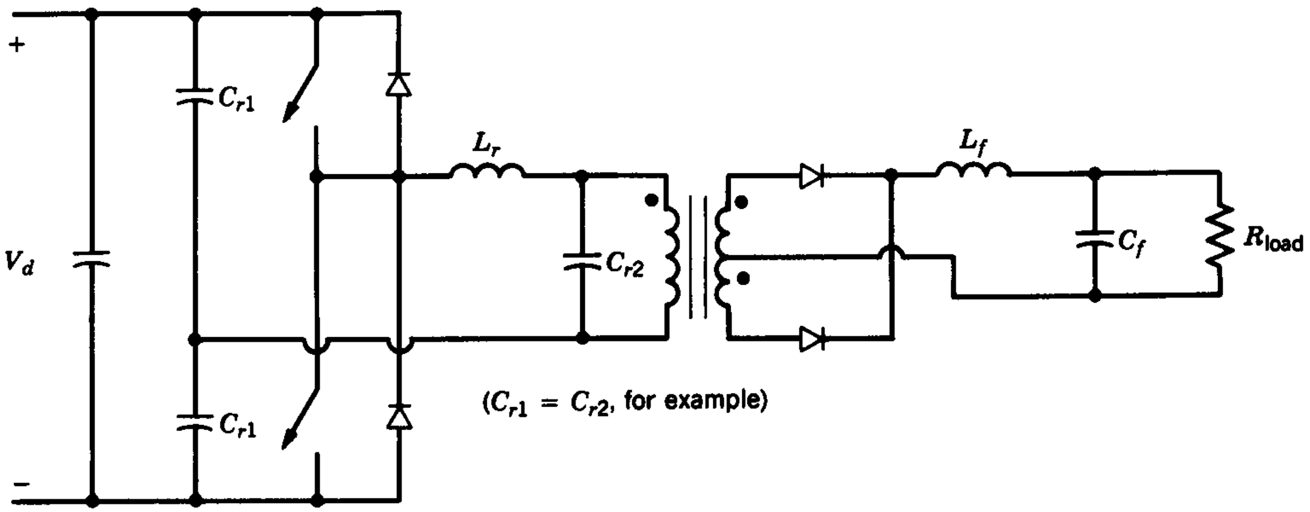


Figure 9-22 Hybrid-resonant dc–dc converter.

- Combination of series and parallel resonance

Parallel-Resonant Current-Source Converter

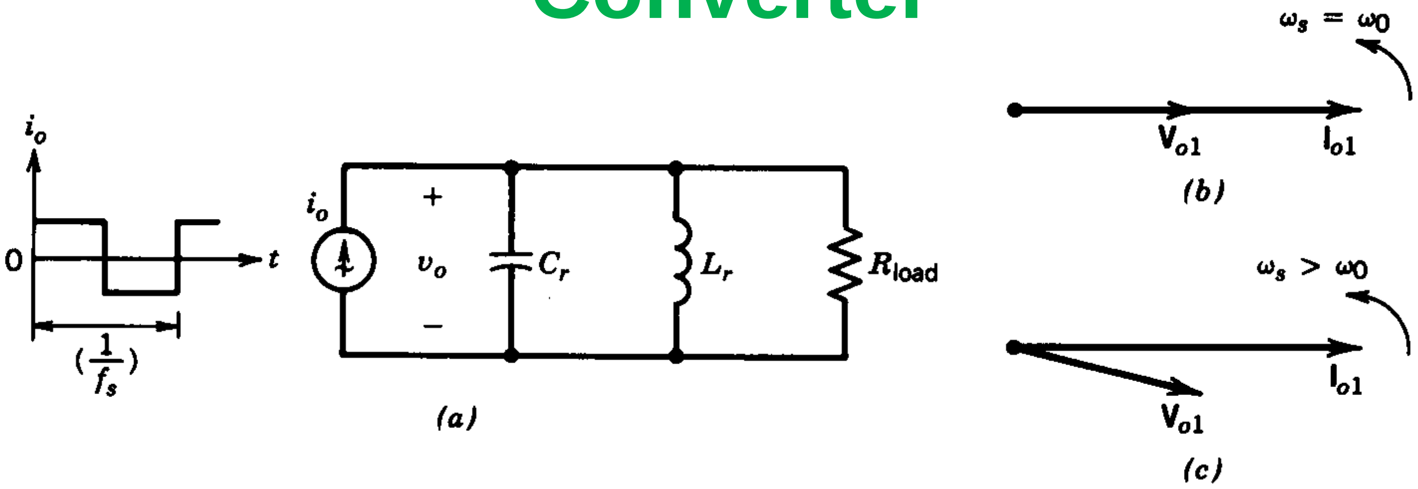


Figure 9-23 Basic circuit for current-source, parallel-resonant converter for induction heating: (*a*) basic circuit; (*b*) phasor diagram at $\omega_s = \omega_0$; (*c*) phasor diagram at $\omega_s > \omega_0$.

- Basic circuit to illustrate the operating principle at the fundamental frequency

Parallel-Resonant Current-Source Converter

- Using thyristors; for induction heating

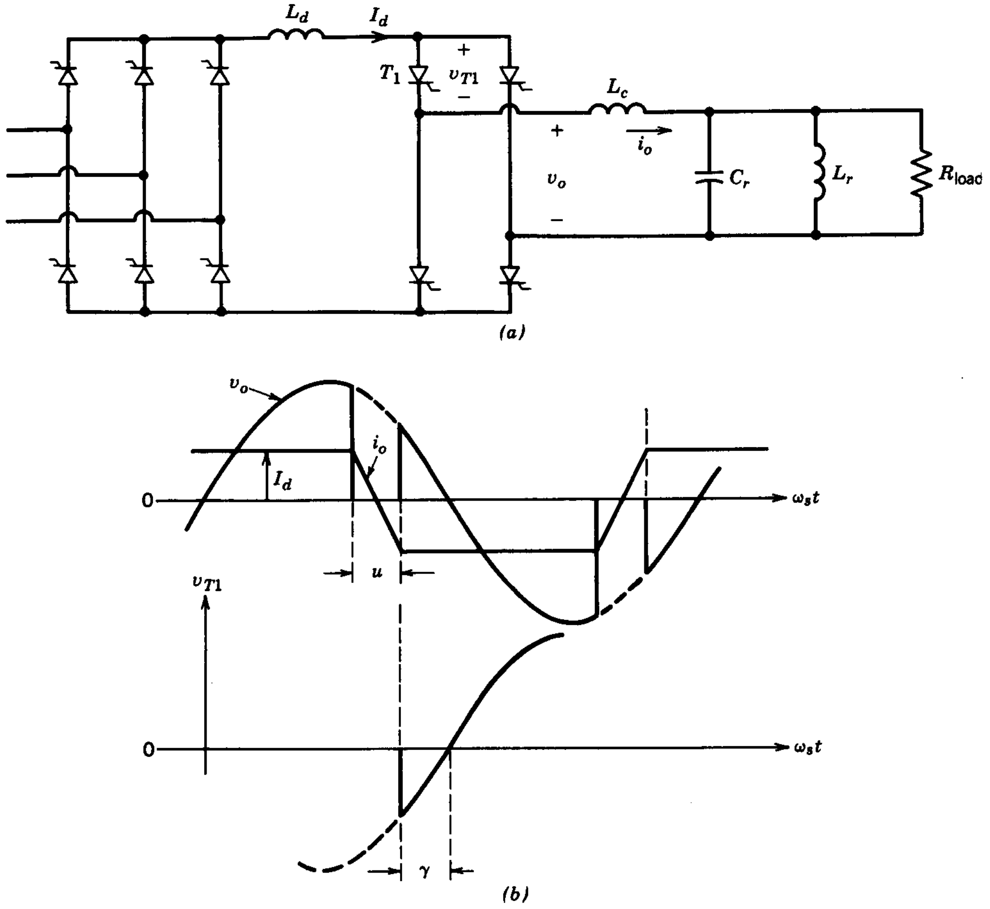


Figure 9-24 Current-source, parallel-resonant inverter for induction heating: (*a*) circuit; (*b*) waveforms.

Class-E Converters

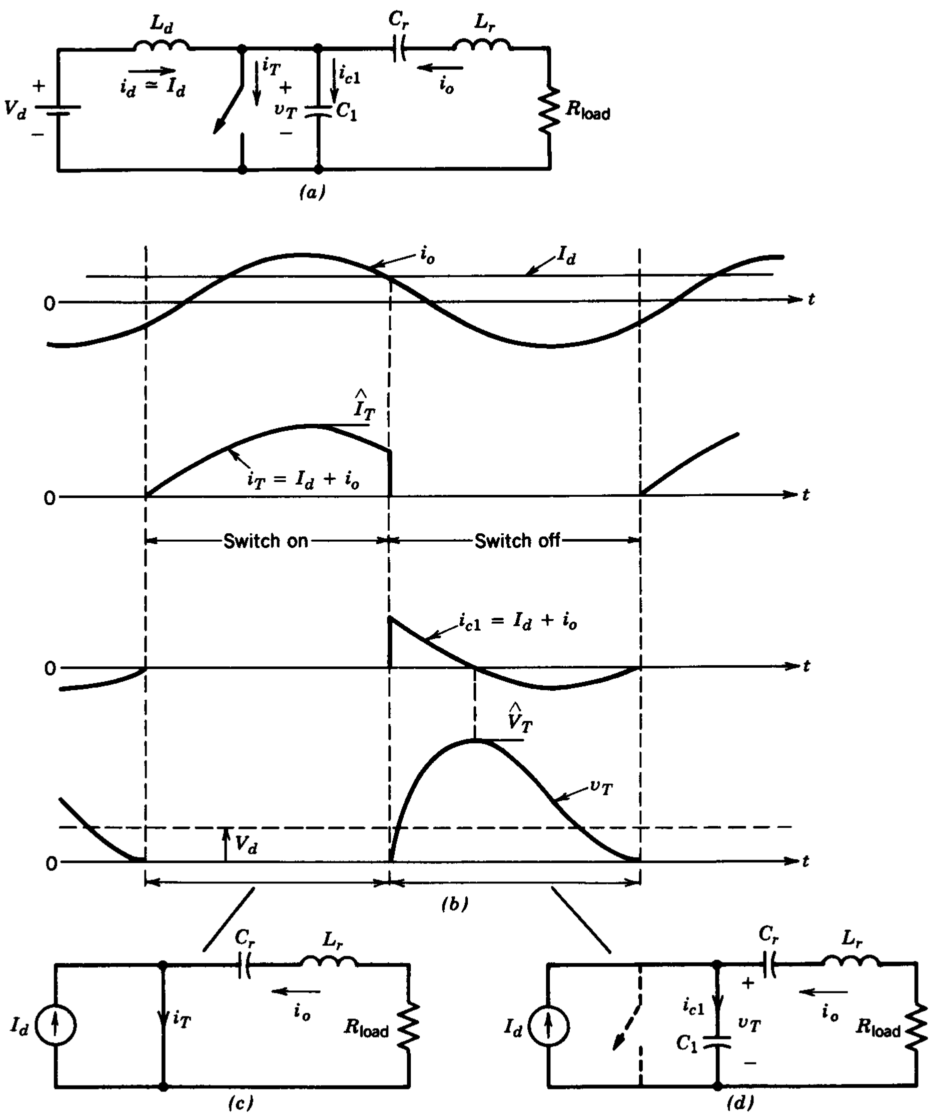


Figure 9-25 Class E converter (optimum mode, $D = 0.5$).

Optimum mode

Class-E Converters

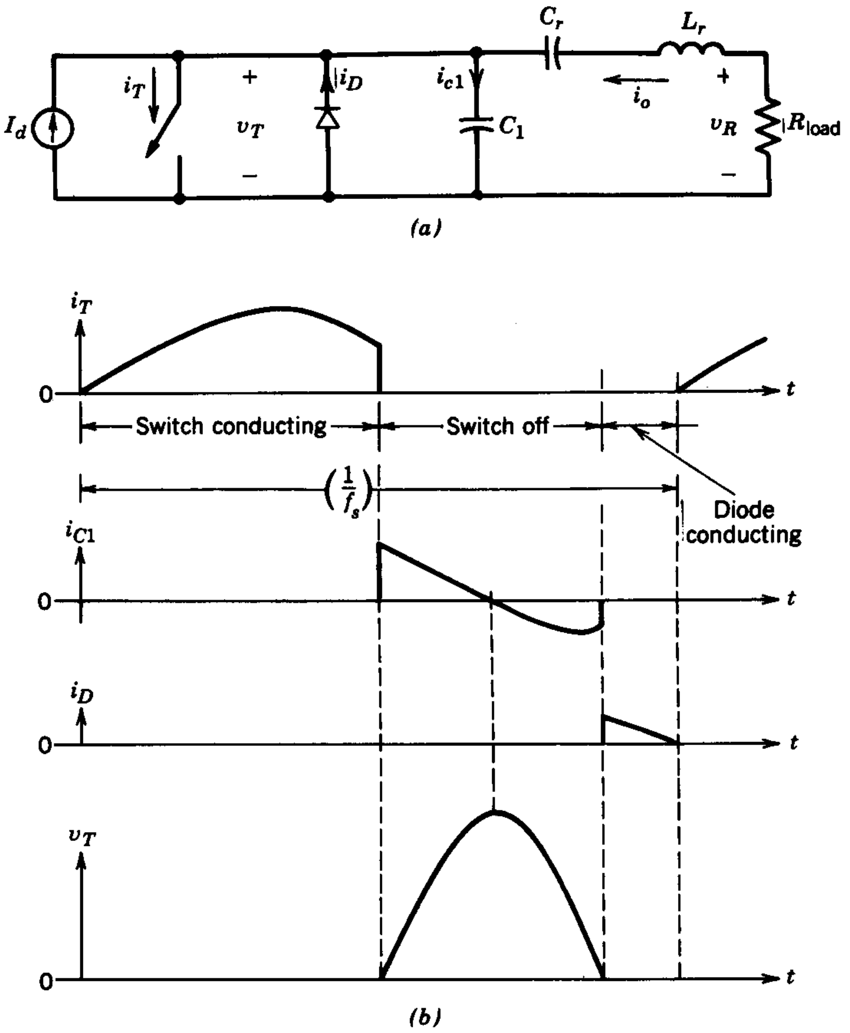


Figure 9-26 Class E converter (nonoptimum mode).

Non-Optimum mode

Resonant Switch Converters

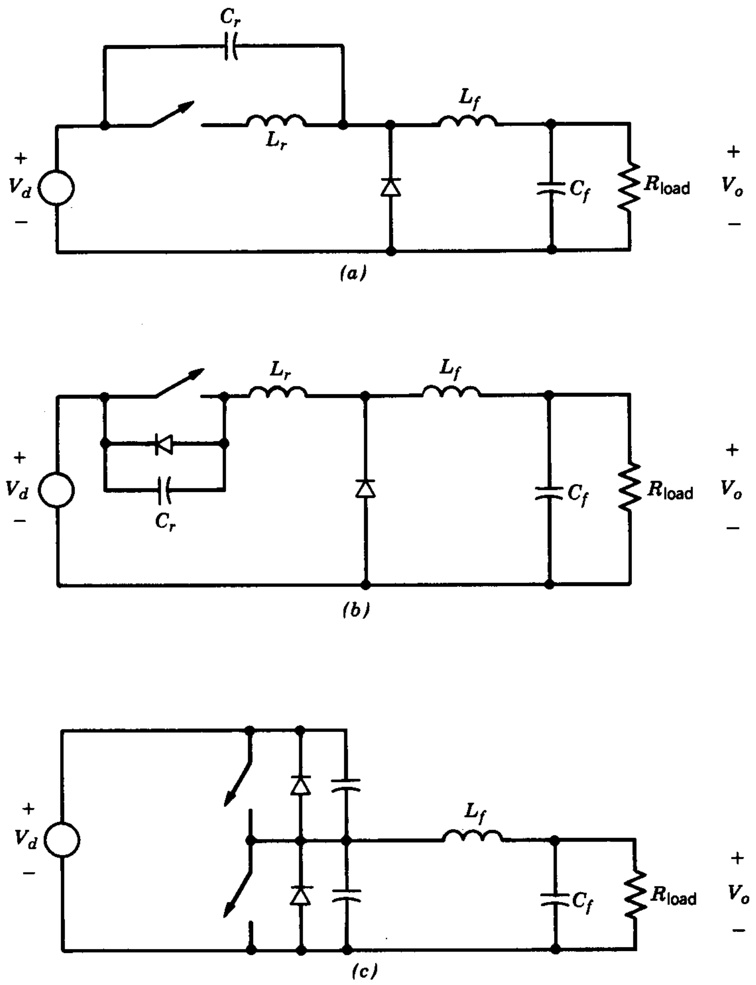


Figure 9-27 Resonant-switch converters: (a) ZCS dc–dc converter (step-down); (*b*) ZVS dc–dc converter (step-down); (*c*) ZVS-CV dc–dc converter (step-down).

Classifications

Resonant Switch Converters

- Similar ideas was used before gate turn-off devices
  - Thyristors were used in dc-dc converters and dc-ac inverters => additional LC circuit used to turn-off conduction thyristor (e.g. McMurray-circuit)
- Nowadays also in power supplies
- Transformer parasitic inductances and other parasitics can be used in LC-circuits

Classification

- ZCS, zero-current-switching
  - Switch turns on and off without current
- ZVS, zero-voltage-switching
  - Switch turns on and off without voltage
- ZVS-CV, zero-voltage-switching, clamped voltage
  - As before but at least two switches
  - Voltage over switch is limited to the supply voltage

ZCS Resonant-Switch Converter

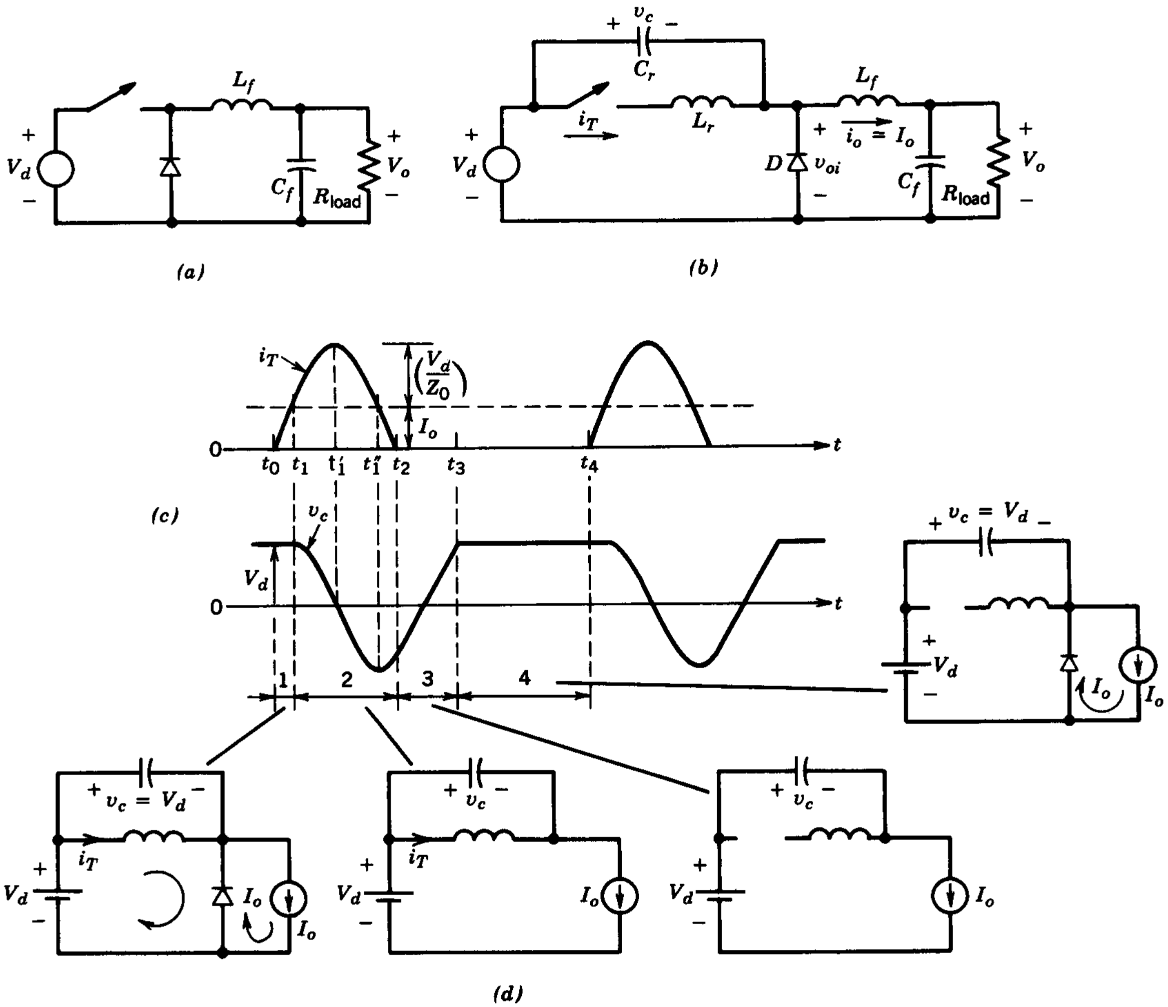


Figure 9-28 ZCS resonant-switch dc–dc converter.

Operation principle

- Current I_o goes through the diode
  - C_r is charged to the supply voltage U_d
- Switch is turned on
  - Diode D conducts untill at t_1 current is equal to the load current
- L_rC_r is a resonant circuit discharging C_r
  - At t_2 current goes to zero and switch turns off
- Output current I_o charges C_r to the supply voltage
  - At t_3 diode starts to conduct

ZCS Resonant-Switch Converter

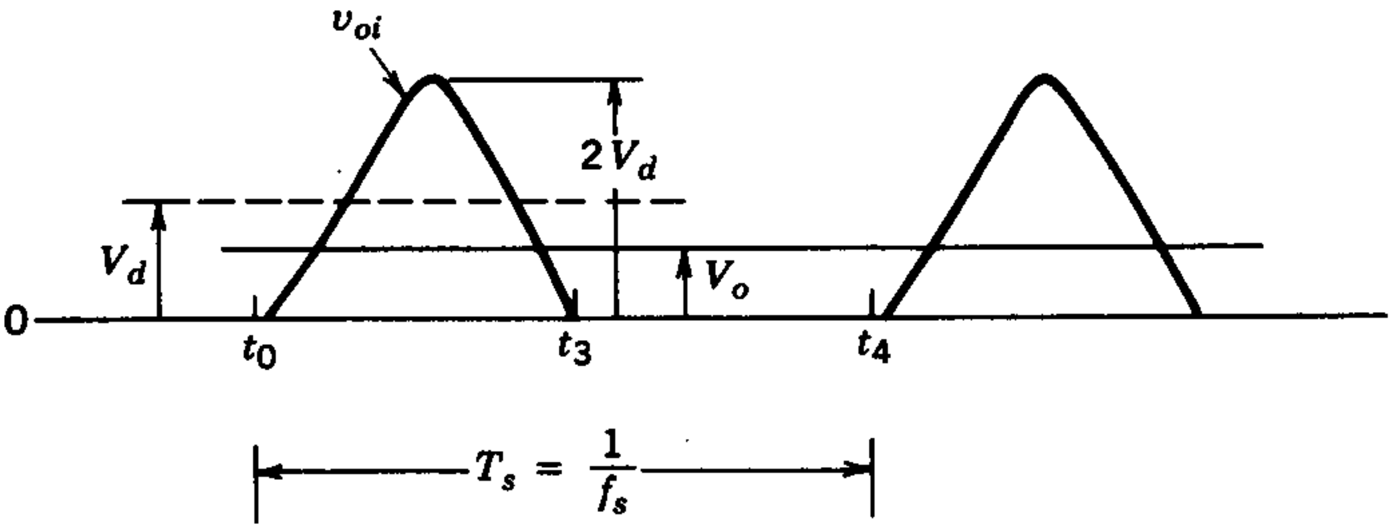


Figure 9-29 v_{oi} waveform in a ZCS resonant-switch dc–dc converter.

- Waveforms; voltage is regulated by varying the switching frequency, time interval t_4 - t_3

Properties

- Resonant frequency in MHz area resonanssitaajuus valitaan MHz-alueelle
- Switch turns on and off without current
  - At turn-off switch voltage is U_d => turn-off losses
- Output current $I_o < V_o / Z_0 \, , Z_0 = \sqrt{L_r / C_r}$
- When output current increases output voltage decreases
  - Switching frequency is increased
- Antiparallel connected diode
  - At low load resonant circuit energy can be supplied back to the supply

Electromagnetic Interference, EMI

- Losses and EMI due to the converter are reduced when soft switching is used
- Peak current of switch
  - High when compared to the output current
  - Conduction losses are higher than in hard switching
  - EMI increases???

ZCS Resonant-Switch Converter

- A practical circuit
- Capacitor is in parallel with the diode

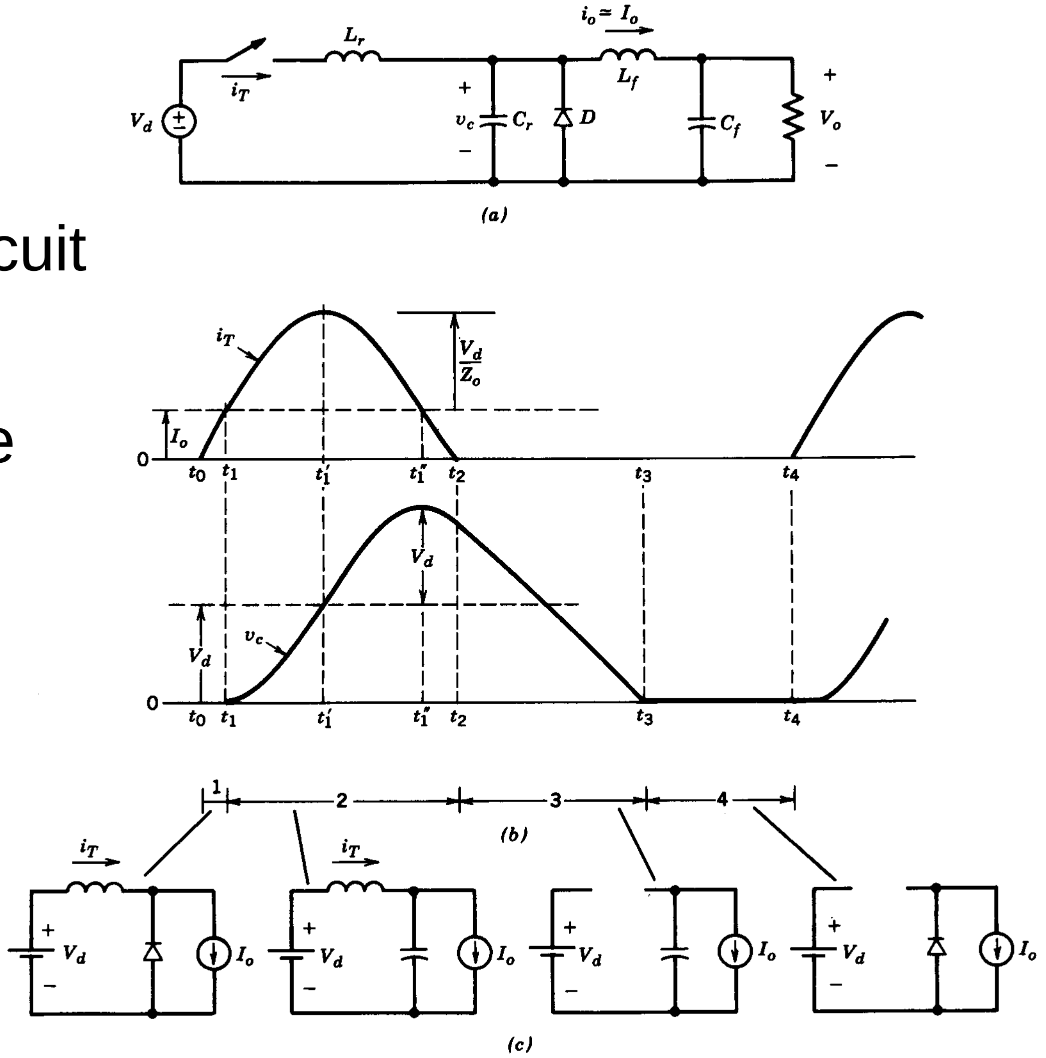


Figure 9-30 ZCS resonant-switch dc–dc converter; alternate configuration.

Operation

- When switch is turned on its current increases linearly untill $i_T = I_o$
  - Diode turns off
- Current $i_T - I_o$ charges capacitor after t_1
- At t_2 current i_T goes to zero and switch turns off
- Capacitor is discharged with output current

ZVS Resonant-Switch Converter

- Capacitor is connected in paralle with the switch => limits voltage changes
- Serious limitations

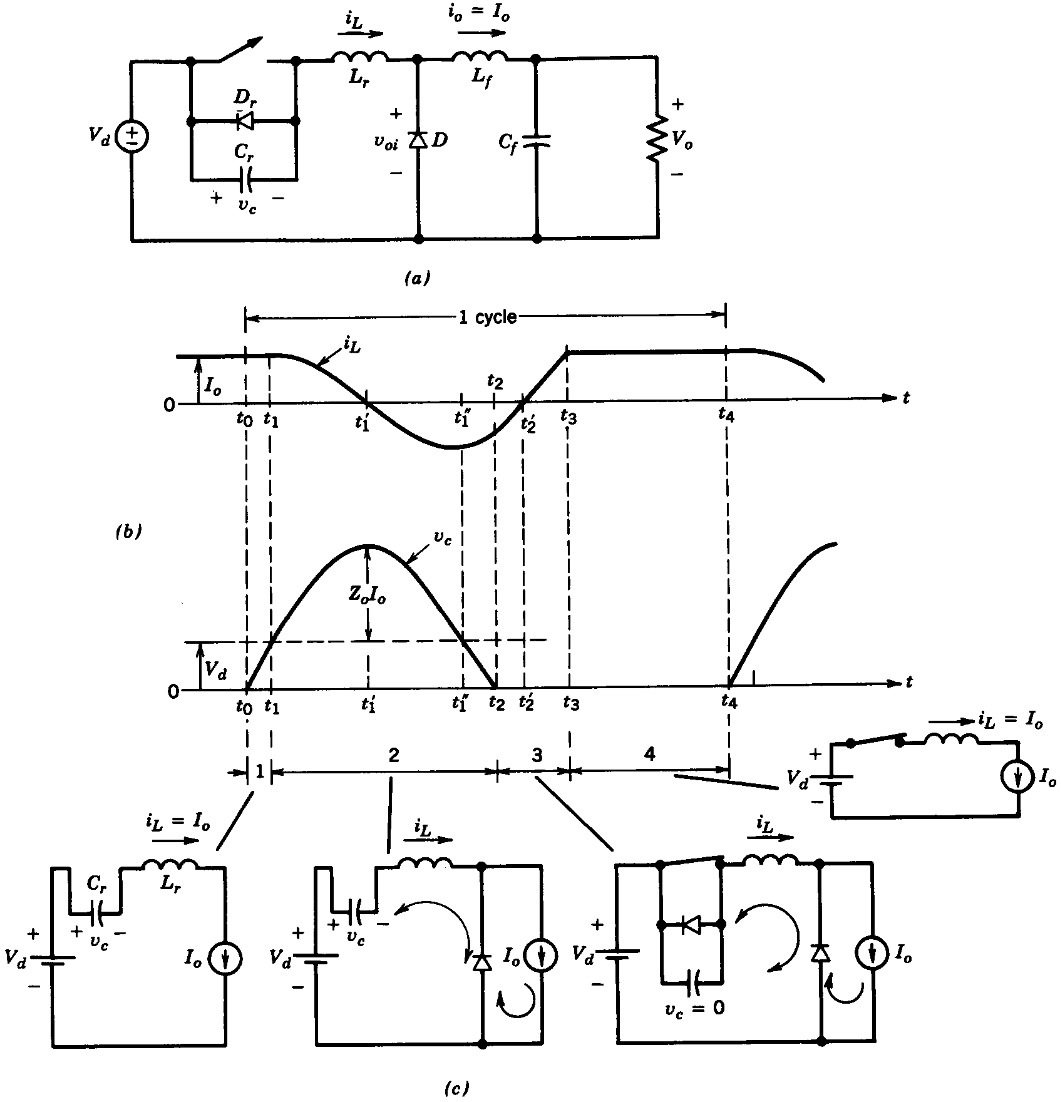


Figure 9-31 ZVS resonant-switch dc–dc converter.

Operation

- Switch is turned off when it conducts I_o
  - Capacitor C_r charges with constant current
- At t_1 $u_C = U_d$
  - Diode D conducts, C_r L_r resonant circuit
- At t_2 C_r voltage becomes zero
  - D_r starts to conduct, gate control is given to switch and current i_L increases linearly
  - A $t_2´$ current is positive and it goes through the switch
- At t_3 i_L is equal to I_o and D stops to conduct

ZVS Resonant-Switch Converter

Output voltage

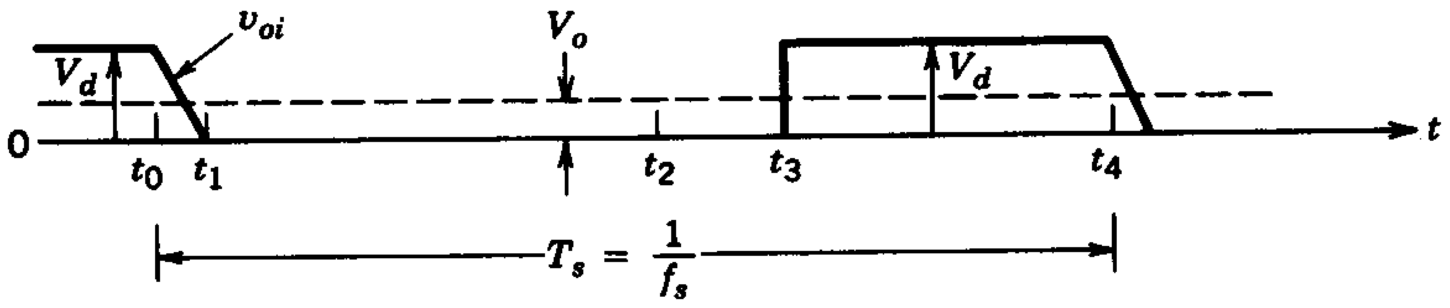


Figure 9-32 The v_{oi} waveform in a ZVS resonant-switch dc–dc converter.

Comparison of ZCS and ZVS

- ZCS
  - Switch maximum current $I_o + V_d / Z_0$
  - Output current limited $I_o < V_o / Z_0 , Z_0 = \sqrt{L_r / C_r}$
- ZVS
  - Switch maximum voltage $V_d + I_o Z_0$
  - Output current must be larger than V_d / Z_0
  - High voltage switch is needed if output power variation is large

MOSFET Internal Capacitances

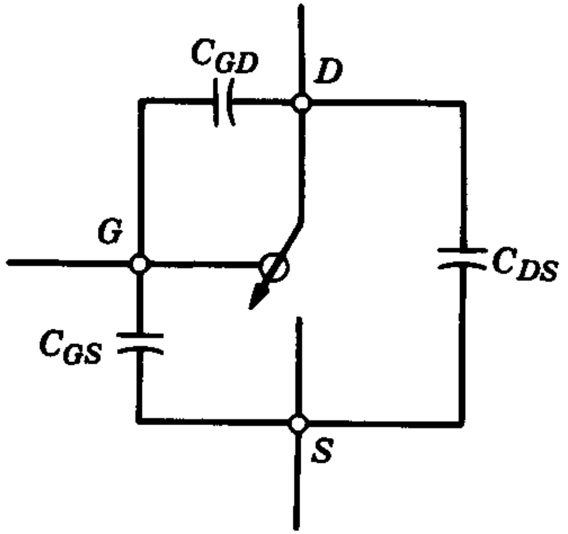


Figure 9-33 Switch internal capacitances.

- These capacitances affect the MOSFET switching
- ZVS is better for MOSFET
- ZCS good e.g. for IGBT’s because of tail current

Zero-voltage-switching, clamped-voltage, ZVS-CV

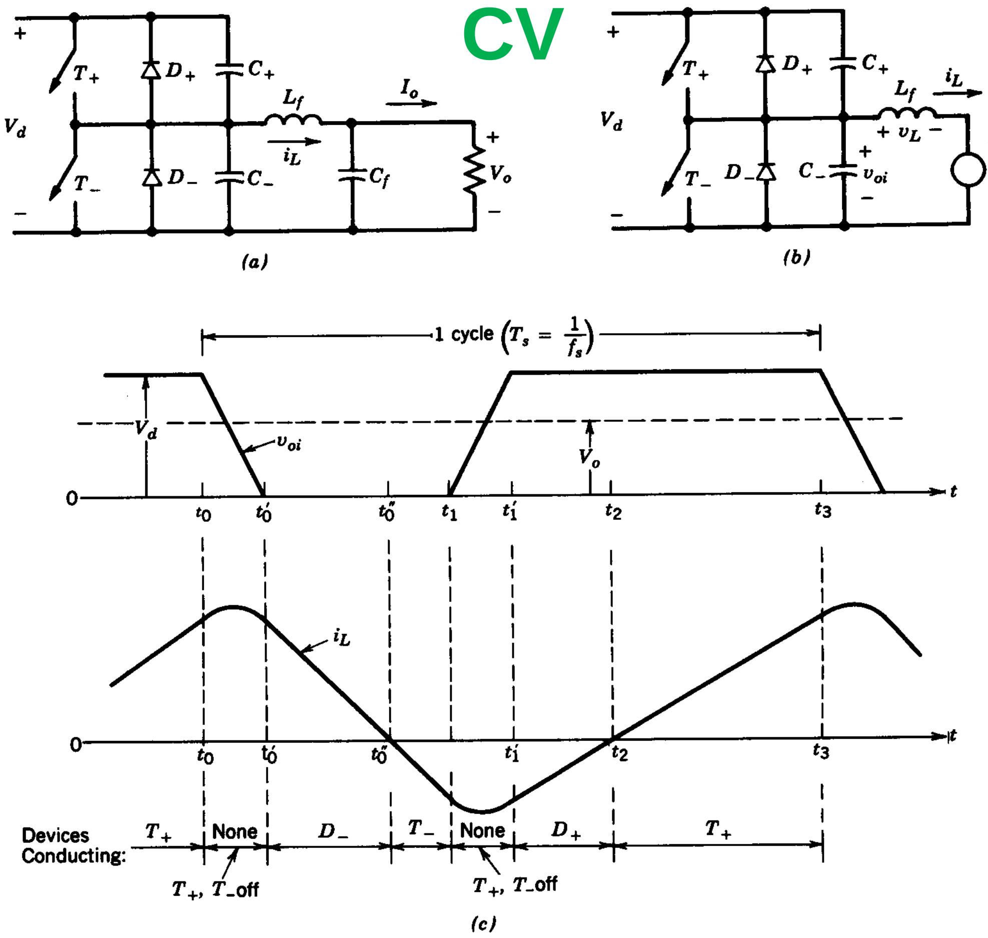


Figure 9-34 ZVS-CV dc–dc converter.

- The inductor current must reverse direction during each switching cycle

ZVS-CV

- Switch turn on and off with zero voltage
  - Maximum voltage is clamped to input voltage
- L_f is small when compared to hard switching
  - Its current is both positive and negative
- T+ conduct current and it is turned off
  - Voltage over it is zero because of C_+

ZVS-CV DC-DC Converter

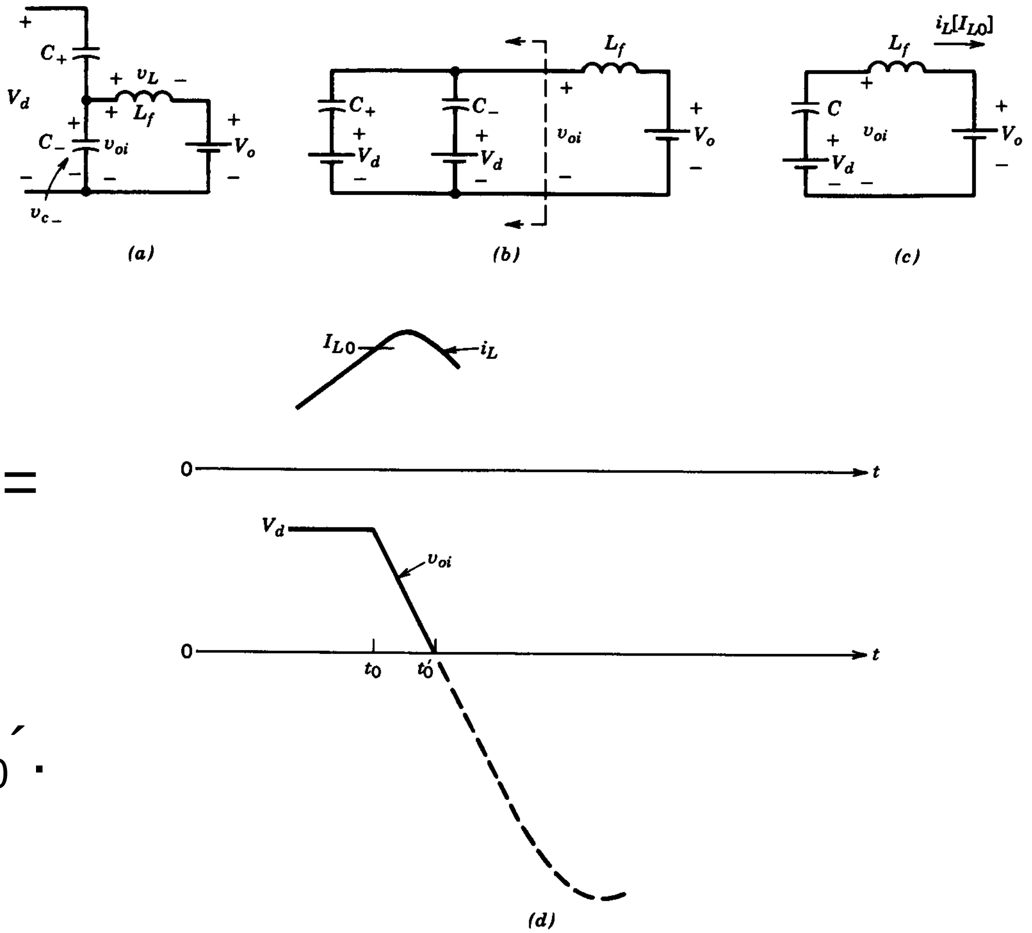


Figure 9-35 ZVS-CV dc–dc converter; T_+, T_- off.

- One transition is shown
- In Fig c) $C_+ = C_- = C/2$
- i_L is not change much during t_0 - t_0'.

Operation (1/2)

- Condensator $C\_$ has discharged at $t_0´$
  - Inductor's current decreases linearly as D- conducts and u_L = -U_o.
  - At the same time gate control to T-
  - When current polarity changes at $t_0´´$ switch starts to conduct
- T- is turned of at t_1 with zero voltage (u_{C-} = 0)
  - When C_- is charged to U_d and C_+ has discharged, negative current flows through diode D+

Operation (2/2)

- After $t_1´$ voltage over inductor is positive
  - Its current is positive after t_2 when T+ conducts
- For ZVS capacitor is connected parallel to the switch
  - Capacitor must be discharged when switch is turned on
  - It is discharged if antiparallel diode has been conducting
  - Therefore current i_L has to have both polarities

Control of output voltage

- Constant frequency PWM can be used
  - Durations t_0 - $t_0´$ and $t_1´$ – t_1 can be assumed short
  - Output voltage is square wave => $U_o \approx D\, U_d$
- L_f must be dimensioned so that
  - Even with smallest U_d and highes load current instantaneous value of i_L is also negative

ZVS-CV Principle Applied to DC-AC Inverters

- Even in dc-dc converter inductor current had negative values, now both polarities are equal
- Very large ripple in the output current

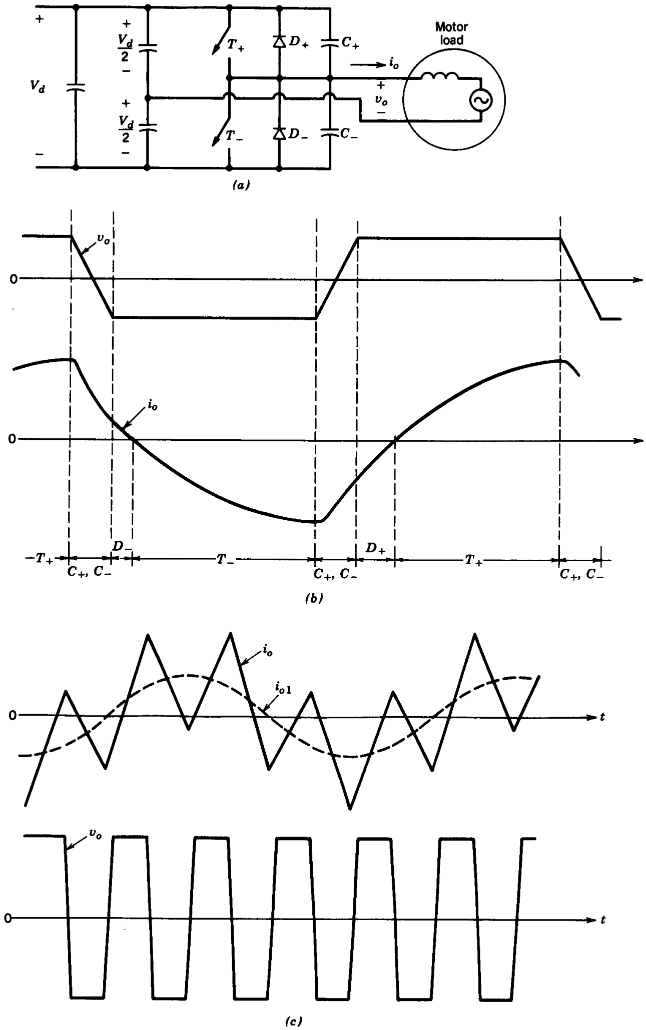
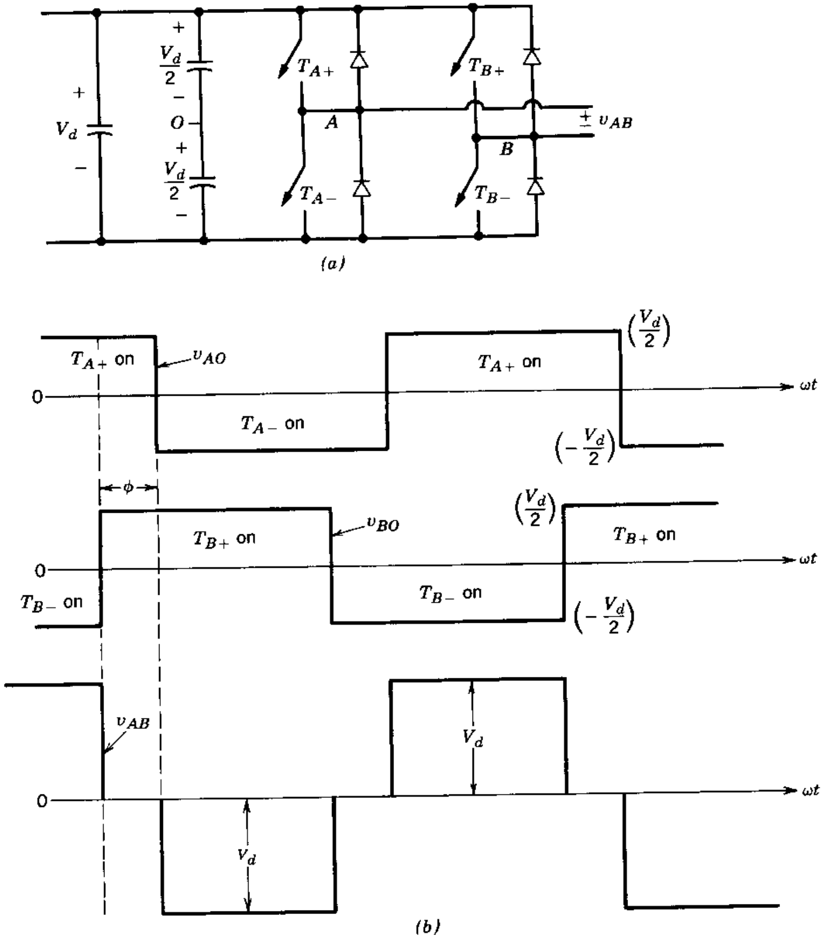


Figure 9-36 ZVS-CV dc-to-ac inverter: (*a*) half-bridge; (*b*) square-wave mode; (*c*) current-regulated mode.

Control of output voltage

- In full bridge delay between pole voltages can be adjusted



Three-Phase ZVS-CV DC-AC Inverter

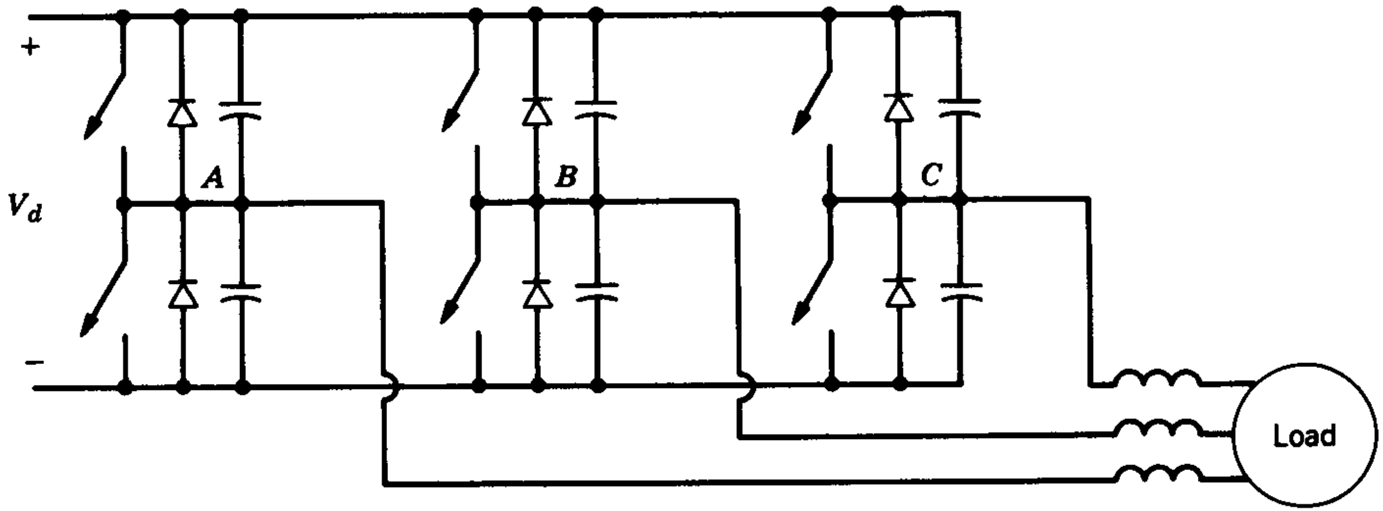


Figure 9-37 Three-phase, ZVS-CV dc-to-ac inverter.

- Very large ripple in the output current

ZVS-CV with Voltage Cancellation

- Commonly used
- Lm is magnetizing inductance of transformer

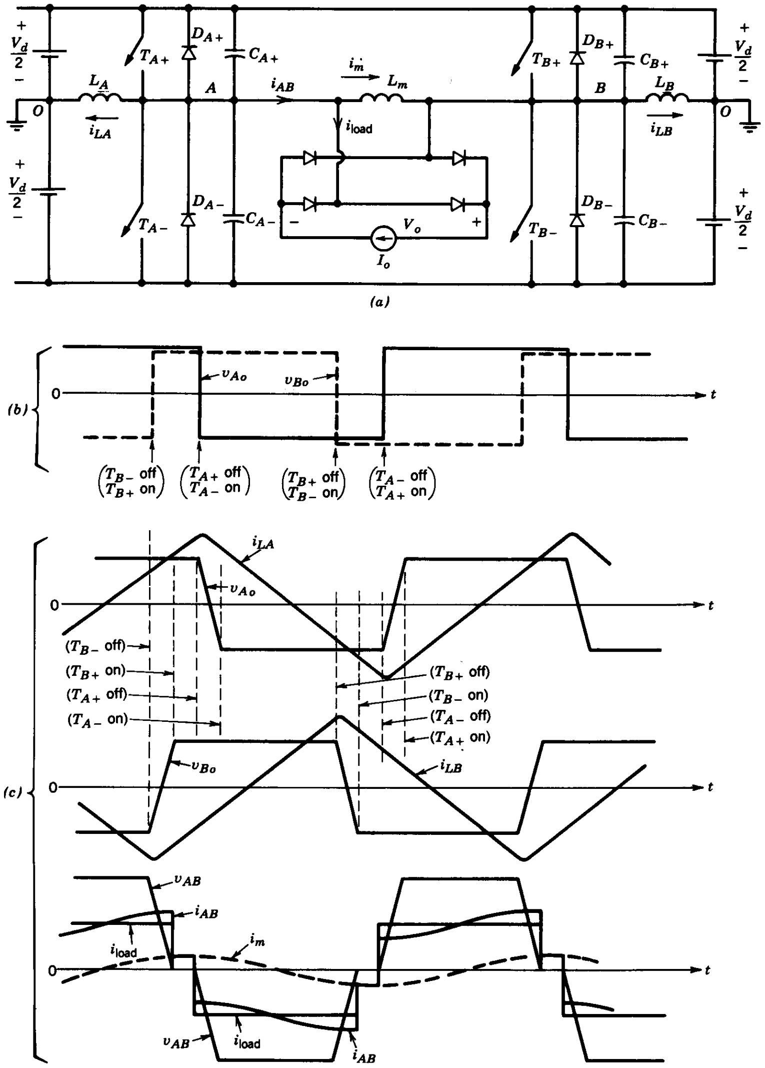


Figure 9-39 ZVS-CV full-bridge dc–dc converter: (*a*) circuit; (*b*) idealized switch-mode waveforms; (*c*) ZVS-CV waveforms.

Resonant DC-Link Inverter

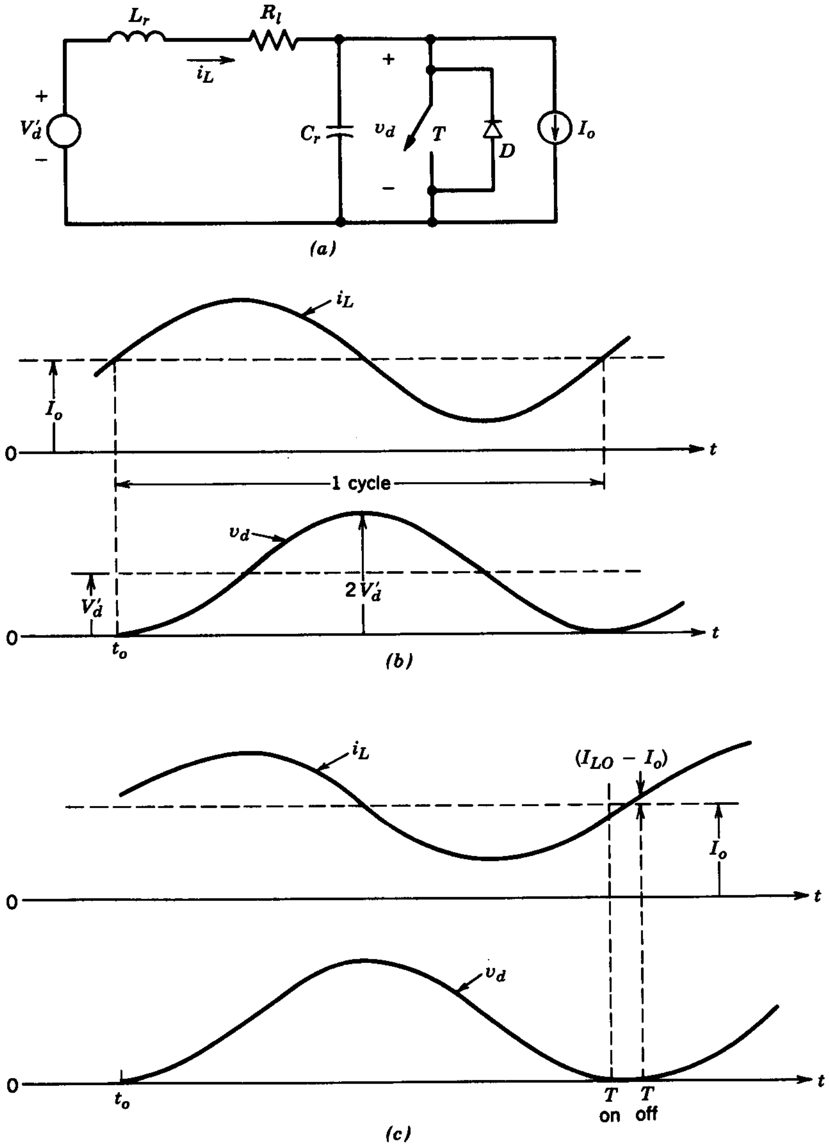


Figure 9-40 Resonant-dc-link inverter, basic concept: (*a*) basic circuit; (*b*) lossless $R_l = 0$; (*c*) losses are present.

- The dc-link voltage is made to oscillate

Three-Phase Resonant DC-Link Inverter

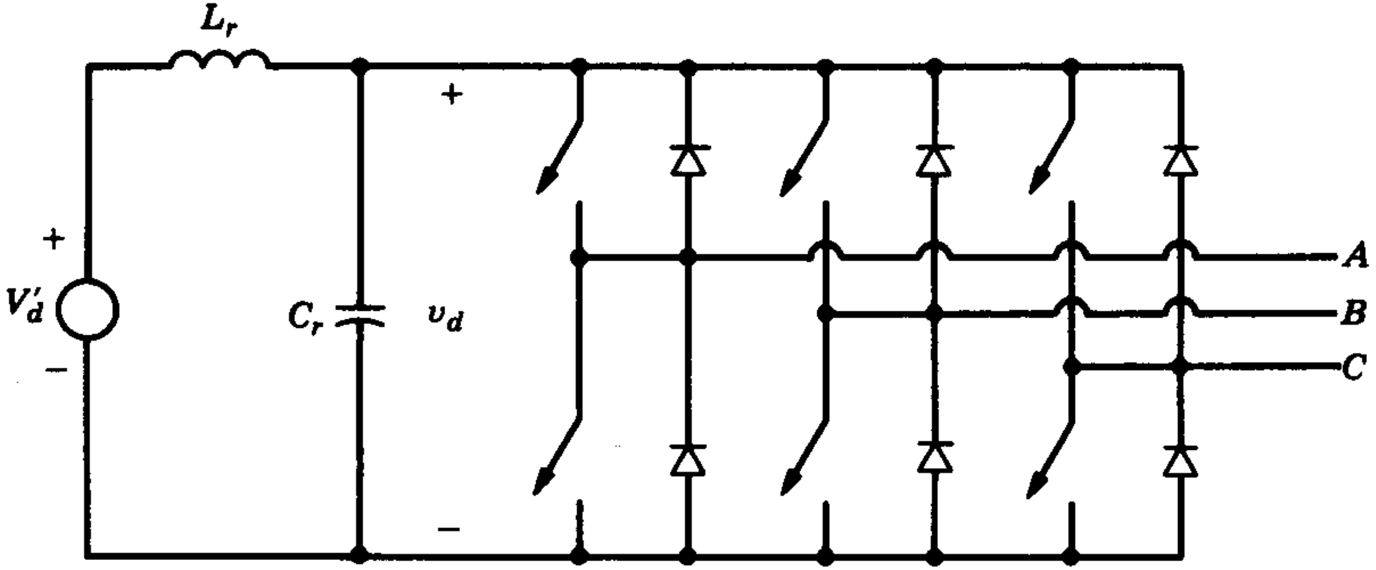


Figure 9-41 Three-phase resonant-dc-link inverter.

- Modifications have been proposed

High-Frequency-Link Inverter

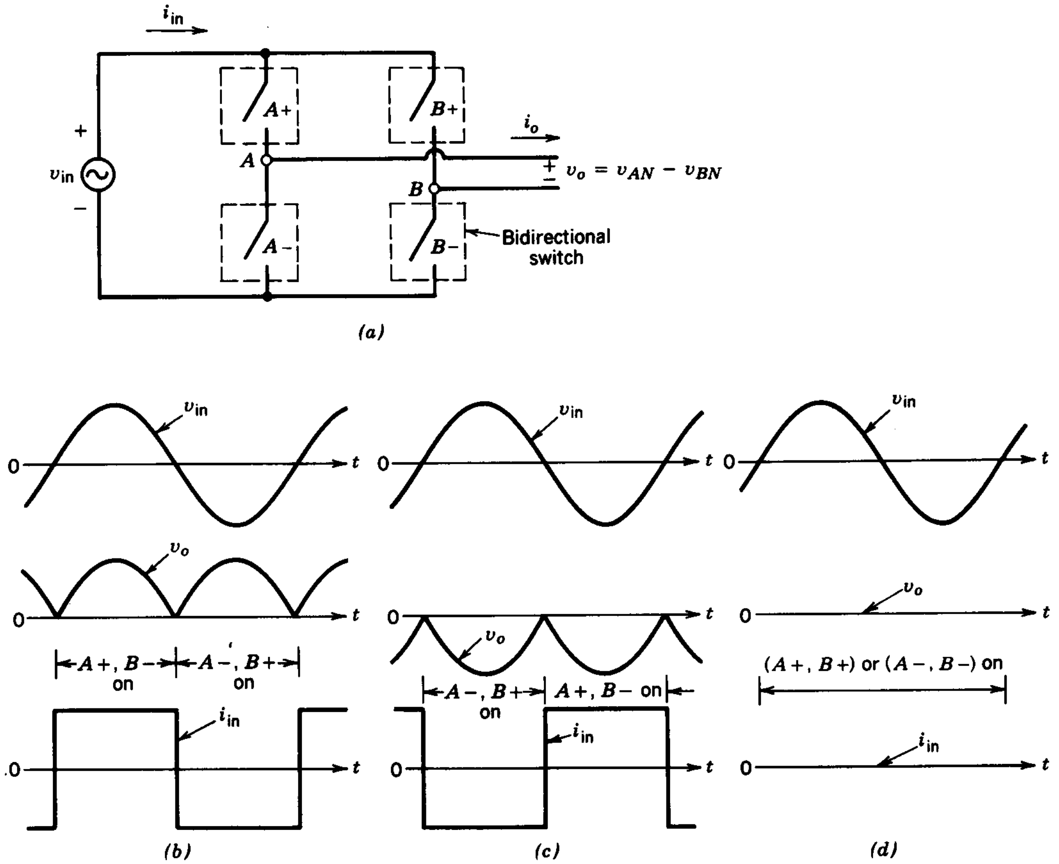


Figure 9-42 High-frequency-link integral-half-cycle inverter.

- Basic principle for selecting integral half-cycles of the high-frequency ac input

High-Frequency-Link Inverter

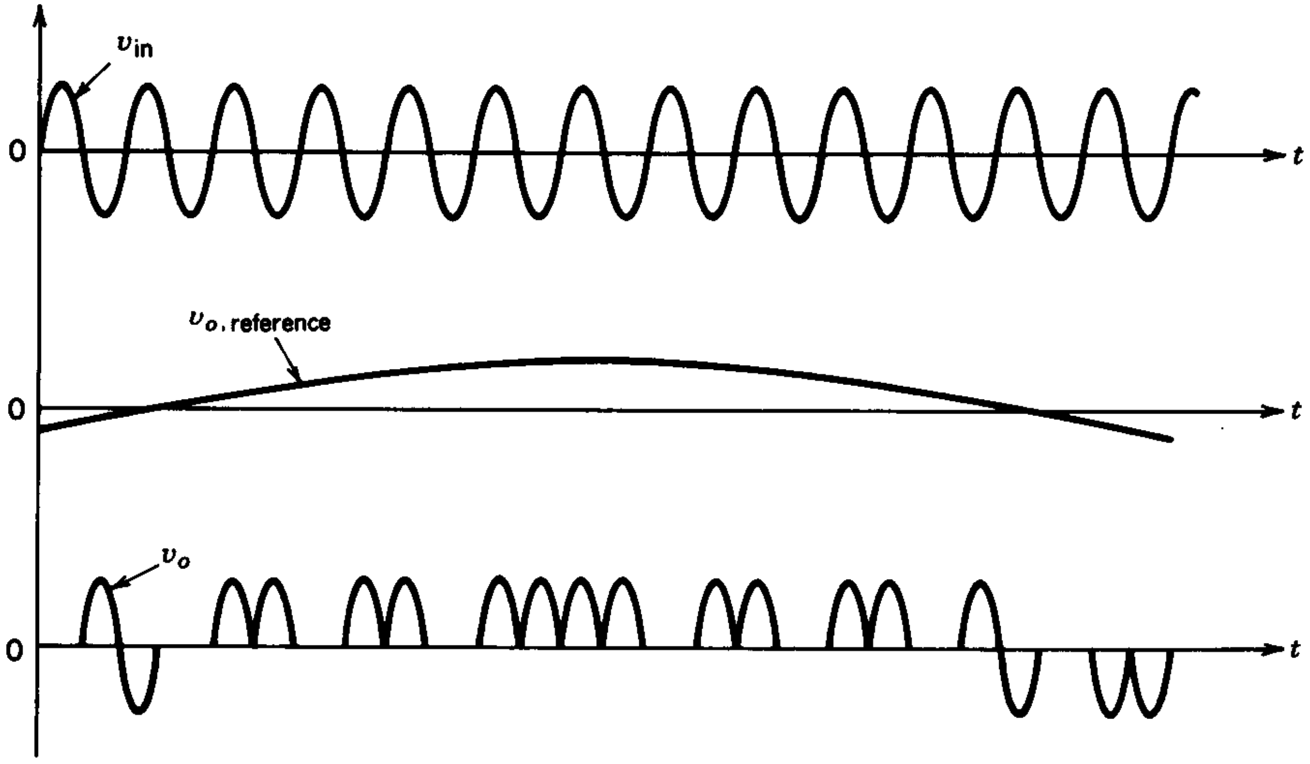


Figure 9-43 Synthesis of low-frequency ac output.

- Low-frequency ac output is synthesized by selecting integral half-cycles of the high-frequency ac input

High-Frequency-Link Inverter

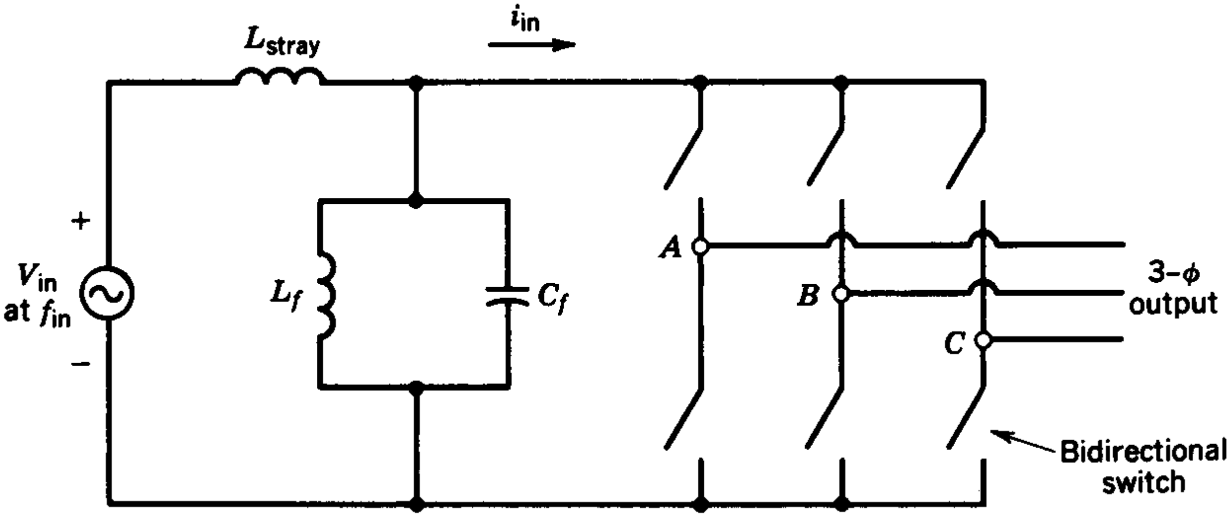


Figure 9-44 High-frequency ac to low-frequency three-phase ac converter.

- Shows how to implement such an inverter